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DESIGN OF A USER-FRIENDLY BICYCLE REGISTRATION AND TRACKING SYSTEM

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Abstract
Bicycle registration and tracking systems are also gaining significance to aid in sustainable urban mobility, ownership verification, theft deterrence, and recovery support. Most current solutions are however disjointed, complex, expensive or poorly linked with overarching transport and security systems. This review analyzes how to design an easy-to-use bicycle registration and tracking system by synthesising the literature regarding cycling behaviour, bike-sharing systems, Internet of Things architecture, mobile usability, data security, tracking technologies and smart mobility integration. The review points out that to be effective, good systems need more than just technical tracking; they need to integrate both easy registration processes, successful bicycle identification, trustworthy data management, privacy conscious location management, and open user interfaces. Comparative analysis reveals that manual registries, web-based, IoT-enabled trackers and community-based reporting systems have their own benefits, yet also significant limitations. It is advisable to have a hybrid model, where digital registration, passive identification, optional active tracking, alert notification, and authorized recovery support are incorporated into it. The review also points out the major issues that are associated with interoperability, adoption, cost, privacy, and institutional coordination. On the whole, the paper offers a systematic basis on how to design scalable, secure and user-friendly bicycle registration and tracking systems in urban settings.

Keywords: *Bicycle registration; bicycle tracking; user-centered design; Internet of Things; data security; smart mobility; theft prevention.*

1. Introduction

Bicycles are increasingly recognised as a key element of sustainable urban mobility due to their affordability, low carbon emissions, and efficiency in terms of space. Bicycles are encouraged as an effective way to ease congestion, improve health, and foster sustainable travel behavior in many urban areas. But the adoption of bicycles as a means of mobility is influenced not only by infrastructure and policy initiatives but also by the presence of robust systems that can secure bicycle ownership, deter theft, and facilitate recovery of lost or stolen bicycles. Previous research on bicycle commuting indicates that cycling is influenced by a range of factors, such as the distance travelled, infrastructure, attitude and convenience [1]. This suggests that a bicycle registration and tracking system should be developed as part of an integrated mobility system, rather than a stand-alone technical system.

The increasing popularity of bicycle commuting and shared mobility has resulted in a need for an organized system for bicycle identification, ownership verification and, if needed, tracking. Existing bicycle registration methods typically involve manual registers, stickers, or databases maintained by local authorities, but these may suffer from a lack of interoperability, user adoption and updating processes. With increasing integration of cycling into transport systems, users need a system that is easy to use, update, and trustworthy. Studies on attitudes towards bicycle commuting reveal that the choice to ride is related to perceptions of utility and trust, implying that bicycle registration should not be overly complicated and should facilitate good user experiences [2].

A user-friendly bicycle registration and tracking system should therefore be technically sound, accessible, usable and privacy-sensitive. The registration process should enable users to input key bicycle and owner information via digital platforms, and tracking features should support crime prevention, bike recovery, and law enforcement coordination. The system should also consider diverse user needs such as students, employees, cyclists, delivery drivers, bike-sharing companies, and police departments. Research on bike-sharing systems shows that bicycle-related systems are best served by considering operational efficiency, user acceptance and implementation processes [3]. This is particularly pertinent to bicycle registration and tracking systems because they are dependent upon a user's view of the system as being useful, safe, and convenient.

While bicycle registration and tracking systems have considerable potential, there are still significant gaps. Some systems are not integrated across institutions, cities or service providers, which hampers the ability to provide interoperable ownership verification or integrated tracking. Other tracking systems are hardware-based and may be prohibitively expensive for the public, or may have privacy and surveillance issues. Furthermore, technically sophisticated but impractical systems may not be adopted. Research on cycling intentions highlights the role of social identity, control and motivation in influencing cycling-related behaviours [4]. This suggests that when designing systems, both technological and human factors need to be considered.

