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How does bike-sharing enable (or not) resilient cities, communities, and individuals? Conceptualising transport resilience from the socio-ecological and multi-level perspective

Tommy H.Y. Chan

Transport Studies Unit, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford, OX1 3QY, UK

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ABSTRACT

Bicycles play a crucial role in promoting resilient urban mobility, yet current approaches often focus primarily on engineering resilience, emphasising short-term resistance, adaptability, and recovery from disruptions. This perspective tends to overlook the equally important social dynamics and institutional factors. Socio-ecological resilience theory fills this gap by viewing disruptions as opportunities for renewal, innovation, and transformation, recognising that systems operate in dynamic, non-equilibrium states where change is inevitable and unpredictable. However, its application in transport studies has been limited due to the complexity of empirical implementation. This paper utilises the Multi-Level Perspective (MLP) to offer a framework for understanding transport systems as complex socio-technical networks—encompassing artifacts, infrastructure, human actors, regulations, and cultural meanings. MLP's nested, layered ontology helps conceptualise the complexity and evolution of transport systems. Using Hong Kong's dockless bike-sharing system during the social movements and pandemic, this study explores how individual, community, and organisational resilience interact across scales. It shows how institutions both shape and are shaped by human agency, with interpretive flexibility allowing individuals to adapt institutional rules to personal contexts. The structuration of parking practices—shaped by voluntary digital communities managing bike parking and formalised through organisational and regulatory frameworks—illustrates how multi-level resilience arises through interactions among diverse actors, rather than from the mere accumulation of individual actions. While higher degrees of structuration, shaped by the scale of fields and number of actors reproducing them, foster stability, they can also perpetuate social exclusion, highlighting the need for equitable policies that balance individual responsibility with inclusive institutional strategies.

1. Introduction

Recent global crises have catalysed socio-political transformations, disrupting established socio-institutional structures and fostering new system forms. In 2019, major social movements like Extinction Rebellion in Western Europe (Gardner et al., 2022) and the 'Be Water' pro-democracy protests in Hong Kong (Holbig, 2020) and Thailand (Teeratanabodee, 2023) highlighted how social movements can foster new knowledge practices, reinterpret scientific understanding, and inspire bottom-up solutions. In 2020, the coronavirus pandemic put mass protests on hold, yet social movements strengthened internal networks, fostering mutual support and solidarity within and beyond communities (Chan et al., 2021; Fransen et al., 2022). These crises have prompted a rethinking of transport resilience, focusing not on mere recovery but on adaptation to a 'new normal.' Bicycles and bike-sharing services have gained attention as valuable tools for resilient urban mobility during global crises. However, most perspectives emphasise physical infrastructure and immediate usage during disruptions (e.g., Bi et al., 2022; Chen et al., 2022; Cheng et al., 2022; Kim and Cho, 2022; Li et al., 2024; Teixeira et al., 2023; Teixeira and Lopes, 2020; Zhang et al., 2022). This focus aligns with 'engineering resilience', which assumes transport systems return to a baseline or adapt to a new normal after disturbances (Cretney, 2014; Holling, 1996; Meerow et al., 2016). However, defining this new normal is complex, given ongoing crises like energy shortages, economic instability, and conflicts that impact transport systems both directly and indirectly.

In response, the transport literature has turned towards socio-ecological perspectives that emphasise resilience and system change

E-mail address: ho.chan@ouce.ox.ac.uk.

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through a diverse set of methods (Hayes et al., 2019; Schwanen, 2021). While quantification and modelling remain central (Chan et al., 2024a; Feng et al., 2024; Peng et al., 2024; Wang et al., 2022), socio-ecological approaches consider uncertainty over risk and possibility over probability, which is more challenging to quantify (Cantelmi et al., 2021; Karreinen et al., 2023). Interpretive and narrative methods that highlight individuals' lived experiences also help to reveal how resilience emerges from everyday interactions (Hayes et al., 2019; Schwanen, 2021). Unlike the top-down engineering approaches, socio-ecological resilience emphasises stakeholder participation, making knowledge creation a collective, interactive process (Chester et al., 2021). However, operationalising socio-ecological resilience remains challenging (Sterk et al., 2017). Due to non-linear feedback, self-organisation, and interdependencies, transport systems are not easily isolated from other complex systems like energy, land use, and technology. Disturbances in one system often cascade into others, creating multiple direct and indirect effects (Markolf et al., 2019). For instance, urbanisation may increase traffic congestion, making cycling less safe and more inconvenient, thus reducing cycling rates, impacting public health, and heightening reliance on motorised transport, which further increases congestion and pollution.

This study addresses a research gap in the transport literature on the limited conceptualisation of transport systems and operationalisation of socio-ecological resilience. By framing transport systems as socio-technical networks composed of interconnected elements such as artifacts, knowledge, regulations, cultural meanings, and infrastructure, it broadens our understanding of resilience. The Multi-Level Perspective (MLP), widely used in socio-technical transition studies (Geels, 2004, 2012, 2020), has proven valuable in transport and sustainability research by providing a systemic view of socio-technical change. Although it has been advocated in transport literature for over a decade (see Geels, 2012; Whitmarsh, 2012), MLP applications have mostly focused on long-term transitions over decades (e.g., Hoffmann et al., 2017; Küffner, 2022; Roberts and Geels, 2018; Schwanen, 2015). This research promotes a broader application of MLP by integrating socio-ecological principles, positioning transport systems as multi-level spaces where institutions operate at various levels of structuration. Focusing on Hong Kong's dockless bike-sharing system, this paper examines how resilience at individual, community, and organisational levels interact to shape a resilient transport network, especially amid socio-political disruptions. This study contributes to the theoretical advancement of multi-level transport resilience by exploring the interplay between agency and social structures. Additionally, it highlights how social group formation, while beneficial, can unintentionally lead to exclusion, potentially locking institutions into strategies that perpetuate social inequalities.

2. Literature review

2.1. The engineering and socio-ecological approach to transport resilience

Urban transport systems encounter frequent disruptions from both human and natural factors, making resilience—the capacity to withstand, recover, and adapt—a central focus in their design and operation. Despite its importance, resilience lacks a universal definition in transport literature, creating challenges for consistent application across different contexts (Wan et al., 2018). The dominant approach, known as 'engineering resilience', originates from engineering, operations research, and disaster management. It prioritises a transport system's robustness (ability to withstand impacts), bounce-back capability (recovery to pre-disruption states), and adaptability to varying operational conditions (Gonçalves and Ribeiro, 2020). This approach emphasises linear cause-and-effect relationships and prescriptive solutions, often quantifying resilience in terms of service levels (supply) and mobility (demand), assuming a predictable and stable system. Although recent research calls for broader resilience concepts that include adaptation and transformation (Gonçalves and Ribeiro, 2020), traditional engineering resilience remains prevalent (Hayes et al., 2019).

The socio-ecological approach offers valuable insights, especially for understanding transport resilience through adaptive capacity—defined as a system's ability to adjust, learn, and innovate in response to new challenges (Hayes et al., 2019; Schwanen, 2021; Tsoi et al., 2021; Walker et al., 2004). Rooted in ecological and environmental sciences (Holling, 1996), socio-ecological resilience highlights continuous improvement, adaptation, and stakeholder capacity-building. It acknowledges complex, multi-scale interactions, from local to global, which are crucial for effective resilience strategies in transport systems (Bale et al., 2015; Chester et al., 2021; Cote and Nightingale, 2012; Grafius et al., 2020; Schwanen, 2015). This perspective recognises that transport systems cannot be isolated from regional, national, or global networks and that resilience strategies at one scale can affect others, including interconnected systems like energy, technology, and water. Consequently, disturbances in one area can cascade, creating extensive direct and indirect impacts (Markolf et al., 2019; Shepherd, 2014).

Diversity and redundancy are also critical in socio-ecological resilience, as they enhance a system's capacity to handle disruptions (Grêt-Regamey et al., 2019; Jones et al., 2013). In transport, this translates to offering multiple routes and various transport modes, such as buses, trains, bicycles, and walking, which create backup options when one mode is compromised (Chan et al., 2023; Liu et al., 2022; Zhang et al., 2024). Less attention, however, has been given to diversifying cycling practices, which can greatly boost resilience. Options like personal bicycle ownership, rental services, and bike-sharing schemes, such as Hong Kong's dockless bike-sharing system, provide flexibility during peak hours or public transport disruptions. This study examines the role of cycling practices in urban transport resilience by analysing responses and adaptations during the 2019 socio-political crisis and the pandemic. It investigates how individual, community, and organisational resilience interact, contributing to the theoretical development of multi-level resilience and addressing equity concerns around social inclusion and exclusion (Lucas, 2012; Schwanen et al., 2015). The following section introduces the MLP as a framework to conceptualise transport systems and support multi-level, socio-ecological resilience thinking.

