Article

Shared Bicycle Systems as Circular Urban Infrastructure: Resource Utilization and Sustainability Implications from Holiday Travel Behavior

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Abstract: Shared bicycle systems are widely promoted as sustainable urban mobility solutions due to their potential for resource sharing and emission reduction. However, assessments of their sustainability performance often rely on aggregate usage indicators, providing limited insight into how shared mobility assets are actually utilized across time and space. From a circular economy perspective, uneven utilization patterns may undermine resource efficiency and long-term infrastructure sustainability. This study examines shared bicycle systems as circular urban infrastructure by analyzing temporal and spatial patterns of resource utilization during a public holiday period. Using large-scale shared bicycle order data from Shenzhen during the Labor Day holiday, the study investigates how demand is distributed within daily cycles and across urban space, with particular attention to concentration and inequality in usage. The results reveal pronounced temporal and spatial concentration of shared bicycle trips. A substantial proportion of trips is concentrated within a limited number of peak hours, while spatial usage remains highly clustered in specific urban zones. Importantly, these concentration patterns persist even during peak demand periods, indicating limited temporal and spatial elasticity of the system under stress conditions. These findings suggest that the sustainability of shared bicycle systems depends not only on overall demand levels, but also on the structure of resource utilization. By highlighting distributional inefficiencies in time and space, this study contributes to ecological economics and management research on circular urban infrastructure and offers practical insights for the governance and operation of shared mobility systems.

Keywords: shared mobility; bike-sharing; circular economy; urban infrastructure; resource utilization; sustainability

1. Introduction

Urban mobility systems play a critical role in shaping the sustainability performance of contemporary cities. As urbanization accelerates and environmental pressures intensify, shared mobility solutions—particularly shared bicycle systems—have been widely promoted as low-carbon, resource-efficient alternatives to private motorized transport. By enabling the repeated use of a single physical asset across multiple users, shared bicycles are commonly framed as an inherently sustainable form of urban transport that contributes to emission reduction, congestion mitigation, and improved accessibility.

However, the sustainability of shared bicycle systems cannot be fully assessed through aggregate usage indicators alone. While total trip volumes and modal substitution effects provide useful insights into system adoption, they offer limited understanding of how shared mobility assets are actually utilized over time and across

urban space. From an ecological economics perspective, sustainability is not only a question of whether an infrastructure is used, but also how intensively, unevenly, and efficiently resources are deployed and circulated within the system.

Public holidays represent a distinctive yet underexplored context for evaluating shared bicycle systems. Unlike regular weekdays dominated by commuting patterns, holiday travel is characterized by leisure-oriented, short-distance, and highly time-concentrated mobility behaviors. Such periods act as natural stress tests for urban infrastructure, revealing structural mismatches between demand and resource allocation that may remain obscured during routine conditions. Understanding shared bicycle usage under these conditions is therefore essential for assessing system resilience and long-term sustainability.

Against this background, this study examines shared bicycle systems as circular urban infrastructure, focusing on temporal and spatial patterns of resource utilization during a major public holiday. Using large-scale shared bicycle order data from Shenzhen during the Labor Day holiday, the analysis investigates how demand is distributed across time and space, and what these distributional patterns imply for ecological efficiency and system management. By shifting attention from aggregate demand to utilization structure, this study contributes to a more nuanced understanding of the sustainability challenges and governance implications associated with shared mobility systems.

2. Literature Review and Research Gaps

2.1. Shared Mobility and Urban Sustainability

A growing body of literature has examined shared bicycle systems within the broader framework of sustainable urban mobility. Existing studies have primarily focused on the environmental and transport-related benefits of bike-sharing, including reductions in greenhouse gas emissions, substitution of private car trips, and improvements in first- and last-mile connectivity [1–3]. From a policy and planning perspective, shared bicycle systems are often framed as an integral component of low-carbon urban transport strategies and sustainable mobility transitions [4,5]. Recent scholarship further highlights that cycling-related infrastructure and shared mobility systems have gained renewed policy attention in the post-pandemic era, with implications for sustainable urban mobility planning [6,7].

In addition to system-level impacts, empirical research has explored factors influencing bike-sharing adoption and demand, such as built environment characteristics, weather conditions, pricing schemes, and socio-demographic attributes [8–10]. While these studies provide valuable insights into the determinants of usage and the overall contribution of shared bicycles to sustainable transport, they tend to rely heavily on aggregate indicators, including total trip counts, average ridership levels, or city-wide usage rates. Beyond mobility outcomes, bike-sharing has increasingly been examined as a digitally mediated platform phenomenon, particularly in China, where operational logics and governance arrangements shape sustainability performance in practice [11].

As a result, less attention has been paid to the distributional characteristics of usage, particularly how demand fluctuates across time and concentrates in specific urban locations. This emphasis on averages risks overlooking structural imbalances in infrastructure utilization that may undermine long-term system efficiency, operational resilience, and sustainability performance [1].

2.2. Circular Economy and Urban Infrastructure

The concept of the circular economy emphasizes the efficient circulation of resources through repeated use, extended product lifecycles, and minimized waste generation [12,13]. Within this framework, urban infrastructure systems are increasingly conceptualized as resource-intensive assets whose sustainability depends not only on availability or scale, but on how resources are utilized, maintained, and governed over time [14,15].

From a circular economy perspective, infrastructure that is underutilized for prolonged periods represents inefficient resource allocation, while infrastructure that is overstressed during short peak intervals may experience accelerated degradation, increased maintenance requirements, and reduced lifecycle efficiency [16,17]. Recent work explicitly connects shared bicycle systems to circular futures, emphasizing tensions between short-term service maximization and long-term circular value creation through durability and maintenance regimes [18]. These dynamics highlight the importance of examining utilization structure, rather than aggregate demand alone, when evaluating the sustainability of urban systems.