This review explores the design of user-friendly bicycle registration and tracking systems by reviewing literature on cycling behavior, bike-sharing systems, IoT-based architecture, usability, data security, tracking technologies and smart mobility applications. There are four key contributions of this review. First, it offers a multidisciplinary perspective combining insights from transport systems, Internet of Things (IoT) architecture, user-centered design, and data security to holistically understand bicycle registration and tracking systems. Second, it offers a systematic classification and comparative summary of system models: manual, digital, IoT-based and hybrid systems. Third, it outlines the design considerations and challenges associated with technology implementation in terms of user-friendliness, scalability, data security, and interoperability. Last, it identifies key research gaps and suggests a user-friendly hybrid-based approach for future system designs. Through its emphasis on both the technical and user perspectives, the review seeks to offer a framework for the design of reliable, accessible, secure and modern urban mobility systems for bicycle registration and tracking. This review uses a thematic synthesis of literature to explore the design of user-friendly bicycle registration and tracking systems. The literature was classified based on the conceptual framework adopted, including cycling habits, bicycle-sharing services, Internet of Things (IoT) infrastructure, mobile user interface design, data security, tracking technologies, system models, and smart mobility.

The identified studies were reviewed to identify common design requirements, technological solutions, usability, privacy, and security considerations, implementation challenges, and research gaps. The review takes a multidisciplinary approach to bicycle tracking as opposed to a technical-only perspective and integrates transport, computing, and user-centered design perspectives to provide a holistic view of how bicycle registration and tracking systems can be designed for practical, scalable, and reliable deployment.

2. Overview of Bicycle Registration and Tracking Systems

2.1 Definition and Core Functionalities

Bicycle registration and tracking systems are formal systems designed to establish an official association between a bicycle, owner and identification details. Typically, these systems capture information like serial number, manufacturer, model, colour, photos, purchase details, owner's contact information, and so on. Sophisticated systems also feature e-certificates of ownership, QR codes, radio-frequency identification (RFID), GPS devices, or smartphone apps. Primary features include ownership authentication, deterrent, recovery support, owner notification, and law enforcement integration. Research on bike-sharing programs indicates that success of bicycle-based systems hinges on well-established operational processes, trustworthy data management, and willingness to use, rather than pure technology [5].

2.2 Evolution of Bicycle Registration Systems

The initial bicycle registration systems were primarily manual or organisational. They were typically administered by local governments, universities, police stations, or private groups and involved physical registration forms, stickers or stamped identification numbers. While these approaches assisted in creating ownership records, they were plagued by isolated databases, limited data updates, and limited geographical coverage. As urban cycling and bicycle sharing grew, computer platforms replaced stand-alone manual registers. These facilitated quicker registration, search and contact between users and managers. Research on successful sustainable bicycle systems show that successful bicycle platforms generally need to have standard operating procedures, scalable management and integration with other urban transportation systems [6].

2.3 Classification of Existing Systems

Existing bicycle registration and tracking systems can be classified into four broad categories. The first category includes manual or authority-led registries, where ownership details are maintained by police, municipal agencies, campuses, or community organizations. These systems are relatively inexpensive but often suffer from limited interoperability. The second category includes web-based and mobile-based registration platforms that allow users to register bicycles, upload evidence of ownership, update records, and report theft online. The third category consists of IoT-enabled tracking systems that use GPS, GSM, Bluetooth, RFID, or NFC technologies to support identification and location monitoring. The fourth category includes community-driven and crowdsourced platforms, where users, volunteers, and cycling communities contribute to stolen bicycle reporting and recovery. The diffusion of public bicycle systems across Europe and North America indicates that adoption depends strongly on institutional support, user awareness, and system visibility [7].

2.4 Role in Theft Prevention and Recovery

A key goal of bicycle registration and tracking is to prevent bicycle theft and increase recovery rates. Registration systems deter the sale of stolen bicycles by facilitating verification of ownership, while tracking systems can help to recover bicycles that are moved without permission. But recovery is not simply a matter of data capture; it relies also on reporting, identification, law enforcement and public education. Spatial analysis of bicycle-sharing systems demonstrates that bicycle movement is highly regular in urban spaces, so it is possible that bicycle tracking and registration systems can use location-based data models and mobility analysis [8].