2.2. Understanding transport systems as socio-technical systems

Addressing the limitations of traditional engineering approaches to transport resilience, this study frames transport systems as socio-technical systems. This perspective recognises that transport networks are not mere collections of physical infrastructure but complex, interconnected systems comprising technologies, actors, institutions, and social practices (Chan et al., 2024b; Star, 1999). In such systems, transport resilience depends on aligned elements, including artifacts, regulations, infrastructure, cultural meanings, and maintenance networks (Geels, 2004; Simoens et al., 2022). Socio-technical systems provide stability through several mechanisms, such as guiding actor behaviour, embedding organisations within interdependent networks, and establishing physical and social barriers that make structural changes challenging.

Socio-technical systems play a significant role in shaping production and consumption patterns, making them critical in both political and societal contexts. In response to these influences, the field of sustainability transitions studies long-term processes of systemic change (Kivimaa and Rogge, 2022; Turnheim et al., 2020). This study employs the MLP, a prominent framework in transition studies, to analyse transport systems. The MLP conceptualises transitions as non-linear processes occurring at three nested levels: niches (innovation hubs), regimes (established practices and norms), and the socio-technical landscape (wider, external pressures over which regimes have limited short-term influence) (Geels, 2012). By organising transport systems

into these layers,[1] the MLP provides a comprehensive framework for examining both stability and change in transport resilience (Fig. 1).

Stable transport systems exhibit predictability, lock-in, and path dependency, leading to incremental changes along established trajectories (Martin, 2010; Unruh, 2002). Radical innovations, in contrast, emerge through experimentation by social movements, entrepreneurs, and other regime outsiders. These alternatives face hurdles, such as scaling and infrastructure needs, that hinder widespread adoption. MLP investigates these dynamic stability processes by examining interactions across industry, technology, markets, and policy (Geels, 2012). Institutions are central to the MLP's understanding of resilience; they act as rule-sets that shape actor and organisational actions, fostering stability but also constraining change (Geels, 2004, 2010; Geels and Schot, 2007). While tightly coupled regimes reinforce stability, loosely coupled niches introduce flexibility, supporting both gradual and transformative shifts.

Viewing transport resilience through a socio-technical lens offers several insights. First, this approach highlights the interdependence between transport and broader socio-economic and environmental systems (Geels, 2012; Geels et al., 2017; Roberts and Geels, 2019). Disruptions within transport systems can cascade into other areas, affecting supply chains, emergency services, and economic activities, underscoring the need for holistic resilience strategies. Second, human and organisational factors are essential to resilience (Geels, 2004, 2010; Geels and Schot, 2007). Resilience depends not only on technical durability but also on the ability of individuals and organisations to adapt, respond, and learn from disruptions (Fuenfschilling and Truffer, 2016). For instance, Werschmöller et al. (2024) showed how grassroots movements pressured local governments to adapt cycling policies in response to community needs. Third, socio-technical systems are inherently dynamic, continuously evolving due to technological advances, regulatory shifts, and changing user behaviours. This dynamism requires resilience strategies that are flexible and adaptive. The socio-technical approach has been used to examine various aspects of urban transport systems, especially in the context of climate change and low-carbon transitions (Geels et al., 2017). Research has identified multiple transition niches within urban mobility (Geels, 2012), including intermodal travel, public transport innovations, demand management, telecommuting, and green propulsion technologies. Given the complexity and scale of transport systems, future-focused thinking and strategic planning are necessary to address resilience in these contexts.

While research has explored socio-technical changes in public transport across different contexts, further studies are needed to examine active transport systems, such as cycling and walking. Current methods for assessing resilience in socio-technical transport systems remain limited. There is a shortage of practical, narrative-based approaches in the transport field that can clarify uncertainties and support strategic resilience planning. Traditional methods focus primarily on past trends and potential threats without providing a robust framework for understanding resilience in complex, evolving socio-technical systems. The following section will introduce how integrating the MLP with socio-ecological resilience can address these gaps, providing a more comprehensive approach to enhancing transport system resilience.

[1] Other scholars (Fraser and Glass, 2020) propose exploring the 'deep' transition (c.f., Kanger and Schot, 2019; Schot and Kanger, 2018) at the 'root' level within socio-technical systems. This emerging concept emphasises deep empowerment through individual agency and lived experiences, where social practices are internalised and shape individual and community resilience in often unseen ways (c.f., Hargreaves et al., 2012, 2011; Keller et al., 2022; Shove and Walker, 2010). While still a developing idea, it aligns with multi-level resilience by recognising the role of both personal and collective agency in driving system-wide resilience.

2.3. Towards a multi-level framework for transport resilience

2.3.1. Compatibility of theoretical frameworks

Transport literature increasingly adopts socio-ecological resilience concepts (Hayes et al., 2019; Schwanen, 2021; Sulikova and Brand, 2021), but the complexity of these systems makes operationalising resilience challenging. This paper uses the MLP to define resilience's fundamental unit—resilience of what. Despite their differing origins, socio-technical and socio-ecological resilience share core principles that support an integrated framework (Loorbach et al., 2017; McPhearson et al., 2022). Both approaches emphasise adaptation and learning: socio-technical systems focus on the adaptability of technologies, organisations, and practices, while socio-ecological systems highlight the adaptive capacity of social processes. Both frameworks employ systems thinking, recognising the interdependencies within complex networks and emphasising diversity and redundancy as resilience strategies (Fuenfschilling and Truffer, 2016; Geels, 2012).

While the MLP primarily examines transitions, resilience offers a temporal lens on maintaining function and identity amid disturbances. Resilience thinking extends beyond linear shifts to address persistence, adaptation, and transformation, as outlined in Section 2.1. It provides a cyclical perspective on change, reflecting the constant tension between stability, adaptation, and transformation (see Geels, 2010, on Holling (2001)'s adaptive cycle). This view aligns well with MLP's depiction of niche innovations as incremental rather than instantaneous regime transformations (Geels, 2020), incorporating resilience's emphasis on continuous adaptation and the potential for rapid change when systems cross tipping points.

In this paper, the transport system, with cycling as the focus, is conceptualised through the MLP with resilience analysis grounded in a socio-ecological approach. Integrating socio-technical and socio-ecological resilience provides a holistic framework for transport resilience analysis, encompassing:

- *Complex reality*: Transport systems are complex networks involving physical infrastructure, human actors, organisations, and environmental contexts (Tsoi et al., 2023; Woodcock et al., 2007). This perspective is essential for identifying vulnerabilities and developing resilience strategies across multiple dimensions and scales (Geels et al., 2017; Roberts and Geels, 2019).
- *Adaptive agents*: Effective resilience strategies are adaptive, fostering a culture of learning, innovation, and experimentation. Building agents' capacity to respond to and recover from disruptions is critical for system-wide resilience (Fuenfschilling and Truffer, 2016).
- *Multi-scale interactions*: Resilience planning should account for interactions across scales, from local to global, understanding how local networks connect with broader systems and influence each other (Geels, 2012).
- *Sustainability and resilience*: Sustainability and resilience are interrelated but distinct. While sustainability often addresses environmental aspects, resilience includes both environmental and social dimensions. Walker and Salt (2006) note that a system may be 'environmentally resilient but not socially desirable' (as cited in Cretney, 2014, p.635). Long-term resilience requires addressing environmental and social challenges.

Despite the recognised complexity of socio-technical systems, limited research employs a multi-level approach to analyse resilience (Moya and Goenechea, 2022). This gap persists due to the challenge of understanding how social resilience emerges from technical resilience and identifying mechanisms that facilitate this process (Adger, 2000; Brown, 2014). Resilience spans multiple levels, encompassing individual, community, societal, and global responses to disruptions (Glavovic et al., 2003).