Despite their physical, asset-based nature, shared bicycle systems have rarely been analyzed through the lens of circular infrastructure. Most existing research treats bike-sharing primarily as a transport service or a digitally mediated platform, rather than as a system of durable assets subject to uneven wear, spatial congestion, and temporal idleness [19,20]. Moreover, emerging studies have begun to address end-of-life and reuse pathways for shared-bike

assets, extending circular economy reasoning from utilization to material recovery and repurposing [21]. This analytical orientation limits our understanding of how shared mobility systems contribute to—or potentially constrain—urban circularity in practice, particularly in relation to asset durability and long-term resource efficiency.

*2.3. Research Gaps and Study Contribution*

Two key gaps emerge from the existing literature. First, while spatiotemporal characteristics of bike-sharing demand have been explored in several studies, empirical evidence on how usage is distributed across time and space remains fragmented, and is often derived from routine weekday conditions rather than non-routine contexts [22,23]. In particular, limited attention has been paid to demand distribution under short-term stress conditions such as public holidays, during which travel behavior is dominated by leisure activities and concentrated time windows [24].

Second, the circular economy implications of these distributional patterns remain insufficiently explored. Existing shared mobility research rarely links temporal and spatial concentration of usage to issues of asset durability, operational resilience, and sustainable infrastructure management, despite their relevance for circular urban systems and policy design [25,26].

This study addresses these gaps by examining temporal and spatial concentration patterns of shared bicycle usage during a major public holiday and interpreting these patterns within a circular infrastructure framework. Rather than evaluating sustainability through aggregate demand alone, the analysis highlights how uneven utilization structures shape ecological efficiency and managerial challenges. In doing so, the study extends shared mobility research into the domain of ecological economics and management, offering insights relevant to scholars, urban planners, and policymakers concerned with the sustainable governance of shared urban infrastructure.

3. Conceptual Framework

Figure 1 conceptual framework illustrates the analytical logic of this study. Shared bicycle systems are conceptualized as circular urban infrastructure composed of reusable mobility assets. From a circular economy perspective, sustainability performance depends on how these assets are utilized across time and space. The framework emphasizes two key analytical dimensions—temporal utilization structure and spatial utilization structure—which jointly shape patterns of utilization inequality. These patterns provide the basis for assessing ecological efficiency, operational resilience, and managerial and policy implications of shared bicycle systems, particularly under short-term demand stress such as public holidays.
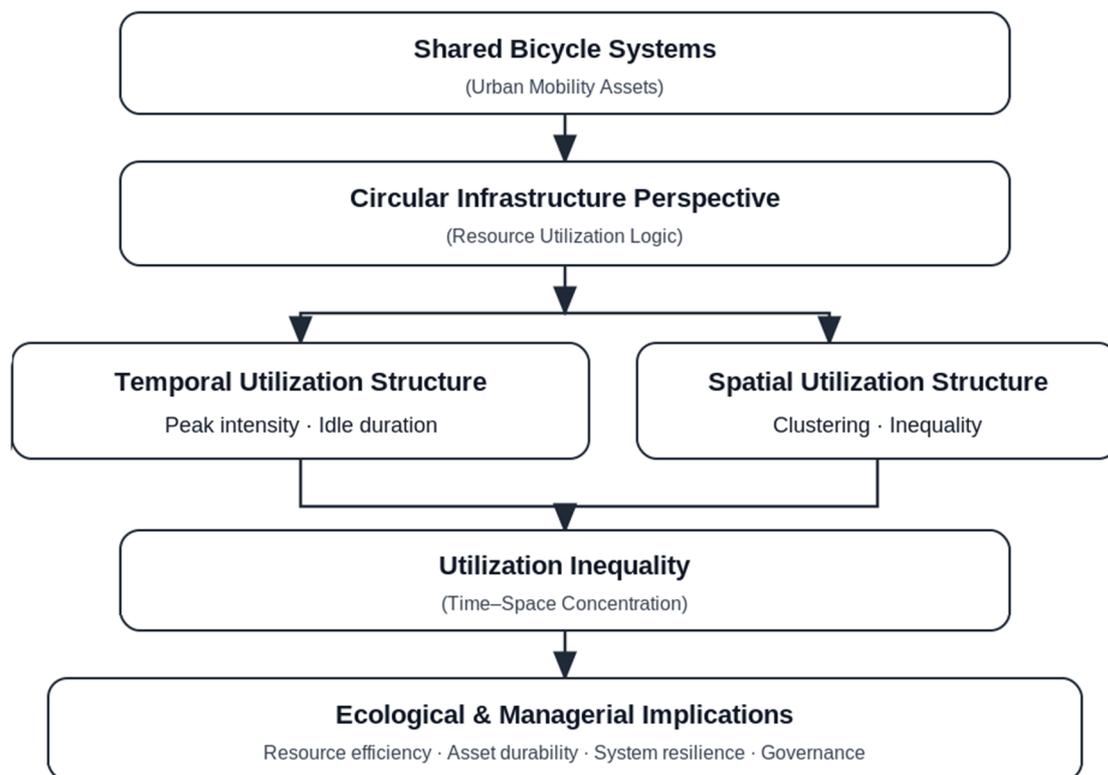
Figure 1. Conceptual framework for analyzing shared bicycle systems as circular urban infrastructure.

3.1. Shared Bicycle Systems as Circular Urban Infrastructure

In this study, shared bicycle systems are conceptualized as circular urban infrastructure. Unlike conventional transport infrastructure, which is typically fixed and location-bound, shared bicycles consist of mobile and reusable assets that circulate continuously among users and urban locations. Their operation embodies key principles of the circular economy, including repeated use, shared access, and the potential to reduce material demand relative to privately owned vehicles.