2.5 Key Stakeholders

Key stakeholders are individual users, mobility operators, manufacturers, retailers, transport planners, police, insurance companies and local governments. These stakeholders have different priorities: riders want ease of use and confidence in the system, the government wants to be able to validate the information, and the provider wants to be able to manage the system. Research on impacts of bike-shares demonstrates that bicycle systems affect travel patterns and mobility, suggesting the need to design bike registration and tracking platforms in the context of a broader sustainable transport system [9].

3. System Architecture and Design Frameworks

3.1 General System Architecture

To implement an easy-to-use bicycle registration and tracking system, we need a layered architecture linking users, bicycles, sensors, networks, databases, and management services. The user layer supports bicycle registration, ownership updates, theft reporting and receipt of alarms via a mobile or web application. At the device layer, bicycles might be equipped with QR codes, RFID/NFC chips, Bluetooth beacons or GPS devices. The network layer communicates data about identification or location to a server; the application layer allows authentication, data access, alerting, and administration of the system. This architecture is similar to Internet of Things (IoT), in which physical items are uniquely identified, connected to a network, and connected to services [10]. The layered structure of the proposed bicycle registration and tracking system is shown in Figure 1.

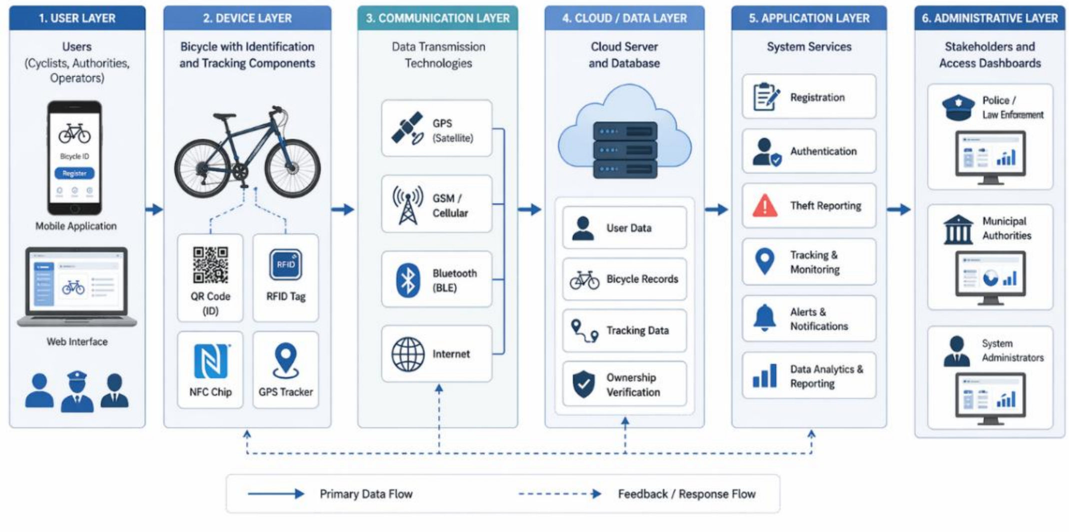

Figure 1. Layered system architecture of a user-friendly bicycle registration and tracking system.

The proposed bicycle registration and tracking system is shown in Figure 1. The system connects users, bicycle identification or tracking devices, communication systems, data storage in the cloud, applications, and administrator interfaces. It also illustrates the separation of primary and response flows, explaining how the components of registration, tracking, alerting and verification are integrated.

3.2 Front-End Design and User Interface Layer

The interface decides on the ease of use. A bike registration interface should only ask for the necessary details, such as frame number, model, color, photos, and owner's contact details. These forms should include guided forms, icons, multi-language support (if necessary), and easy reporting options. For bicycle tracking, the dashboard should show bicycle status, last location, proof of ownership, and theft reporting without being too cluttered. Many cyclists are not tech-savvy, so the interface should be easy to understand and use, and help users complete tasks quickly. Mobility is essential for updating record or reporting theft.

3.3 Back-End Infrastructure and Database Layer

The back-end system manages bicycle registration, ownership, bicycle identifiers, tracking data, theft reports and user accounts. Structured bicycle and owner data can be stored in a relational database, and photos, paperwork and tracking data can be stored in the cloud. The system should use unique bicycle ID to avoid duplication and provide ownership transfer, record verification, and audit trail. Designing the system for scalability is important because it may be used by individuals, universities, cities or the national registry. IoT system architecture prioritises scalable storage, service-oriented architecture, and data processing from IoT devices [11].