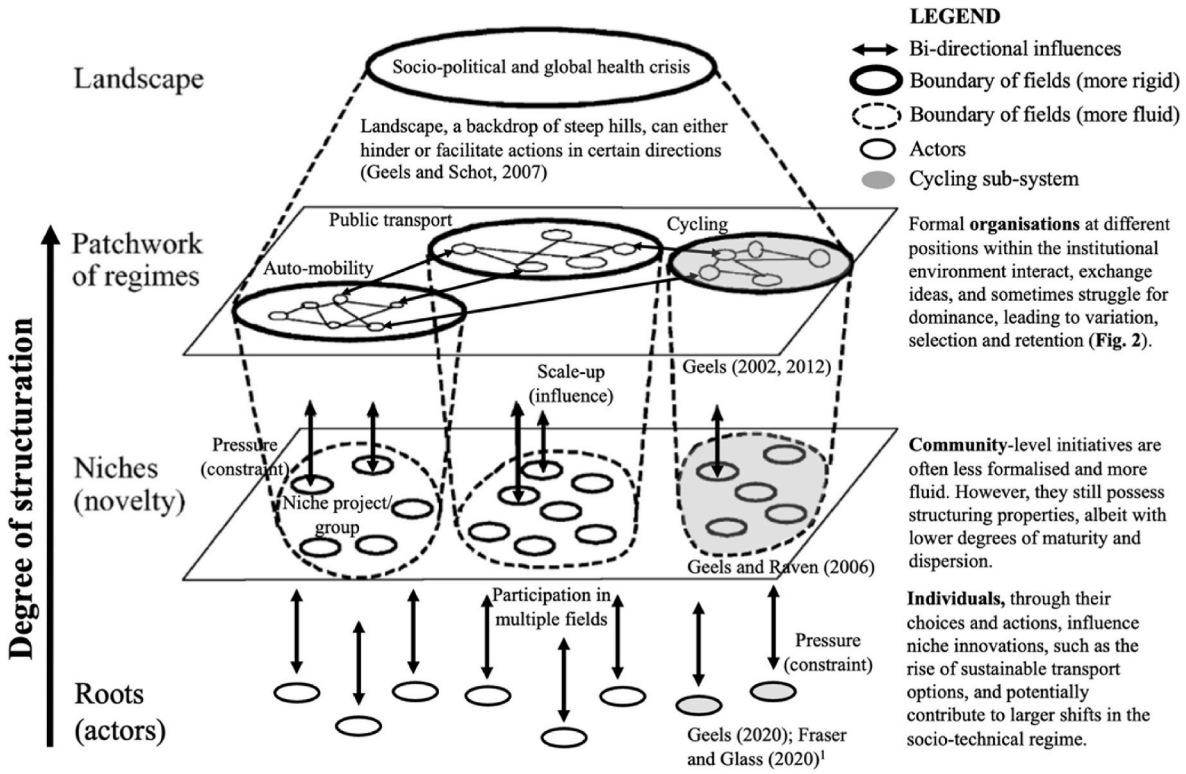

Fig. 1. Conceptualising transport system based on the MLP framework (adapted from Geels, 2002).

2.3.2. Field approach to transport resilience

This paper examines resilience through the lens of the MLP, focusing on varying degrees of structuration across social fields, such as organisations and place-based communities. Resilience here is understood not as a feature of isolated entities but as a product of broader relational dynamics within these organisational fields (Geels, 2020). Shifting the focus from organisations to fields emphasises an interactive, relational view of institutions, where diverse actors engage within a shared system of actions and relationships. In these fields, actors occupy different positions, offering varying degrees of institutional influence (Fig. 2): central actors hold substantial power to shape institutions, middle-positioned actors often conform to institutional pressures, and peripheral actors are more inclined to deviate and experiment with new practices. This differentiation fosters a bidirectional influence, where institutions shape actors' perceptions, identities, and actions, while organisations, in turn, seek to influence institutional frameworks.

Field approaches increasingly view institutions as evolving processes rather than static entities. Following Geels's (2020) reformulation of

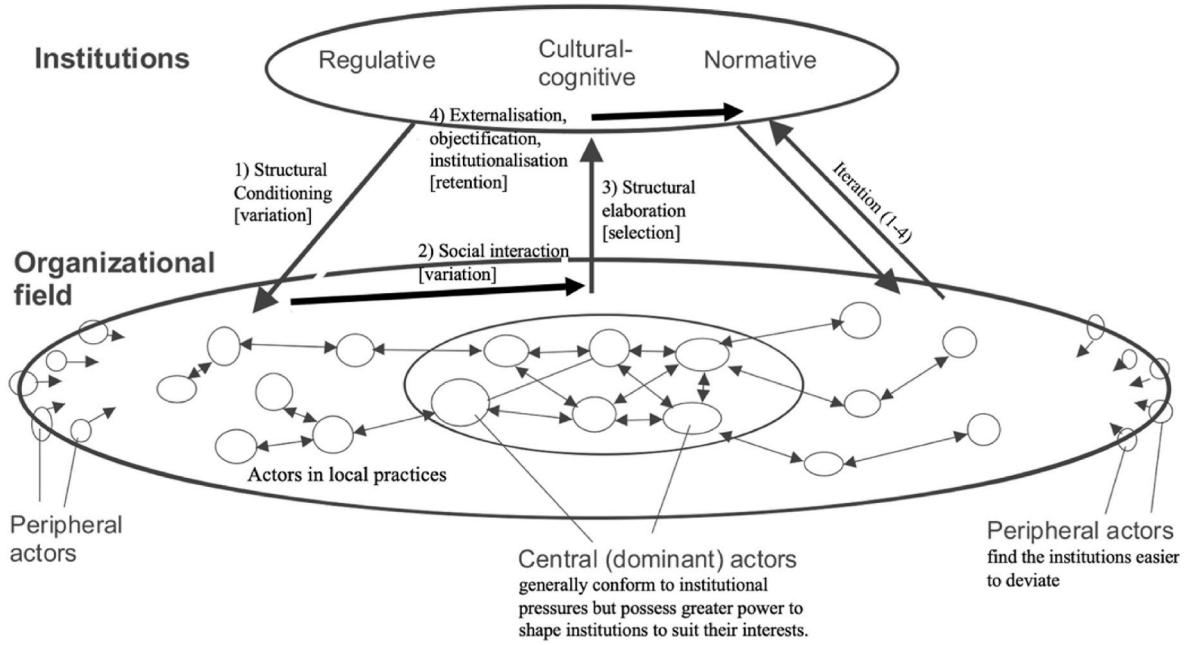

Fig. 2. Field-level trajectories as evolutionary resilience cycles (adapted from Geels, 2020).

Archer's (1982) morphogenetic cycle, this study employs a processual model of institutional change that aligns with evolutionary resilience mechanisms (Fig. 2). The morphogenetic cycle provides a dynamic framework for understanding socio-ecological resilience in institutions through four sub-processes:

1. *Structural conditioning*: Institutions exert a 'downward' influence, shaping actors' behaviours through existing regulative, normative, and cultural-cognitive rules, which carry historical precedents. Regulative rules, such as laws, set direct constraints or incentives. Normative rules establish expected behaviours linked to social norms or professional standards, while cultural-cognitive rules define shared understandings and assumptions. These pressures privilege certain strategies, limiting the potential for change.
2. *Social interaction*: Within these structural constraints, actors engage in routine or strategic actions, competing for influence within the institutional framework. Regulative rules may enforce compliance, but actors have interpretive flexibility, particularly regarding normative and cultural-cognitive elements. Social interaction involves moves and countermoves as actors seek influence. Whether these interactions are incremental or transformative depends on the rigidity or flexibility of existing rules.
3. *Structural elaboration*: Actors aiming to reshape institutions engage in institutional entrepreneurship, advocating for new ideas and practices within the field. Regulative rules may be reinterpreted, while normative and cultural-cognitive frameworks can be redefined through framing and coalition-building. However, institutional change is not guaranteed, as incumbent actors may resist new initiatives to protect the status quo. Successful change relies on actors' ability to navigate and influence the existing rules.
4. *Externalisation and Institutionalisation*: For institutional changes to endure, they must gain broad acceptance, formalisation, and endorsement by key authorities. Regulative rules, such as formal policies, provide legal support, while normative expectations and cultural-cognitive rules help cement new behaviours and shared understandings. Resilience is achieved when institutions adapt to external pressures, embedding changes within their regulatory, normative, and cultural-cognitive structures.

These processes enable institutions to balance stability with adaptability. Resilience, in this context, arises from the continuous interplay between maintaining established structures and incorporating adaptations over time, allowing institutions to evolve while supporting long-term resilience.

2.3.3. Contextualising multi-level for cycling subsystem

First, in the MLP framework, the classification of levels—niche, regime, and landscape—are still relevant. Niche and regime structures share institutional characteristics, though they differ mainly in stability and scale, with regimes representing stable sets of formal and informal rules, while niches are more experimental and loosely structured (Geels, 2004; Geels and Schot, 2007). In contrast, landscape-level changes, such as the 2019–2021 socio-political shifts in Hong Kong, exert influence at a broader scale, affecting both niche and regime dynamics in ways unique to that level.

Second, while the niche-regime distinction may be less useful for resilience analysis (see Svensson and Nikoleris, 2018, for a related discussion on material structures and the MLP), focusing on different degrees of structuration (Fig. 1) remains valuable (see Geels, 2011, for responses to critiques of 'hierarchical levels'). Geels (2012) proposes distinguishing niches or regimes by transport modes, identifying several mobility regimes such as automobility and subaltern regimes like cycling. Schwanen (2015) adds that whether cycling constitutes a niche, or regime depends on its dominance and stability. Although distinctions may blur, the niche-regime framework is a useful analytical tool for examining the degrees of structuration within transport systems. For resilience analysis, this study emphasises social fields, such as organisations and communities, and their associated rules to highlight how varied institutional layers foster or inhibit resilience.