From a circular economy perspective, infrastructure sustainability is not solely determined by availability or adoption rates, but by how efficiently resources circulate throughout their lifecycle. Shared bicycle systems illustrate this principle clearly: each bicycle represents an embodied investment of materials, energy, and labor whose ecological value depends on sustained, balanced utilization over time. Excessive concentration of usage—either temporally or spatially—can accelerate physical wear, increase maintenance and replacement frequency, and undermine lifecycle efficiency. Conversely, prolonged underutilization reflects idle capacity and inefficient allocation of embodied resources.

Assessing shared bicycle systems as circular infrastructure therefore requires attention to both overuse and underuse. Sustainability outcomes emerge from the interaction between utilization intensity, asset durability, and management practices, rather than from aggregate demand alone. This perspective aligns with ecological economics approaches that emphasize throughput, lifecycle performance, and the structural conditions under which resource circulation occurs.

3.2. Analytical Dimensions: Time, Space, and Utilization Structure

Building on this theoretical perspective, the analytical framework focuses on three interrelated dimensions of resource utilization: time, space, and utilization structure.

The temporal dimension captures how shared bicycle demand fluctuates within daily cycles. Temporal concentration reflects the extent to which infrastructure capacity is shaped by short peak periods rather than continuous use. From a circular infrastructure perspective, systems dominated by sharp temporal peaks may experience stress that exceeds what is implied by average usage levels, with implications for asset degradation, maintenance scheduling, and system resilience.

The spatial dimension examines how trips are distributed across urban locations. Spatial concentration indicates whether shared bicycles function as broadly accessible public infrastructure or are effectively confined to a limited number of high-demand zones. High spatial clustering may generate localized congestion and uneven asset wear, while large areas remain under-served or underutilized.

Utilization structure integrates these temporal and spatial dimensions by assessing the degree of inequality in usage distribution. Rather than viewing concentration as inherently problematic, the framework treats utilization inequality as a diagnostic indicator. Persistent concentration in time or space suggests structural mismatches between asset deployment and actual demand, revealing potential inefficiencies and vulnerabilities in system design and management. In this sense, utilization structure serves as a bridge between empirical usage patterns and sustainability-oriented evaluation.

3.3. Holiday Periods as Stress Tests for Circular Infrastructure

Public holidays provide a particularly suitable context for examining utilization structure in shared bicycle systems. During holidays, travel behavior is less constrained by routine work schedules and more influenced by leisure activities, tourism, and discretionary mobility. These conditions often generate short-term demand surges and localized congestion, placing shared mobility systems under stress.

By analyzing shared bicycle usage during a holiday period, this study treats such events as natural stress tests for circular urban infrastructure. Stress conditions amplify underlying structural characteristics of resource allocation that may remain obscured during routine periods. Temporal peaks become more pronounced, spatial clustering intensifies, and management limitations are more likely to surface.

From an ecological economics and management perspective, stress tests offer valuable insights into system resilience and adaptive capacity. Observing how shared bicycle systems perform under short-term demand shocks helps to identify whether existing governance and operational arrangements are compatible with long-term circularity objectives. Holiday periods therefore provide a meaningful empirical setting for evaluating the sustainability performance of shared bicycle systems beyond average, day-to-day conditions.

4. Methods

4.1. Study Context and Data Source

This study examines shared bicycle systems as circular urban infrastructure under peak travel demand conditions. Shenzhen, one of China's most densely populated and digitally advanced metropolitan areas, provides an appropriate empirical context for analyzing the sustainability performance of shared micro-mobility systems. The city has widely adopted shared bicycle programs as part of its urban transportation and low-carbon mobility initiatives.

The analysis is based on operational data obtained from the Shenzhen Municipal Government Open Data Platform. The dataset covers all recorded shared bicycle trips during the 2021 Labor Day holiday, spanning three consecutive days. In total, the dataset contains more than 3.36 million trip records, ensuring comprehensive temporal and spatial coverage of holiday travel behavior.

Each trip record includes the trip start time, end time, geographic coordinates of origins and destinations, and anonymized user identifiers. No personal demographic information is available. All analyses are conducted at an aggregated level to examine system-wide patterns rather than individual behavior.

4.2. Conceptual Framework: Shared Bicycles as Circular Urban Infrastructure

From an ecological economics and management perspective, shared bicycle systems are conceptualized as circular urban infrastructure rather than conventional transportation services. In this framework, bicycles are treated as shared urban assets that generate mobility services through repeated use, while digital platforms coordinate their allocation across time and space.

Accordingly, system performance is assessed along three interrelated dimensions:

(1) resource utilization intensity,
(2) temporal and spatial distribution of demand, and
(3) implications for sustainable urban mobility management.

This framework shifts the analytical focus away from individual travel preferences toward system-level outcomes relevant to resource efficiency, operational resilience, and sustainability governance.

4.3. Measurement of Resource Utilization

Given the absence of bicycle inventory and operational data, resource utilization is assessed using demand-side proxy indicators derived from trip records. Such proxies are commonly employed in studies of urban sustainability and shared mobility management to evaluate system performance at an aggregate level.

➢ Temporal Utilization Intensity

Temporal utilization intensity is measured by aggregating the number of shared bicycle trips into hourly intervals across the holiday period. This approach captures fluctuations in system demand and identifies periods of sustained high usage.

Rather than focusing on isolated peak moments, the analysis emphasizes whether high utilization is maintained over extended periods, which reflects the ability of the system to continuously circulate shared mobility resources under intensified demand.