3.4 Communication and Connectivity Layer

Bicycles and the registration system are connected by communication technologies. GPS and GSM sensors can offer real-time location tracking, but may increase the cost and power consumption of the tracking device. Bluetooth Low Energy may be used for short-range identification via smartphones or beacons, and RFID and NFC are low-cost identifiers for manual verification. A hybrid scheme could use passive identification for basic registration, and active tracking for high-value or commercial applications. Network connectivity is an issue because tracking data may be lost in basements, dense shops and markets, or with low cellular coverage. IoT studies demonstrate that the challenges of interoperability, communication diversity, and resource limitation are key issues [12].

3.5 Application Services and Administrative Framework

The application layer translates the data into services. Primary services might include bicycle ownership verification, theft reporting, notifications, suspicious transactions, and law-enforcement access. Service modules should enable administrators to search, validate, update the stolen status, and report on bicycles. Roles for retailers, law enforcement, campus security and urban transport may also be supported. To ensure usage and governance, access should be restricted to the necessary data. In smart cities, bicycle registration systems can be integrated with urban mobility services, parking and public transport systems to facilitate transport management [13].

3.6 Design Framework for User-Friendly Implementation

The design should be modular, usable, private, and interoperable. Modularity enables independent development and upgrade of registration, tracking, verification and reporting. Usability means the system is easy for the average cyclist to use. Privacy by design minimises location data and allows users to share data. Interoperability allows integration with smart city platforms, law enforcement, retailers and bike-share programs. Adaptive systems can enhance effectiveness by enabling context-aware computing to adapt to location, travel patterns, theft, personal preferences, and weather [14]. So, the architecture should be viewed as a socio-technical system that trades-off confident tracking for ease of use.

4. User-Centered Design and Usability Considerations

4.1 Principles of User-Friendly Design

The importance of user-centered design is that a bicycle registration and tracking system relies on voluntary engagement and ongoing use. If the process is too complex, too hard, or too time-consuming, many cyclists won't register their bikes, or won't update their records if ownership changes. Thus, the design should focus on simplicity, reducing mandatory input requirements, easy navigation and feedback. Primary tasks, such as registering or reporting a bicycle as stolen, authenticating ownership or transferring ownership, should be supported in a few steps. Methods of accessibility and usability evaluation for mobile apps stress that effectiveness, efficiency, satisfaction and inclusiveness should not be considered in isolation [15].

4.2 User Experience in Registration and Tracking

The design should instil trust in the user journey. At registration, users should be provided with explanations for the information requested especially frame numbers, photos and proof of purchase. While tracking, users should see bike status, last seen location, alerts, and recovery instructions without having to interpret technical details. Error messages should be both informative and instructive, like how to find the frame number, or to re-take a blurry photo. Research on mobile usability suggests that quality of applications is determined by context of use, task performance, learnability, memorability and satisfaction [16].

4.3 Accessibility and Inclusivity

A review-level design should account for a range of users such as students, elderly people, delivery cyclists, tourists, low-income, and those with low digital resources and literacy. The system should be in plain language, legible type, high contrast, multiple language support, and should work with assistive technologies. It should also provide other registration options, such as online portals, municipal kiosks, bicycle stores or campus offices. This allows greater inclusion of users who lack a smartphone, or of users with poor internet coverage. Universal design is of particular importance where bicycle ownership is distributed across social classes.

4.4 Design for Trust and Adoption

Users' trust is a major factor in their willingness to share ownership and location information. The system should present clear privacy statements in a simple-to-understand format, indicate who can access the data and provide control over notifications and tracking settings. Interactivity and simplicity also predict satisfaction and trust in mobile services, suggesting that an interactive and simple interface can enhance user retention [17]. A trusted system should not have hidden processes, undisclosed data sharing and permissions.