Third, the assumption of 'protected' niche spaces (Lai, 2023) for cycling often does not hold. It is essential to identify the key actors leading cycling initiatives and their relationships with regime actors. For example, in São Paulo, cycling activists collaborated with pro-cycling administrations but adopted radical measures when facing pro-car leadership (Schwanen and Nixon, 2020). Similar patterns emerged in Santiago de Chile and Mexico City (Castañeda, 2022), and in Istanbul, where nascent cycling infrastructure often shares roads with other users, reflecting spatial-temporal constraints on resilience strategies (Canitez, 2019).

Fourth, MLP often overlooks spatiality, scale, and place (Coenen et al., 2012; Lawhon and Murphy, 2012; Schwanen, 2018). MLP assumes that different levels occupy the same geographical space, but in reality, transport modes like cycling operate across varied spaces with place-specific dependencies. This study considers cycling practices within distinct place-based communities, recognising that different levels of structuration contribute to resilience in interconnected yet distinct social fields. By investigating Hong Kong's cycling network within its multi-modal transit system, this paper illustrates how urban and rural settings intersect within resilience mechanisms.

This study examines resilience at three levels (Fig. 1)—organisational, community, and individual—using the MLP to illustrate the contributions of each to overall resilience in the bike-sharing subsystem:

- *Organisational resilience*: Organisational resilience pertains to bike-sharing operators within an institutional context shaped by economic and regulatory forces. Operators navigate formal institutional rules (van Waes et al., 2020) while adapting to external pressures like regulatory changes (Wang et al., 2023a), public discourse (Egan and Caulfield, 2024a) and technological disruptions (Dia et al., 2021). Organisational resilience emerges from a dynamic interplay of conforming to, deviating from, and shaping institutional expectations.
- *Community Resilience*: Community resilience focuses on digital communities, such as those on Telegram, that address local bike management needs. These digital groups serve as localised niche initiatives within the socio-technical system, influenced by global trends like democratic movements (Au, 2022; Stokols, 2023). Geels and Raven (2006) describe local and global niche interactions, where local projects are shaped by broader socio-political contexts. The distinction between community and organisational resilience lies in the varying degrees of structuration (Fuenfschilling and Truffer, 2014, 2016; Geels, 2011; Geels and Schot, 2010). Unlike more formal organisational resilience, community initiatives are less institutionalised but possess structuring properties, helping communities rapidly adapt and collectively problem-solve in response to disruptions (Chan and Zhou, 2021; Nixon and Schwanen, 2024).
- *Individual resilience*: Individual resilience relates to agency, where individuals are not passive but actively shape socio-technical systems, as Giddens's (1984) structuration theory suggests. Individuals adapt to the constraints of regimes and landscapes, fostering innovation within niches and challenging dominant regimes (Geels, 2010; Sorrell, 2018). Users of bike-sharing systems demonstrate resilience by integrating new practices despite infrastructure or social norms favouring cars (Bruno and Nikolaeva, 2020; Egan and Caulfield, 2024b). This individual agency contributes to broader socio-technical shifts, as resilient individuals pioneer new technologies or practices that drive larger changes.

3. Methodology

3.1. Research context

Hong Kong is a global exemplar in transit-oriented development

(TOD), with a multi-modal public transport system integrated closely with land use and urban planning. Like many developed regions, Hong Kong's transport planning and management have been significantly impacted by social shocks, including public protests (Chan et al., 2022; Huang and Loo, 2023; Loo and Leung, 2017; van Exel and Rietveld, 2001) and the coronavirus pandemic (Chan et al., 2021; Schwanen, 2021). These events have sparked grassroots innovations and transport-related activities, creating a dynamic setting to study how resilience develops at individual, community, and organisational levels amid disruption. While Hong Kong's transport system is predominantly monopolistic, with over 90% of mechanised trips relying on public transit, cycling has gained prominence as a resilient alternative mode, particularly during and after the pandemic (Teixeira et al., 2023). Despite being a marginalised part of the dominant public transport regime, cycling offers a unique opportunity to explore resilience within a niche mode. Currently, our understanding of how such niche innovations emerge, persist, and contribute to the resilience of Hong Kong's largely monopolistic system remains limited.

In this context, a local bike-sharing operator—founded and operated by Hongkongers—stands out. It is currently Hong Kong's only bike-sharing company, having withstood substantial stress and challenges, including fierce competition during the bike-share boom (Chan, 2020). The operator's local, place-based roots facilitate access to resources, community legitimacy, and social value creation (Vlasov et al., 2018). Unlike previous operators, the founders and core members of this organisation are all local residents, enabling them to foster effective communication between the operator, residents, and other organisations. This study investigates the interactions among social agents within this transport context, examining how these interactions contribute to building resilience among individuals, organisations, and place-based communities. Focusing on Hong Kong's bike sharing system within a broader public transit framework, this research aims to shed light on the interactions between cycling practices, societal norms, and institutional frameworks, contributing to the theoretical discourse on multi-level resilience and socio-technical systems.

3.2. Research data and methods

In socio-ecological resilience research, interpretivist and narrative methods, including qualitative scenario analysis, are frequently emphasised for exploring uncertainty and possibility (Hayes et al., 2019; Schwanen, 2021). These methods are particularly suited for resilience studies because they offer deeper insights than quantification and modelling, capturing the multi-level processes of resilience across individual, community, and organisational levels. Collective participation and deliberation are essential to understanding how resilience is built, sustained, and transformed, making qualitative approaches ideal for this investigation.

This study is based on six months of ethnographic fieldwork and 40 semi-structured interviews with urban mobility stakeholders in Hong Kong, including bike-sharing users, general residents (non-users), and bike rental operators (Table 1). The data were gathered as part of a research project focused on everyday mobility practices. Findings from other mobility aspects will be published separately. The semi-structured format allowed flexibility in exploring participants' daily travel experiences, particularly regarding cycling and bike-sharing, while following set themes. This approach provided structure and also encouraged participants to discuss personal experiences and perceptions of resilience. Combining interviews with ethnographic fieldwork (c.f., Murto et al., 2020) enabled a comprehensive examination of multi-level resilience within the MLP framework shown in Fig. 1. While interviews captured individual and community interactions with socio-technical regimes, ethnographic observations contextualised these interactions, highlighting daily practices that contribute to resilience across various scales.

Most interviews were conducted via Microsoft Teams from April to July 2023, with in-person resident and ride-along interviews held during fieldwork from July to September 2023. Participants were recruited through online community groups in Hong Kong. Interview questions focused on resilience at individual, community, and organisational levels, particularly in adapting to transport disruptions. Key questions (with more specific versions for different interview groups outlined in Appendix A) addressed daily mobility challenges, the role of bike-sharing in transport resilience, and responses to socio-political and infrastructural disruptions. Examples included:

- How have recent events, such as the coronavirus pandemic and social movement, impacted your (or your organisation's) transport practices?
- What challenges do you face, and how do you adapt to them?
- Who (e.g., government, community groups, entrepreneurs) should be responsible for strengthening resilience against adverse events and environmental changes?

Ethnographic fieldwork, conducted from July to September 2023, supplemented these interviews. This approach aimed to capture the culture created through interactions and employed 'negative case analysis' (Hanson, 2017; Morse, 2010). Field notes were taken over nine cycling sessions, with travel routes informed by pre-fieldwork interviews, to minimise positional bias (Tessier, 2012). This method facilitated critical reflection (Maharaj, 2016), and notes were used to prompt follow-up interviews. These post-fieldwork interviews allowed for additional insights, enabling deeper interpretation and refinement of the analytical framework.

The study gathered 807 min of audio recordings, which were transcribed and analysed using reflexive thematic analysis (RTA) (Braun and Clarke, 2021). This process involved six steps: familiarisation with transcripts and secondary data, systematic coding, theme generation (e.g., competition, demand/supply, service/parking, physical artifacts, social/technological innovation, transport disruption, corporate reputation, staff/user composition), refining themes during writing, defining three levels—individual, community, and organisational—and developing the paper based on these levels. The analysis identifies key themes that reflect multi-level resilience in Hong Kong's cycling system, illustrated with verbatim quotes and fieldnotes (denoted as Q and F in the text, referencing Appendix B). Together, these methods provide a comprehensive view of resilience as it unfolds across individual, community, and organisational levels within the urban cycling context in Hong Kong.

3.3. Reflections on qualitative and ethnographic approach

The ethnographic approach in this study provides valuable insights but also has limitations, especially when applied to the MLP and socio-ecological resilience frameworks. A key limitation is the relatively short study duration. MLP studies typically examine long-term transitions within socio-technical systems, requiring extended observation to fully capture interactions among niche innovations, regimes, and landscapes. The six-month timeframe may miss some of these dynamics, particularly

Table 1
Interview stakeholder groups, number of interviews and duration.