➢ Spatial Utilization Patterns

Spatial utilization patterns are examined by mapping trip origins and destinations onto uniform spatial grids. For each grid cell, the number of trip starts and ends is calculated to identify areas of concentrated bicycle usage.

Spatial concentration is interpreted as an indicator of localized resource pressure. Instead of treating concentration as inefficiency in itself, the analysis focuses on what such patterns imply for resource allocation, system coordination, and adaptive management during peak demand periods.

4.4. Temporal–Spatial Imbalance and System Resilience

To assess system resilience, the study examines the interaction between temporal demand intensity and spatial concentration. Periods characterized by both high trip volumes and strong spatial clustering are treated as stress conditions for the shared bicycle system.

System resilience is evaluated by observing whether shared bicycle usage remains continuous and broadly distributed across the study period, rather than collapsing into isolated time windows or spatial zones. This approach emphasizes functional continuity and adaptability, consistent with sustainability-oriented evaluations of urban infrastructure.

4.5. Analytical Approach and Interpretation Strategy

The analysis adopts a descriptive–interpretive approach grounded in ecological economics and management principles. Quantitative indicators are used to identify utilization patterns, while interpretation focuses on their implications for circular resource use, low-carbon mobility support, and urban governance.

Rather than optimizing predictive accuracy or deploying complex algorithms, the study prioritizes interpretability and policy relevance. This approach ensures that the findings can inform management strategies and sustainability-oriented decision-making beyond the specific empirical context.

4.6. Ethical Considerations and Data Limitations

All analyses are conducted using anonymized and publicly available data. Individual users cannot be identified, and the study complies with relevant ethical standards for data use.

Several limitations should be acknowledged. First, the study does not directly measure environmental outcomes such as carbon emissions, relying instead on system-level usage patterns as proxies for sustainability performance. Second, the absence of supply-side operational data limits the assessment of fleet-level efficiency and redistribution costs.

These limitations are addressed by focusing on management and policy implications rather than precise environmental quantification, which is consistent with the scope of ecological economics and management research.

5. Results

5.1. Temporal Concentration of Shared Bicycle Usage

Figure 2 illustrates the hourly distribution of shared bicycle trips during the Labor Day holiday period. The results reveal a pronounced temporal concentration of usage, with demand remaining at very low levels during nighttime hours (0:00–5:00), followed by a rapid increase after early morning. Trip volumes peak during the afternoon and early evening hours (approximately 15:00–19:00) before declining again at night.
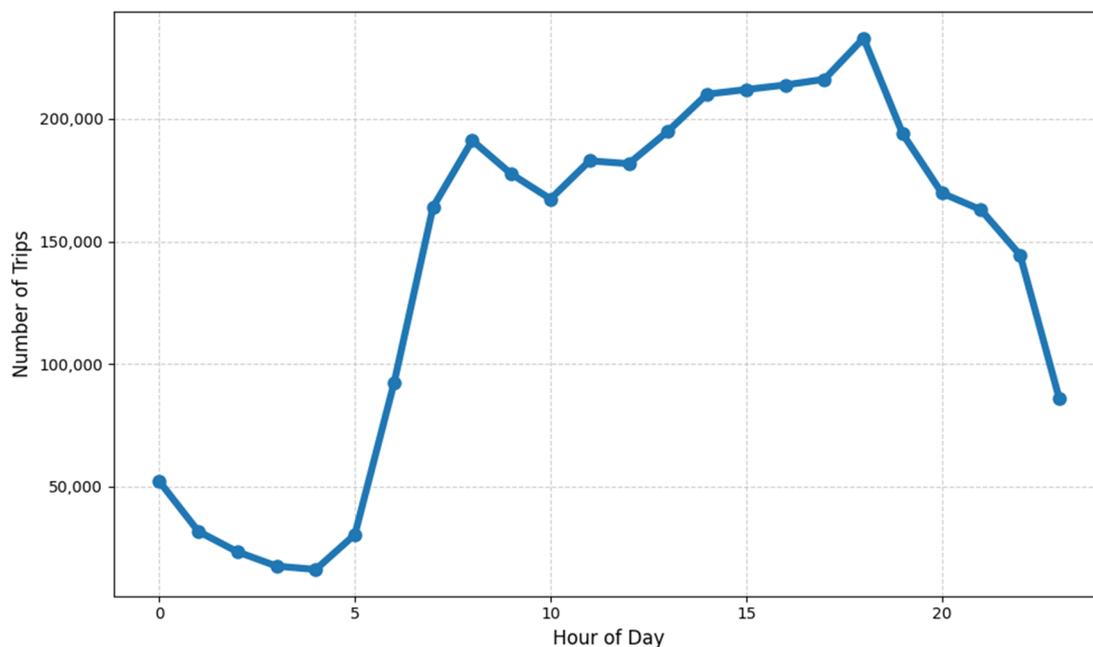

Figure 2. Hourly distribution of shared bicycle trips.

Rather than exhibiting a smooth or evenly distributed usage pattern, shared bicycle demand follows a strongly pulsed temporal structure aligned with urban activity rhythms. Notably, approximately 38.04% of all trips are concentrated within a limited number of peak hours**,** indicating a substantial imbalance in time-based infrastructure utilization. This pattern suggests that a large share of shared bicycle assets remains underutilized for extended periods, while experiencing intensified pressure during short peak intervals.

From a resource efficiency perspective, such temporal concentration implies that system performance is not constrained by overall demand volume, but by short-term demand surges that shape operational stress, maintenance intensity, and fleet turnover rates.