Stakeholder group	Number of interviews	Total duration (mins)	Average duration (mins)
Bike-sharing operators	2	139	70
Bike-sharing users	12	93	8
General residents	20	155	8
Traditional cycling shops	3	22	8
Ride-along interview (local informant)	2	300	150
Government officers	1	98	98
Total	**40**	**807**	**20.2**

in complex systems like urban transport, where broader institutional or policy shifts might not be observed. Additionally, ethnography often focuses on micro-level interactions, offering detailed insights into individual and community resilience but potentially overlooking macro-level processes that shape system-wide resilience. This focus on real-time, context-specific practices restricts the ability to track long-term systemic changes central to MLP. To mitigate this, interviews in the study provided complementary perspectives, adding breadth to the ethnographic findings (Murto et al., 2020).

Despite these constraints, ethnography proves highly effective for examining Hong Kong's marginalised cycling sub-system. As a mode of transport largely overlooked in the city's public transport framework, cycling benefits from an ethnographic approach that offers a nuanced understanding of resilience in cyclists' daily lives. This method captures users' lived experiences and adaptive behaviours within a system primarily structured for buses, trains, and private vehicles. By engaging directly with cyclists, ethnography uncovers the real-time, context-specific dynamics of cycling and highlights how this sub-system operates within the broader socio-technical regime. It reveals how cyclists manage challenges like limited infrastructure and institutional barriers, providing a ground-level view of resilience often missed in macro-level studies.

The iterative feedback loop between fieldwork and interviews further enhances the study's responsiveness, capturing resilience as it unfolds in daily practices. This approach is particularly relevant for a marginalised sub-system like cycling, where adaptability to issues such as congested roads or limited parking is critical. Moreover, ethnography reveals the socio-cultural and political contexts shaping cycling in Hong Kong, including how local norms, political pressures, and social expectations impact cyclists' behaviours. This depth of engagement enriches the analysis, illustrating how micro-level interactions contribute to broader system change and revealing cycling's potential role in long-term transitions within the urban transport landscape.

4. Findings

4.1. Individual resilience

Individual resilience within bike-sharing systems is multifaceted, encompassing adaptive behaviours, the integration of cycling into daily routines, acceptance of system imperfections, and active participation (cf., Teixeira et al., 2022). The role of individuals is crucial in shaping and maintaining socio-technical systems, as emphasised by both socio-ecological resilience and MLP frameworks. The field comprises diverse agents, reflecting evolutionary economics' view of agent heterogeneity. Traditionally, the MLP suggests that niche-level activities accumulate over time and combined with external landscape pressures, can disrupt the dominant regime. However, this notion of 'accumulation' oversimplifies the complex aggregation of micro-events. Recent MLP literature critiques this individualistic approach and emphasises the relational dynamics between agents (Schmitt et al., 2023). This view prioritises the interpretive flexibility of agents, highlighting variations rather than simply aggregating actions. It underscores the limitations of relying solely on individual resilience for broader systemic resilience, as some argue for decentralising resilience responsibility (e.g., Budd and Ison, 2020). Effective individual resilience requires systemic support mechanisms to maintain accessibility and service quality. By examining the composition and interaction of individual resilience within the system, we can enhance the sustainability and resilience of bike-sharing services over time.

4.1.1. Structural conditioning and adaptive behaviours

Individual resilience is evident in users' adaptive behaviours. One user, for example, integrates night-time bike rides for personal fitness, explaining, *'I'm accustomed to taking night-time rides … These rides are more efficient … and they contribute to the company's profits, while also helping me improve my fitness through training*' (Q1). This illustrates how individuals use bike-sharing systems to achieve personal goals, like physical fitness, while simultaneously bolstering the system's resilience by maintaining off-peak demand and reducing idle bike times. Such behaviours align with the **structural conditioning** of broader socio-technical regime's structure (Geels, 2020; Hassink et al., 2018), reinforcing system profitability and operational continuity. The growing emphasis on fitness and health trends—further accelerated by the recent global health crisis (Rérat et al., 2022; Younes et al., 2023)—is part of the cultural-cognitive fabric of the socio-technical regime, with bike-sharing meeting this demand. This alignment between personal behaviours and regime stability shows how individual resilience, though motivated by personal objectives, can strengthen the broader system by enhancing regular use and minimising operational inefficiencies.

4.1.2. Interpretive flexibility and social interactions

Individual resilience also emerges through users' acceptance of minor system imperfections. One user shared:

> *Occasionally, I do forget to lock the bike properly, resulting in deductions from my balance through the app. While the deducted amount is small and doesn't bother me much, I see it as a contribution to the company's operations. It's my way of supporting a local business, especially one operated by fellow Hongkongers. This makes me feel like I'm playing a part in enhancing my community* (Q2).

This sentiment can be interpreted through socio-ecological resilience, where minor setbacks, like balance deductions for improper bike-locking, are reframed as positive contributions rather than failures. This acceptance, common among individuals committed to supporting local start-ups, highlights a form of individual resilience. The user's acceptance of small penalties as a way to support local businesses reinforces social institutions, as such actions are often shared in local social media groups, where they receive recognition from others (ethnographic data). The willingness to participate in the bike-sharing community, such as reporting damages or improper usage (Q3-4), demonstrates a high level of personal responsibility and commitment to the bike-sharing community. These **social interactions** showcase how individual resilience reinforces the broader system's resilience; while individuals exercise agency and flexibility, their actions simultaneously strengthen the norms and structures of the system. By accepting minor consequences, users contribute to the economic and operational resilience of the bike-sharing company within the larger socio-technical regime. This dynamic illustrates that individual resilience practices are embedded in institutional frameworks, creating a feedback loop that sustains the system.

Adaptive behaviours are also shaped by the **structuring conditioning** from the consumer nationalism niche project, where supporting local businesses is viewed as an act of civic pride and autonomy (Li and Whitworth, 2023). In this context, the user's acceptance of the deduction or simply using a shared bike as support for a local business reflects a broader social movement in Hong Kong that aims to bolster community resilience amid socio-political challenges. The movement's decentralisation principle, which encourages flexibility and alignment of personal experiences with collective goals like community solidarity and responsibility, further exemplifies the MLP's recognition of interpretive flexibility in socio-technical systems (Holbig, 2020). In this case, the user's actions align with the 'be water' principle, reinforcing community resilience by supporting local businesses and contributing to civic duty (Tang and Cheng, 2022). This reinterpretation of minor setbacks into positive contributions reflects not only individual resilience but also the ways in which personal actions sustain community resilience and reinforce local socio-technical systems.

4.2. Community resilience

Community resilience is essential for sustaining transport systems (Anderson et al., 2022; Lara et al., 2023). It emerges through networks

and social groups that support the system's operation and maintenance, demonstrating how community dynamics enhance technology adoption and functionality. However, conflicting social practices can lead to resistance against new technologies. This reliance on technological solutions can create systemic lock-in, reproducing practices that may exclude certain individuals and communities. To achieve long-term resilience and inclusivity, bike-sharing systems need to balance technological integration with respect for local culture and social dynamics.

4.2.1. Formation of spaces for social interactions

An example of community resilience in bike-sharing systems is the creation of a Telegram group for social interaction and real-time communication between users and management. This platform serves multiple functions: users report issues, share bike availability, and receive operator updates. As one user stated:

> *The Telegram group has become an essential tool for us. It's where we share experiences, report broken bikes, and get immediate feedback from the company. It feels like we are part of a community working together to make this system better* (see also Q4-5).

The group exemplifies community-driven problem-solving, a cornerstone of socio-technical resilience. This digital space reflects the **structural conditioning** from a broader niche project toward digitalisation of social activism, where socio-political events like crises drive technological adoption (Chan et al., 2021; Chan and Zhou, 2021; Stokols, 2023). Beyond technical problem-solving, the group fosters a strong sense of ownership among users, as they actively report damages and provide feedback. This engagement aligns with socio-ecological resilience principles, emphasising local stakeholder involvement in maintaining system sustainability. The feedback loop between the community and the system strengthens overall resilience by creating a proactive user base.

In addition to community engagement, users—especially older ones—have adapted to using digital platforms for bike rentals and payments (Q6). The disruptions from socio-political and health crises have encouraged older users to adopt new technologies and exchange knowledge across generations. This adaptability highlights the integration of individual resilience within socio-technical systems, a key concept in MLP's socio-technical transitions (Geels, 2020). **Social interactions** between younger and older users demonstrate adaptability and flexibility in response to external pressures, reinforcing system resilience.