5.2. Spatial Clustering of Trip Origins

Figure 3 presents the spatial distribution of trip origins across the urban area. The results demonstrate a clear spatial clustering of shared bicycle usage, with a large proportion of trips originating from a limited number of geographic locations. Rather than being evenly dispersed across the city, usage is concentrated in specific zones, likely associated with leisure destinations, commercial areas, and transport hubs during the holiday period.
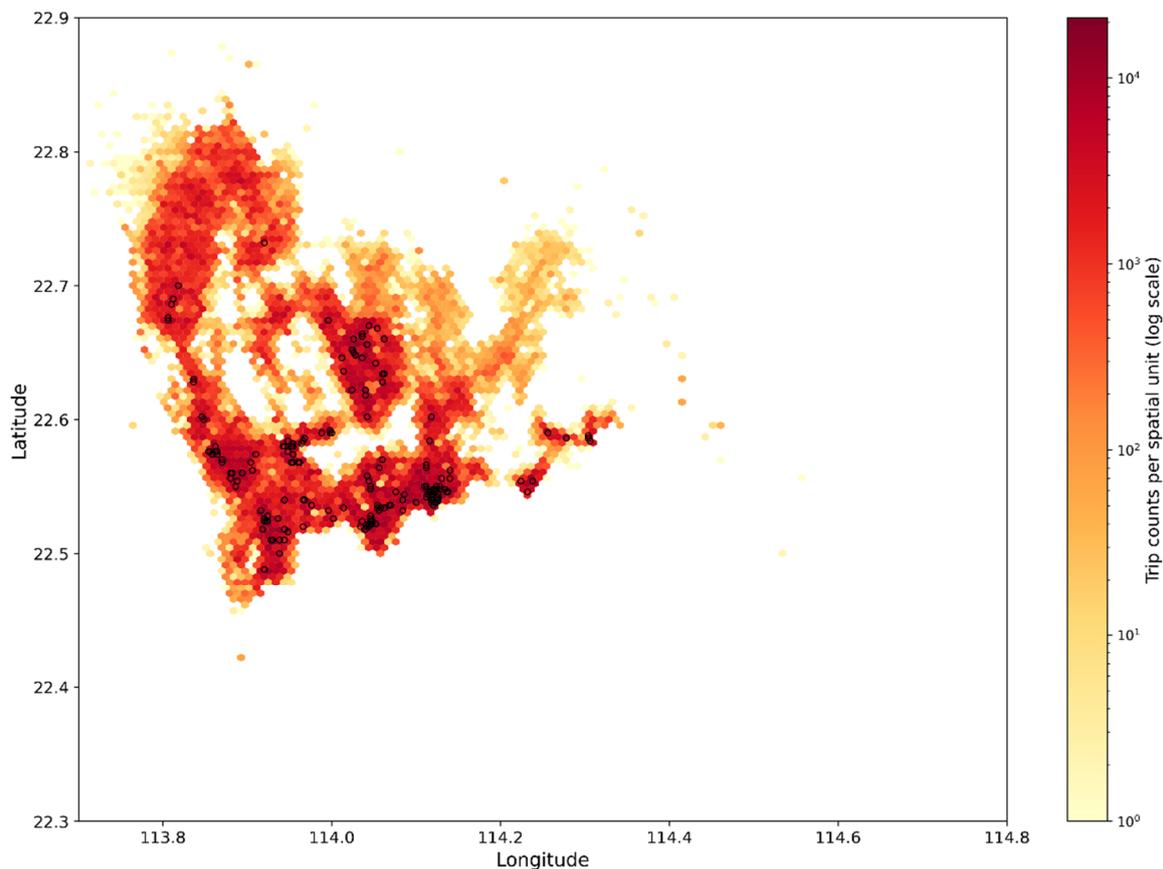
Figure 3. Spatial concentration of shared bicycle trip origins (All hours).

This spatial pattern indicates that shared bicycle systems, although designed as city-wide public infrastructure, function in practice as selectively utilized assets. Large areas of the urban space exhibit relatively low levels of demand, while a small subset of locations accounts for a disproportionate share of trips. Such uneven spatial utilization highlights a structural mismatch between uniform infrastructure deployment and heterogeneous user demand.

5.3. Spatial Inequality in Infrastructure Utilization

To further quantify spatial imbalance, Figure 4 reports a Lorenz-type concentration curve for shared bicycle usage across spatial units. The curve deviates markedly from the line of perfect equality, confirming a high degree of spatial concentration. A small proportion of locations contributes to the majority of trip volumes, while the remaining spatial units play a marginal role in overall system usage.

This finding provides robust evidence of spatial inequality in resource utilization within the shared bicycle system. Importantly, this inequality does not necessarily reflect system inefficiency or failure. Instead, it reveals how user behavior and urban functions interact to produce uneven utilization patterns that are intrinsic to shared mobility systems operating under real-world conditions.

From a circular economy perspective, such concentration implies that asset lifecycles are experienced unevenly across space, with bicycles in high-demand zones undergoing accelerated wear and operational turnover, while those in low-demand zones remain comparatively idle.
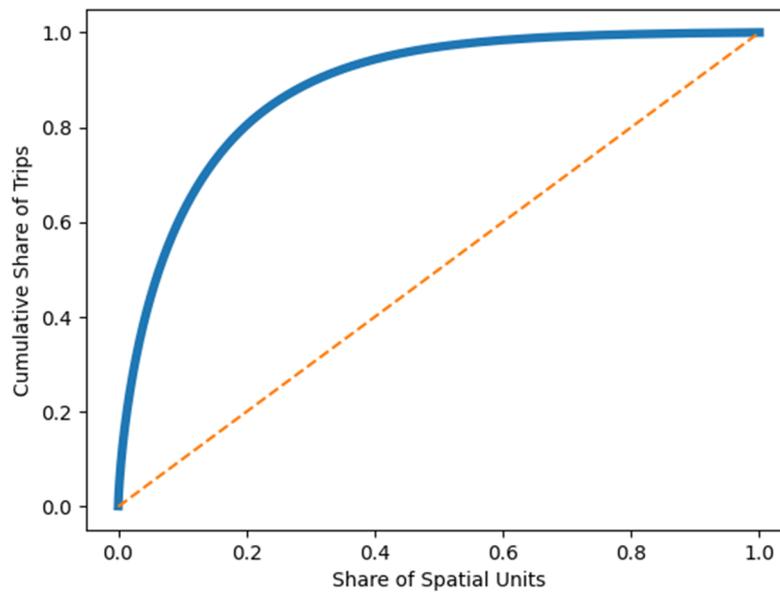
Figure 4. Spatial concentration of shared bicycle usage.

5.4. Persistence of Spatial Concentration during Peak Demand

Figure 5 compares spatial usage patterns during peak demand hours with those observed over the full observation period. The results show that even under conditions of elevated demand, the spatial distribution of trips remains highly concentrated. Peak usage intensifies existing hotspots rather than redistributing trips toward underutilized areas.
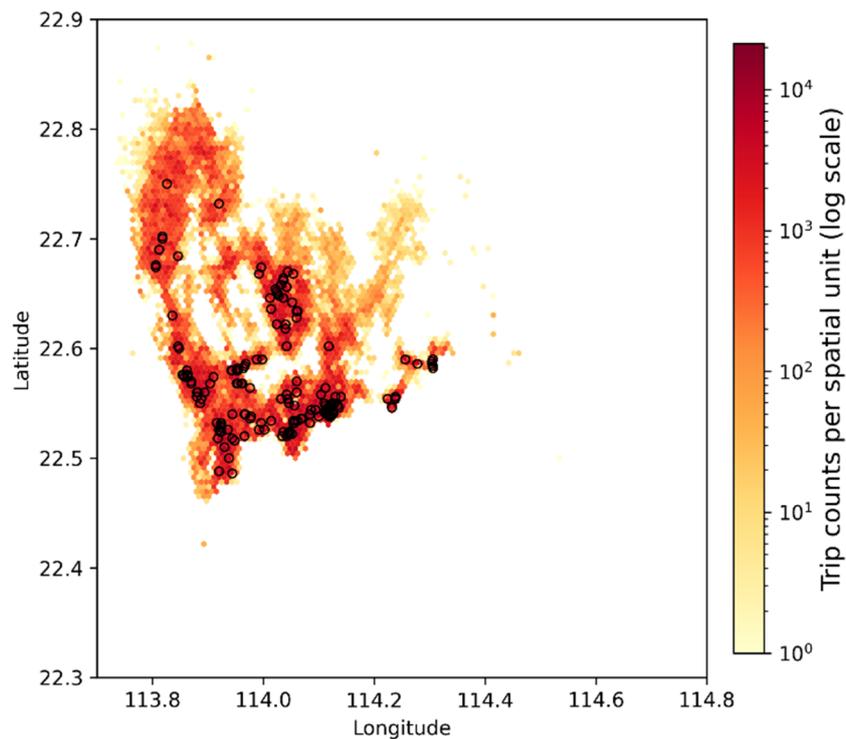
Figure 5. Spatial concentration of shared bicycle trip origins (Peak hours).

This persistence suggests that shared bicycle systems exhibit limited spatial elasticity under demand pressure. Increased demand does not automatically lead to broader spatial diffusion of usage, but instead reinforces pre-existing spatial inequalities. As a result, peak periods amplify operational stress in already congested zones without alleviating underutilization elsewhere.

Taken together, the temporal and spatial results indicate that shared bicycle systems during holiday periods operate under structurally uneven utilization regimes, characterized by concentrated demand in both time and space.

6. Ecological and Managerial Implications

While the preceding results focus on empirical patterns of shared bicycle usage during the Labor Day holiday, their significance extends beyond descriptive observations of travel behavior. The identified temporal intensity, spatial concentration, and system resilience reflect deeper interactions between digital mobility platforms, urban resource allocation, and sustainability objectives.

In the context of ecological economics and management, these findings provide a basis for interpreting shared bicycle systems as circular urban infrastructure whose sustainability performance depends not only on demand levels, but also on adaptive management and governance mechanisms. The following section discusses the broader ecological and managerial implications of the results, with particular attention to resource efficiency, low-carbon mobility, and policy-relevant insights for urban sustainability transitions.

6.1. Implications for Circular Urban Infrastructure

The observed temporal and spatial concentration patterns have direct implications for understanding shared bicycle systems as circular urban infrastructure. While shared mobility is often framed as inherently resource-efficient due to high utilization rates, the results demonstrate that utilization intensity is unevenly distributed across both time and space. In circular economy terms, this indicates that "circulation" is not uniform: a subset of assets and locations bears a disproportionate share of service provision, while others remain underutilized.

Temporal concentration implies that bicycles experience alternating phases of intense use and prolonged idleness, which may undermine asset longevity and reduce overall lifecycle efficiency [27]. From a circular infrastructure perspective, short bursts of high utilization can accelerate physical wear, increase maintenance frequency, and shorten effective service life—especially when high intensity coincides with peak travel stress (e.g., holiday surges). Conversely, prolonged idle periods represent embodied-resource underuse and a potential form of inefficiency in circular systems where value creation depends on sustained, balanced utilization rather than sporadic peaks. This resonates with recent circular-cycling research arguing that bike-sharing sustainability is conditional on how peak pressure, commercialization dynamics, and public support interact to shape circular cycling futures [18,28,29].