The Telegram group embodies grassroots activism, reflecting larger societal movements. Users are more than service consumers; they are active participants in shaping and sustaining the bike-sharing system. This digital space acts as a microcosm of broader societal shifts, where digital platforms become tools for collective resilience during adversity. The community's rapid response to issues—whether bike damage or operational adjustments—demonstrates its adaptability, especially during crises like the 2019 socio-political unrest and the pandemic (Chan et al., 2021; Chan and Zhou, 2021; Stokols, 2023). During these times, the Telegram group was repurposed for bike-sharing management, illustrating the process of **structural elaboration** on how community networks respond to external pressures to support system resilience by ensuring service continuity. Personal access to bike-sharing resources is sustained through the collaborative efforts of the community and the organisation. This engagement fosters a sense of ownership, as users actively report issues and provide feedback. As one user shared, '*We feel more responsible for the bikes because we're actively involved. When you report something and see it fixed quickly, it makes you care more about the service*' (see also Q7 for operator's reflections). This participatory approach aligns with socio-ecological resilience principles, where local stakeholders actively contribute to system sustainability, creating a feedback loop that reinforces overall resilience.

4.2.2. Social exclusion from resilient practices

Despite its benefits, community resilience also has limitations. Not all users are comfortable with or prefer digital methods. Some users still favour personal interactions at local bike rental shops rather than using app-based services. As one resident explained:

> I prefer going to the local bike shop because I can talk to the people there and get their advice. It's more personal than just using an app (see also Q8 and F1 for interactions with local villagers).

This preference underscores the tension between technological innovation and the need for human-centred service. It also highlights the importance of considering social dynamics and local culture when implementing technological solutions. Success in bike-sharing depends on more than technology; it must align with users' social practices.

Digital spaces like Telegram undergo **social elaboration**, as not all users participate equally. While some volunteer actively, others view it as an information source without engaging in volunteering: '*It helps me identify areas with bike issues or damage, allowing me to steer clear of those spots when renting or parking a bike. I don't have the intention of actively joining the volunteering efforts within the group, given that our mobile application already has a formal reporting feature*' (Q4). This reflects different levels of user engagement, where some are more active while others remain passive. For instance, some perceive the group's tracking of rule violators as alienating, referring to it as a '*hunter game*' (Q4), which can lead to disengagement. The purpose of the 'game' is to confront local villagers (Q9), who are often viewed as supporting anti-democratic factions and behaving uncivilly (Q10). Users may avoid parking bikes in certain areas to steer clear of groups they view unfavourably, resulting in uneven distribution of bike-sharing services (Q11). This dynamic illustrates how community expectations shape new behaviours, creating shared norms around parking practices. The interactions within the group lead to the **institutionalisation** of behaviours that impact the broader bike-sharing system.

To address these challenges, balancing technological innovation with direct human support within digital platforms can help bridge this gap and ensure inclusivity for those who prefer face-to-face interactions. Additionally, developing strategies that cater to diverse user needs, from tech-savvy individuals to those favouring traditional methods, will enhance the resilience and sustainability of the bike-sharing system across different user groups. The global trend toward digitalisation influences these community dynamics, positioning the bike-sharing system in Hong Kong within a global context of digital community action. However, these practices can also unintentionally exclude some users, highlighting the importance of considering both engagement and disengagement in resilience strategies.

4.3. Organisational resilience

The organisational resilience of Hong Kong's sole bike-sharing operator reflects its strategic partnerships and adaptive management practices. This resilience is built through initiatives aimed at maintaining sustainable and efficient services. Similar to community resilience, organisational resilience can lead to lock-in and path dependency, particularly in technological and planning practices, which may inadvertently exclude certain individuals and communities.

4.3.1. Interconnected fields of transport

The establishment of a code of practice for bike-sharing reflects both internal organisational needs and external **structural conditioning** from socio-political pressures from the sharing economy and the dominant public transport regime. In cities like Hong Kong, public transit systems (buses, rail) are key players within urban mobility. Bike-sharing services introduce alternatives that could disrupt these established systems, yet they often operate in regulated environments where socio-political pressures require balancing innovation with existing systems. Public authorities, aiming to maintain quality, safety, and order,

increasingly set codes of practice to regulate bike-sharing. These guidelines, which address bike placement, volume control, and urban clutter, help integrate bike-sharing into the wider transport ecosystem without creating friction with other services. As noted by a committee member of the bike-sharing company, '*Our partnership with the government to establish a code of practice has been crucial. It provides clear guidelines on bike placement and supply volume, helping to maintain order and reduce clutter*' (Q12). The socio-political landscape, shaped also by public concerns over the sharing economy, has added pressure to ensure bike-sharing does not undermine public transit's role as the backbone of urban mobility (Q13). This has led to frameworks that manage the coexistence of bike-sharing and public transit, balancing new mobility solutions with the stability of existing public systems. Thus, codes of practice respond to both the rapid rise of the sharing economy and the need to align bike-sharing with established urban mobility frameworks. This illustrates how organisational resilience is shaped by external political and social forces, integrating both regulatory demands and the complexities of urban mobility within a socio-technical system.

Public-private partnerships also exemplify **social interaction**, where different actors engage within the regulatory structures, competing and collaborating to influence outcomes. These partnerships are critical for organisational resilience as they provide platforms for innovation and expansion. For example, the founder of a bike rental service provider stated, 'Our collaborations with both public and private entities have been pivotal in our expansion efforts. These partnerships enable us to innovate and scale our operations more effectively' (see also Q14-15 for operator's reflections on collaborations with NGOs and the metro operator). The interaction between public institutions and private actors encourages new ideas and practices within the field, contributing to the system's resilience. In addition to responding to external pressures, the bike-sharing operator's **structural elaboration** process—through which it reshapes its business model—was evident when initial efforts to collaborate with Hong Kong's metro service were unsuccessful (Q15). In response, the operator established new partnerships with bus services to provide fare reductions for first- and last-mile trips, ensuring the system's adaptability and integration into the broader transport network (ethnographic data). This flexibility demonstrates how organisational resilience allows the company to expand, despite challenges within the public transport regime.

4.3.2. Technological management practices

The company's adaptive management practices are strongly driven by **structural conditioning** enabled by advanced technologies like AI for real-time monitoring and optimisation of bike distribution. By analysing usage data, the company effectively adjusts bike supply to align with demand, avoiding overcrowding and underutilisation. As a staff member explained, '*We regularly analyse usage data to adjust our bike supply, meeting demand while avoiding overcrowding and underutilisation*' (Q16). These data-driven practices, grounded in institutional guidelines, enhance both operational efficiency and service reliability. The integration of AI and data analytics also enhances **social interaction** within the system, allowing the company to better adapt to fluctuating demand and engage with users more effectively. '*Our use of AI and data analytics allows us to predict demand patterns and allocate bikes accordingly, which not only improves service reliability but also helps in better resource management*' (Q17, see also Q18-19 for demand management practices). This AI-driven approach creates a feedback loop, enabling ongoing adjustments based on real-time insights and user responses, such as positive feedback, growing user numbers, and increased profits. This process of **structural elaboration** allows the company to actively respond to demand fluctuations, optimising bike distribution to reduce shortages or surpluses. Ultimately, AI-based demand analysis bolsters service efficiency and strengthens the company's resilience by adapting to dynamic user behaviours.

The adoption of AI and data analytics reflects a broader **institutionalisation** of technological practices crucial to long-term resilience. Embedding these innovations within daily operations ensures consistent service quality and efficiency. The adoption of AI for demand management (Q17) and electric bikes (Q20) enhances resilience not only through material improvements but also through strategic technological integration, which bolsters the company's standing within the transport sector. Formal policies supporting e-bikes and AI create the **structuring conditioning** necessary for sustainable operations. This process of institutionalisation helps ensure regulatory compliance and scalability, aligning with socio-technical trends in urban transport. As a result, the structured, regulated adoption of AI and e-bikes enhances the organisational resilience, increasing its ability to adapt to user needs, environmental challenges, and evolving technological advancements. This process strengthens the integration of the bike-sharing system within the broader transport ecosystem, ensuring its relevance and operational viability in the future.

4.3.3. Systemic lock-in from resilience practices

While organisational resilience supports stability, it can also contribute to **institutionalisation** and systemic lock-in that limits flexibility and innovation (Crespo et al., 2014; Wilson, 2014). The MLP and socio-ecological frameworks emphasise the need to balance regulatory compliance with adaptive practices. A significant limitation of organisational resilience lies in the reliance on technology and data-driven methods, which can lead to rigid operational frameworks. Strict adherence to codes of practice, while ensuring order and safety, can hinder creative solutions that might better serve community needs. As one operator noted, '*strict adherence to the code of practice makes it difficult to implement creative solutions*' (Q12, see also Q14 for operator's reflections on working with NGOs).

The limitations of organisational resilience become more apparent during **structural elaboration**, where opportunities for transformative change are constrained by a focus on compliance. The emphasis on regulatory compliance, while ensuring order and safety, can also limit the ability to adapt and innovate. Organisations often face a dilemma between maintaining strict adherence to regulations and fostering innovative practices that could better address community needs. This tension is evident in the challenges faced when trying to balance compliance with the need for creative solutions, as highlighted by the interview data. The MLP framework, which examines transitions within socio-technical systems across niche innovations, socio-technical regimes, and the socio-technical landscape, provides a useful lens to understand this systemic lock-in.