Existing studies on bike-sharing sustainability have largely emphasized aggregate indicators such as total trip volumes, substitution effects, and emission reductions, often concluding that higher utilization implies greater resource efficiency. From this perspective, peak-period demand is typically interpreted as evidence of system success rather than as a potential source of stress. The findings of this study do not contradict these assessments but extend them by revealing an overlooked dimension of sustainability performance. While aggregate usage may increase during peak periods, the underlying utilization structure remains highly uneven. This suggests that high demand alone does not guarantee efficient circulation of assets across their lifecycle. By highlighting temporal and spatial concentration, the present analysis complements existing evaluations and suggests that sustainability assessments based solely on aggregate indicators may mask structural inefficiencies within shared mobility systems.

Spatial concentration further reinforces this imbalance by subjecting certain assets to accelerated degradation while leaving others underutilized. Related evidence shows that spatial frictions and infrastructure barriers can suppress latent cycling demand, implying that observed concentration may partly reflect mismatches between infrastructure continuity and mobility needs, with measurable implications for potential emission reduction [7]. This distributional structure highlights a central tension in circular urban infrastructure: maximizing short-term service output in hotspots may appear efficient in the narrow sense of meeting immediate demand, but it can also concentrate wear and operational risk, potentially increasing replacement rates and undermining circularity over the longer term. Therefore, sustainability performance should be evaluated not only through aggregate volumes (total trips), but also through the structure of utilization—how demand is distributed and how that distribution shapes lifecycle outcomes and system resilience.

6.2. Managerial Implications for System Design and Operation

Prior research on shared mobility platforms has emphasized demand responsiveness, real-time matching, and operational efficiency, often framing concentrated usage as a rational outcome of market-driven allocation. From an operational standpoint, hotspots and peak demand are commonly treated as signals for capacity expansion or intensified deployment [30]. In contrast, the circular infrastructure perspective adopted in this study suggests that such efficiency-oriented interpretations require qualification. While platform logic prioritizes short-term service availability, persistent concentration may impose hidden costs in terms of accelerated asset wear, increased maintenance intensity, and reduced lifecycle efficiency. This divergence highlights a tension between platform

performance metrics and circular performance objectives, suggesting that managerial success cannot be evaluated solely through short-term utilization outcomes.

From a managerial standpoint, the results suggest that expanding fleet size alone is unlikely to address performance challenges during peak demand periods. Increased supply may relieve short-term shortages in hotspots, but it can also deepen off-peak idleness and widen spatial underutilization—thereby lowering overall lifecycle efficiency. Instead, targeted interventions aimed at redistributing demand across time and space may offer more sustainable solutions, particularly when framed as resource allocation within a circular asset system.

Operationally, time-sensitive pricing mechanisms and demand-responsive incentives can help shift part of the demand away from extreme peaks, reducing short-term stress on assets and lowering the risk of accelerated deterioration. Similarly, incentive-based redistribution strategies can encourage users to return bicycles to under-served areas, reducing spatial imbalances without relying solely on operator-driven rebalancing. Adaptive deployment policies—especially during predictable holiday surges—can be designed as "stress-prevention" rather than "stress-repair", prioritizing early interventions to avoid the amplification of concentration.

The persistence of spatial concentration during peak hours further indicates that operational flexibility is limited without active management. Data-driven monitoring of demand hotspots can enable operators to anticipate stress points and allocate maintenance and rebalancing resources more efficiently. Recent large-scale empirical work also demonstrates that spatiotemporal pattern discovery from bike-sharing data can support operational planning and integration with public transport, reinforcing the managerial relevance of analyzing utilization structure [31]. Importantly, circular management emphasizes not only moving bicycles toward demand, but also protecting asset health: preventive maintenance scheduling, targeted inspection in high-intensity zones, and durability-oriented component replacement can reduce the long-term material footprint of operations.

Operators face a governance tension between platform performance metrics (e.g., rapid availability in hotspots, high trip counts) and circular performance metrics (e.g., reduced replacement rates, balanced utilization, extended service life). Aligning operational KPIs with circularity goals—such as incorporating durability and lifecycle indicators into performance evaluation—can help shift decision-making from maximizing rides today to maximizing sustainable mobility services over time.

6.3. Policy Implications for Sustainable Urban Mobility

For policymakers, the findings underscore the need to integrate shared bicycle systems into broader urban mobility and land-use planning frameworks. Holiday-specific demand patterns reveal how leisure-oriented mobility can exert concentrated pressure on localized infrastructure, suggesting that shared bicycles should be treated as part of public mobility capacity planning rather than purely commercial services. Coordinated planning across transport modes, public space management, and tourism policy can help mitigate such pressures while enhancing the contribution of shared mobility to low-carbon urban transport systems [32].

The results highlight policy trade-offs that are frequently overlooked. Policies aimed at maximizing availability and convenience in hotspots may improve short-term accessibility but can intensify localized congestion, accelerate asset degradation, and increase the need for frequent replacement—potentially eroding long-term circular benefits. Conversely, policies that prioritize circularity (e.g., balanced deployment, durability standards, maintenance requirements) may appear less responsive to peak demand in the short run but can improve system sustainability and reduce material throughput over time. Policymakers therefore need to balance immediate mobility service goals with longer-term circular infrastructure objectives.

Rather than viewing spatial concentration as a failure of shared bicycle systems, policymakers may interpret it as a diagnostic signal that reveals where supportive infrastructure investments and regulatory coordination are most urgently needed. For instance, hotspot persistence suggests the value of micro-mobility supportive infrastructure (parking with geo-fenced zones, curb-space management, integration with public transit nodes) to reduce negative externalities. At the governance level, mechanisms for data sharing, coordination between operators and municipal agencies, and standards for durability and end-of-life handling can align platform-based operations with urban sustainability objectives.

Cities must navigate a governance tension between market-driven platform operations and public-interest sustainability goals. While platform competition can increase service provision, it may also incentivize short-term expansion and ride maximization without sufficient attention to lifecycle impacts. Regulatory frameworks that incorporate circular performance requirements—such as minimum durability standards, repairability requirements, and transparent reporting of replacement and recycling practices—can help reconcile this tension and ensure that shared bicycles genuinely function as circular urban infrastructure. In the Chinese context, studies

on the platformisation of cycling highlight how regulatory monitoring and standardised management have become integral to aligning platform operations with broader sustainability goals [11].

In the broader circular economy literature, sustainability assessments of infrastructure systems have increasingly emphasized lifecycle performance, durability, and throughput efficiency rather than static capacity provision. However, empirical applications of these principles have focused predominantly on fixed infrastructures such as buildings, energy systems, or water networks. Policy responses that address infrastructure discontinuities and geographic barriers can simultaneously improve accessibility and deliver environmental co-benefits, suggesting that governance should treat spatial concentration as a diagnostic signal rather than a simple operational failure [7]. By applying a circular infrastructure lens to shared bicycle systems, this study extends circular economy thinking to a form of mobile, platform-mediated infrastructure that has received limited attention in ecological economics research. The findings demonstrate that utilization structure—particularly under stress conditions— provides a useful diagnostic bridge between abstract circularity principles and real-world urban mobility systems.

6.4. Summary of Contributions

Overall, this study demonstrates that shared bicycle systems function as conditionally circular infrastructure, whose sustainability outcomes depend critically on how demand is distributed across time and space. By revealing persistent temporal and spatial concentration during holiday periods, the results contribute to a more nuanced understanding of resource utilization, operational resilience, and governance challenges in shared urban mobility systems.

More specifically, the study advances ecological economics and management research in three ways. First, it shifts evaluation away from aggregate adoption metrics toward utilization structure, showing that distributional concentration is a key diagnostic indicator of circular infrastructure performance. Second, it clarifies a central sustainability tension, short-term operational efficiency versus long-term asset durability, highlighting how peak-oriented management can inadvertently increase material throughput and weaken circular outcomes. Third, it identifies circular governance tensions at both operator and municipal levels, emphasizing that sustainability performance depends on how digital platforms, public infrastructure planning, and regulatory frameworks interact under demand stress conditions.

Taken together, these insights suggest that shared bicycle systems can support low-carbon urban mobility, but their circularity and long-term sustainability are not automatic. They require governance mechanisms and management strategies that explicitly aim to smooth extreme concentration, protect asset lifecycles, and align platform incentives with public sustainability objectives.

7. Conclusions

This study examined shared bicycle systems as circular urban infrastructure under holiday travel conditions, focusing on the temporal and spatial structure of resource utilization. Using large-scale order data from a public holiday period, the analysis reveals that shared bicycle usage is characterized by persistent concentration in both time and space, resulting in structurally uneven utilization of mobility assets.

By moving beyond aggregate usage indicators, the study demonstrates that sustainability performance in shared mobility systems cannot be fully assessed through demand volume alone. Temporal and spatial concentration reflects not merely demand volatility, but deeper structural tensions in how shared infrastructure circulates resources under stress. In particular, peak-oriented utilization patterns highlight a fundamental trade-off between short-term operational efficiency and long-term asset durability. While serving intense peak demand may enhance immediate accessibility and platform performance, it can simultaneously accelerate asset wear, increase maintenance intensity, and weaken circular outcomes by shortening effective service lifecycles.

From a governance perspective, the findings point to an inherent tension between market-driven platform logic and circular infrastructure objectives. Platform operators are incentivized to maximize ride availability and throughput, whereas urban sustainability goals emphasize balanced utilization, reduced material turnover, and long-term system resilience. This governance tension suggests that circularity in shared bicycle systems is conditional rather than automatic, depending critically on how operational incentives, regulatory frameworks, and public planning priorities are aligned.

The study contributes to ecological economics and management research by reframing shared bicycle systems as asset-based infrastructure whose sustainability depends on utilization structure rather than adoption levels alone. It highlights utilization inequality as a diagnostic indicator for identifying hidden inefficiencies and vulnerabilities in ostensibly green mobility systems. In doing so, the analysis complements existing low-carbon mobility research by emphasizing circulation patterns, lifecycle considerations, and governance trade-offs. While the empirical setting is Shenzhen and a specific holiday period, related recent studies across different contexts

indicate that spatiotemporal pressure, platform governance, and infrastructure constraints are recurring issues in shared cycling systems, supporting the broader relevance of our circular infrastructure framing [7,11,18].

Several limitations should be acknowledged. The analysis relies on order-level data and does not directly observe asset conditions, maintenance actions, or environmental emissions, which constrains assessment of lifecycle impacts at the vehicle level. In addition, the focus on a single city and holiday period limits generalizability across contexts. Future research may extend this framework through multi-city comparisons, longer observation windows, and integration of operational and maintenance data to more fully evaluate resilience and circular performance in shared urban mobility systems. Compared with existing studies that evaluate shared bicycle systems primarily through aggregate usage or emission metrics, this study demonstrates the value of a utilization-structure perspective for understanding circularity, durability, and governance challenges in shared urban infrastructure.

The findings suggest that shared bicycle systems can support sustainable and low-carbon urban mobility, but their contribution to circular economy transitions depends on governance arrangements that explicitly address utilization concentration, lifecycle durability, and the balance between short-term efficiency and long-term sustainability.

Author Contributions

J.X. and F.H.: conceptualization, investigation, data curation, writing original draft preparation; J.X.: methodology; J.X.: writing review and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data used in this study were obtained from the Shenzhen Municipal Government Open Data Platform. The dataset is publicly available; access details can be provided upon request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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