Finally, **externalisation and institutionalisation** processes further reinforce systemic lock-in by embedding existing practices into the company's operations. Organisational practices that align too closely with existing socio-technical regimes can hinder the emergence of niche innovations that are crucial for system transformation. For example, bike-sharing operators' strategies often represent niche-level innovations that challenge traditional transport regimes, but excessive regulatory focus can impede these innovative efforts. From a socio-ecological perspective, resilience is not just about absorbing disturbances but also about transformative change. However, practices that focus heavily on maintaining existing structures and compliance can prevent the system from evolving. This is particularly relevant in socio-technical systems where the ability to adapt and transform is critical for long-term sustainability.

5. Policy implications

This section discusses policy implications for integrating socio-ecological resilience and the MLP to build resilient transport systems, particularly in cycling and bike-sharing services. It emphasises fostering multi-level resilience by addressing socio-spatial dynamics and balancing institutional stability with inclusivity and innovation. The paper offers insights for policymakers to develop resilience strategies that promote broad participation while maintaining system stability and

adaptability.

5.1. Foster multi-level co-constituted resilience

Combining socio-ecological resilience with the MLP framework provides a comprehensive understanding of resilience in bike-sharing systems. Socio-ecological resilience emphasises a system's ability to absorb disturbances, adapt, and reorganise, which is evident in how individuals and communities manage technological and social challenges in bike-sharing systems (Hayes et al., 2019). The MLP framework complements this by highlighting transitions within socio-technical systems, showing interactions across niche innovations, socio-technical regimes, and the broader landscape (Dudley et al., 2019; Magnusson et al., 2020).

Our findings (Table 2) illustrate how individual and community resilience practices, such as users' adaptive behaviours (Section 4.1.1), interpretive flexibility (Section 4.1.2), and community-driven initiatives like Telegram groups (Section 4.2.1), act as niche-level innovations that challenge established transport regimes. These bottom-up changes, as noted by Magnusson et al. (2020), promote sustainable alternatives by reshaping regional systems. At the organisational level, resilience is tied to structured responses from key regime actors, such as bike-sharing operators, who maintain operational stability through adaptive strategies aligned with regulatory practices. This mirrors Dudley et al. (2019), who describe how new technologies like dockless bike-sharing provoke regime-level negotiations. Additionally, external landscape pressures—such as the 2019 socio-political crisis and the 2020 global pandemic—disrupted the regime, creating opportunities for niche innovations like increased cycling adoption. This interaction among landscape pressures, regime stability, and niche-level innovations underpins the MLP's view of resilience as a multi-level, dynamic process.

The MLP reveals resilience as a fluid process operating across different levels, with each level influencing the others. Organisational resilience generally prioritises stability through institutional adherence (Sections 4.3.1 and 4.3.2), while community and individual resilience emphasise adaptability and innovation (Section 4.2.1). Together, these forms of resilience create an interdependent system where resilience is continually redefined by interactions between actors at various scales. However, this can lead to tensions. Organisational resilience may sometimes result in systemic lock-ins (Sections 4.2.2 and 4.3.3) that stifle flexibility and hinder community and individual innovation. Conversely, community and individual resilience can disrupt these lock-ins, fostering more adaptive and responsive systems.

These findings highlight the importance of social dynamics in resilient transport systems. While individual, community, and organisational resilience collectively strengthen the bike-sharing system, they also raise equity concerns (see also Section 5.3). Institutionalising resilience practices can stabilise the system but may also entrench social exclusions. Thus, resilience is both an opportunity and a risk, where institutionalisation can support system stability while perpetuating social inequities. Policymakers should consider these dynamics, creating strategies that foster both resilience and inclusivity to ensure that resilience benefits are equitably shared across all user groups, resulting in transport systems resilient in both structure and participation.

5.2. Address socio-spatial and dynamics

The socio-spatial dimensions of resilience are shaped by institutional rules and transport policies, aligning with the growing focus on geography (Cretney, 2014; Weichselgartner and Kelman, 2015) and

Table 2
Transport resilience cycle exemplified by the case study.

Resilience cycle	Description	Related level			The Hong Kong case
		I	C	O	
Structural conditioning	• Downward influence on actors through pre-existing regulative, normative, and cultural-cognitive rules. • Interpretive flexibility of agency exists but privileges certain strategies and actors, limiting change.	✓	✓	✓	• Socio-political landscape (socio-political and health crisis) influences bike-sharing as political action and physical activity. • Digital communities formed for local self-help are part of the global digitalisation of social movements. • Socio-political pressure on the sharing economy as well as the dominant public transport regime leads to the establishment of codes of practice for bike rentals. • Personal access to bike-sharing artifacts is sustained through community and organisational efforts, shaped by prior social interactions.
Social interaction	• Actors engage with institutional rules through routine or strategic actions, competing for influence. • Interaction involves moves and countermoves depending on how existing rules enable or constrain them.	✓	✓	✓	• Decentralisation in social movements promotes flexibility and personal alignment with community goals (solidarity, responsibility). • Individual actions shared on social media are recognised and reinforce system institutions. • Public-private partnerships foster collaboration and competition between organisations, enabling actors to work within regulatory frameworks to shape outcomes.
Structural elaboration	• Actors promote new ideas or practices at the field level, but incumbents may resist changes. •Institutional change depends on effective navigation and rule influence.		✓	✓	• Continuity of digital spaces is re-elaborated by operators based on community engagement. • Some citizens leave the group due to exclusion from the 'hunting game' for rule violators. • Data sharing and opinion exchanges in the political landscape promote new ideas or practices in the bike-sharing field.
Externalisation and institutionalisation	• Institutional changes must be widely accepted, formalised, and endorsed by authoritative actors to become permanent. • Regulative, normative, and cultural-cognitive rules provide legal, social, and cognitive backing to institutional changes. • Resilience is achieved when institutions successfully adapt to external pressures and integrate changes into the regulatory, normative, and cultural-cognitive dimensions of their structure.		✓	✓	• Cultural-cognitive rules solidify shared understanding of riding and parking practices. • Normative rules against vandalism and improper parking help protect and secure the artifacts of the bike-sharing system. • New formal policies and code of practices provide legal support for technological approach to resilience, such as AI and electric bikes. • Public-private partnerships exemplify organisational resilience and drive expansion and innovation, but they can also lead to systemic lock-in and reinforce (new forms of) exclusions.

Notes: *I*: individual; *C*: community; *O*: organisational.

spatiality in MLP literature (Lawhon and Murphy, 2012; Murphy, 2015; Raven et al., 2012). In Hong Kong's cycling system, early regulations aimed to limit disruptions by discouraging cycling in certain urban areas. These rules evolved as incidents of vandalism in bike-sharing spaces increased, prompting modifications like parking bans in high-risk areas to reduce damage and theft. This process illustrates how regulative rules and social interactions shape each other. For instance, bike-sharing operators expanded restricted zones based on user feedback and theft incidents, creating guidelines that addressed immediate threats while reshaping spatial access to the service.

This iterative reshaping of spatial strategies, informed by social interactions, led to new norms and expectations around where and when bike-sharing is appropriate. Initially set to control disruptions, these regulations became embedded as normative rules, defining acceptable behaviours within bike-sharing spaces. Additionally, shared understandings around parking and cycling in high-risk areas emerged, reinforcing cultural-cognitive norms that support system resilience. The MLP's emphasis on interpretive flexibility explains how cyclists, operators, and policymakers may interpret and adapt to evolving rules differently based on their social and spatial contexts. For example, strict adherence to parking regulations might be more relevant in dense urban zones concerned with congestion and safety, while a more flexible approach may suit less crowded areas. Such interpretive flexibility underscores the need for resilience strategies that adapt institutional rules to varied spatial and social conditions, supporting system stability while accommodating local needs.

These evolving practices highlight resilience across scales, where institutions at different levels shape transport policies (Bergström and Dekker, 2014; Chelleri et al., 2015; Greene et al., 2022). For instance, city-wide policies often prioritise public transport and restrict cycling in certain areas, reflecting 'meta-rules' (Kanger, 2022) that govern multiple transport systems. Broader socio-political dynamics may also influence public attitudes toward cycling, shaping behaviours that eventually become embedded as normative and cultural-cognitive rules. When these meta-rules align, they can create 'meta-regimes' that coordinate across systems. Localised regulations, like parking bans, are often consistent with these frameworks. Our multi-scalar approach shows that resilience emerges through interactions among local and higher-level institutions. Future research should explore how places are constructed and reconstructed through multi-scalar political dynamics in both formal and informal social settings (Budnitz et al., 2024; Håkansson, 2018; Liu et al., 2024; Murphy, 2015). Such relationships bring together various materials, meanings, experiences, and people, forming what Massey (2004) calls 'temporary constellations' (p. 141), which assign purpose and value to places. Policymakers should consider spatial variability and institutional dynamics to create adaptive, context-specific resilience strategies in transport.

Ultimately, resilient transport systems require dynamic interactions among spatial regulations, social interactions, and agent behaviours. Tailoring policies to the distinct needs of different urban areas can improve compliance and reduce conflicts, avoiding a 'one-size-fits-all' approach. For instance, stricter parking regulations might be necessary in dense areas, while more flexible policies could promote bike-sharing in suburban settings. Community engagement is essential, as involving local stakeholders in policy development supports grassroots innovation and ensures regulations align with user needs. Regular monitoring and adaptation of these policies allow transport systems to respond effectively to evolving urban dynamics. This approach makes regulations both immediately effective and sufficiently flexible to accommodate the unique characteristics of diverse urban areas.

5.3. Promote inclusivity by balancing stability and innovation

While institutionalisation is essential for building resilience, it can also lead to social exclusion. Both the organisational resilience of the bike-sharing operator and community-driven initiatives rely heavily on institutional frameworks to ensure stability. The operator's adherence to policies, data sharing, and collaboration with authorities reflects its institutional resilience, while community efforts—such as volunteer programs and Telegram groups for bike management—also depend on these structures. However, such high levels of institutionalisation can entrench practices that unintentionally exclude certain groups. For instance, the reluctance of some residents to engage with the digital bike-sharing system, along with the operator's difficulties in addressing vandalism and competition from local rental shops, highlights the tension between fostering institutional resilience and ensuring social inclusion.

The study shows that resilience in transport systems can create both inclusion and exclusion. This is particularly apparent in the exclusion of non-digital-savvy individuals and the conflicts between bike-sharing operators and traditional rental shops. The institutionalisation of practices, such as the enforcement of parking regulations and the designation of restricted zones, may improve system stability but can inadvertently create barriers for those unable or unwilling to follow the established rules. Measures aimed at risk reduction, while beneficial for maintaining order, can limit access and convenience for those who do not align with these institutional norms. Policymakers must recognise that institutionalisation, while critical for resilience, can reinforce social inequalities. A balance must be struck between maintaining stability and ensuring inclusivity. This means creating resilience strategies that promote broad access and participation, ensuring that all user groups benefit from the transport system's resilience. This requires not only technical solutions but also an understanding of how institutions can either support or hinder equitable access to services like bike-sharing.

Furthermore, the study raises critical questions about the responsibility for resilience (King et al., 2021; Welsh, 2014). The contemporary governmental and academic discourses (e.g., Budd and Ison, 2020), which increasingly places the burden of resilience on individuals, risks neglecting the role of institutions in supporting vulnerable groups. While individuals play an important role, their efforts must be backed by institutional support to avoid over-reliance on personal resilience. Policymakers should ensure that the responsibility for resilience is shared between individuals, communities, and institutions, with sufficient support mechanisms in place to address the needs of all users. Finally, while institutional stability is essential, it should not stifle innovation. Policymakers should create opportunities for niche innovations to emerge and challenge existing regimes, fostering transformative change. By addressing the tensions between institutional resilience and social inclusion, policymakers can develop transport systems that are both resilient and equitable, ensuring that resilience strategies benefit all users, not just those who conform to institutional norms.

6. Conclusion

The current understanding of resilience in transport literature and planning practices, which predominantly adopts an engineering resilience perspective, fails to capture the complex, interconnected nature of transport systems. The socio-political transformations sparked by recent global crises, such as the social movements and coronavirus pandemic, have disrupted established socio-institutional structures. These disruptions call for a (re)conceptualisation to transport resilience that moves beyond physical infrastructure to consider the social and institutional frameworks that underpin system stability. By using Hong Kong's dockless bike-sharing system as a case study, this paper demonstrates the relevance of multi-level resilience, showing how individual, community, and organisational dimensions interact within a socio-technical transport system.

This study offers several transferable policy implications. First, policymakers must recognise that resilience is not solely a matter of infrastructure but also involves social structures and institutional frameworks. The adaptability of individuals is crucial, but without

support from broader systems, these efforts may remain isolated and ineffective. Policies should therefore encourage the integration of individual adaptations into systemic frameworks, ensuring that users' actions can drive broader resilience initiatives. This may include providing technological and policy support that enables individuals to participate in and contribute to resilient transport systems. Second, while community and organisational resilience significantly enhance stability, they can also perpetuate social inequities. High levels of institutionalisation often create rigid structures that exclude marginalised groups. Policymakers should adopt a balanced, inclusive approach that designs transport policies responsive to local needs and considers the socio-political and spatial contexts unique to each community. This challenges contemporary discourses (e.g., Budd and Ison, 2020) that shift risk responsibility from the state to individuals. Third, the integration of the MLP and socio-ecological resilience frameworks offers a more social-technical understanding of transport systems. By addressing not only the physical but also the socio-institutional and cultural dimensions of resilience, policymakers can develop strategies that foster both innovation and stability. This balance ensures that transport systems remain adaptable to change while preventing the reinforcement of existing inequalities.

While this qualitative study provides valuable insights, further exploration through quantitative modelling of system dynamics, a commonly approach adopted in transport engineering (Shepherd, 2014; Wang et al., 2023b for a Hong Kong case), using the MLP framework (Papachristos, 2011, 2019; Papachristos and Struben, 2019; Prouty et al., 2020) is warranted. Another promising direction is agent-based modelling (Hansen et al., 2019), which allows for simulating individual, heterogeneous, autonomous agents to address the growing complexity of both technical and social phenomena, including diverse actors and non-linear interactions, as suggested by MLP. Such quantitative approaches align with the mainstream of transport resilience research by offering simulations of systemic responses to disruptions and long-term adaptations. Additionally, future research should explore multi-system approaches that encompass various modes of transport, as well as energy and food systems. While multi-system research is often dominated by qualitative case studies (Bakhuis et al., 2024), integrating quantitative techniques can yield more comprehensive insights. By integrating qualitative insights with quantitative analysis, future research can deliver a more comprehensive understanding of how resilience strategies operate across different levels of transport systems. This combination would help policymakers develop more inclusive data-driven practices that ensure transport systems remain adaptable, equitable, and sustainable in the face of ongoing and future challenges. The qualitative exploration in this paper serves as a concrete first step, illustrating the applicability of MLP in transport resilience research while highlighting the need for complementary quantitative methods to enhance policymaking.

Appendix. A Questions in semi-structural interviews

a) **Bike-sharing operators and traditional cycling shops**
   1 How has the coronavirus pandemic and recent political environment facilitated or hindered the development of [organisation name]?
   2 How did [organisation name] adapt its practices when facing crisis?
   3 Are there any challenges for […]? How did [organisation name] overcome the challenges?
      (a) working with different key members and other members in [organisation name]?
      (b) daily operations?
      (c) development of [organisation name] and diffusion?
   4 How did you recruit participants (staffs & customers), especially for the earlier time of operation?
   5 Has [organisation name] been in relationship with any other (transport-related) organisations and citizen-led initiatives? Who are they? How did the relationship form and develop?
   6 Are there any challenges if you collaborate with other (transport-related) organisations and grassroots initiatives? Can you give some examples? Why?
   7 "[Organisation name] contributes to the empowerment of citizens against adverse events", how would you comment on this?
   8 Who (e.g., the government, community groups/entrepreneurship, or individual citizens) should be responsible to building strength against adverse events and the changing environment?

b) **Cyclists and non-cyclist residents**
   1 How has the coronavirus pandemic and recent political environment affected your daily transport practices?
   2 How did you adapt your transport practices when facing crisis?
   3 Have you heard of resilience? In what context? How do you understand the term?
   4 How do you work within any grassroots organisations regarding transport disruptions and operations?
      a) If yes, how would you and/or your organisation ideally work with the government regarding transport disruptions and operations?
      b) Does the term, resilience, mean anything that connect to your organisation?
   5 Who (e.g., the government, community groups/entrepreneurship, or individual citizens) should be responsible to building strength against adverse events and the changing environment?

c) **Government officers**
   1 Is the government aware of any of the transport-related grassroots initiatives?
   2 What are the views of government about transport-related grassroots initiatives?
   3 What are the plans of transport department for responding bike sharing initiatives and transport-related grassroots initiatives?
   4 Do you think it is feasible for them to integrate with the mainstream transport system? How and why?
   5 Have you heard of resilience? In what context? How do you understand the term?
   6 Does the government have special planning for transport resilience planning?
   7 How does the government cooperate with industries and residents for urban transport resilience?
   8 Do you think public participation in urban transport (emergency) management necessary?
   9 Does the government have any management focusing on the improvement of resilience against transport disruptions?
   10 Who (e.g., the government, community groups/entrepreneurship, or individual citizens) should be responsible to building strength against adverse events and the changing environment?

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tranpol.2025.01.020.

Data availability

The authors do not have permission to share data.

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