4.5 Human Factors and Behavioral Aspects

People's behavior affects the quality of registration data, the reporting of loss, and the use of the system. The system is more likely to be used if it integrates with user habits, such as buying, parking, maintaining, or riding a bike. Software architecture analysis and usability testing can determine if software features support user tasks, rather than just meeting technical specifications [18]. Attitudes, demographics and the built environment also influence cycling behavior, so system design should allow for various motivations and use patterns [19]. In general, usability should be considered as a performance requirement as adoption, data quality, and theft recovery depend on long-term user engagement.

5. Data Management and Security

5.1 Data Collection and Storage Models

Data management is a key element of a bike registration and tracking system as the software links ownership data, bike identifiers, user accounts and locational data events without undue risk. Only the minimum data required for registration should be stored, including owner name and contact details, frame number, brand, model, colour, proof of purchase, photos and device ID. Location data should be distinct from ownership data, as location is sensitive and needs to be retained under stringent controls. So a secure database model should involve data minimization, structured data indexing, controlled update privileges and audit trails for ownership, theft and recovery.

5.2 Identity Management and Ownership Verification

Identity management is key to ownership verification. There should be an online record for each bike that associates the owner with verified identity credentials and bike characteristics. The system could allow users to verify their email or phone, upload documents, verify purchase invoices, match QR codes, or authenticate retailers. The transfer of ownership should be a managed transaction, rather than an update, since a claim of ownership may facilitate the resale of stolen bicycles. IoT systems for identity management raise new security and privacy issues because IoT devices, users and service providers are in constant communication and exchange identifying information [20].

5.3 Privacy Concerns in Tracking Systems

Privacy is a critical concern with tracking features. Tracking that is done with higher frequency or continuously can provide information about commuter routes, residential and office addresses, and other personal details, such as habits, preferences, and routines. Consequently, tracking functions should only be enabled for appropriate purposes like theft notifications, owner requests, or legitimate recovery operations. The data collected, access to data, data storage duration, and deletion of data should be disclosed to users. Distributed IoT is at risk because data are shared between devices, gateways, cloud services and third-party apps [21].

5.4 Security Mechanisms

The system should include security measures at the device, network, application and database layers. Data should be encrypted in storage and in transit to ensure the privacy of user credentials and location data. Access control should protect against unauthorised access, and authorization will divide the rights of owners, administrators, retailers, and law-enforcement personnel. The system should also use tamper detection for physical tags or trackers, secure APIs for integration with other systems and anomaly detection for fraudulent ownership transfers. Trust management is also crucial because users will not use the system if they don't trust the system to secure their data and assist with legitimate recoveries [22].

5.5 Location Data Governance

Privacy issues often arise in location-based services, where a user may receive beneficial services (such as personalised or security services) but may at the same time be concerned about privacy (surveillance, misuse, etc). This is also true of bicycle tracking systems, as users may desire recovery services but not exposure of their travel patterns. Hence, system policies should enable users to manage tracking visibility, limit access by third parties and provide them with consent options for data exchange [23]. Privacy risks can also be minimised by regulation, industry practices and user self-protection that balance responsibility between system designers, operators and government agencies [24]. A secure system should thus incorporate technical security with clear governance, accountability, routine security testing, breach management and privacy-by-design. These actions improve system security and maintain user trust in the system, which is needed for voluntary user registration, continued use, institutional acceptance, and ongoing participation in a variety of urban cycling environments and recovery workflow environments.

6. Tracking Technologies and Implementation Approaches

6.1 Real-Time and Passive Tracking Models

Bicycle registration systems can use real-time and passive tracking technologies. Real-time tracking is based on continuous or periodic location reporting using GPS, cellular or IoT-based communication technologies. This type of tracking is beneficial for theft recovery as it can generate alerts and location-sharing after illegal relocation. But it needs hardware mounting, battery supply, network connection and higher costs. Passive tracking, on the other hand, uses QR codes, RFID tags, NFC or Bluetooth proximity detection. It is cost-effective and relatively easy to implement but typically requires manual search or detection. For systems to be user-friendly, the best option is often a combination of low-cost registration and optional real-time tracking.

6.2 GPS-Based Tracking and Mobility Data

GPS is one of the most versatile technologies for bicycle tracking as it can offer outdoor location information and route-level travel history. GPS can be used in bicycle registration systems to determine the last detected location of a bike, trigger alarms in case of theft, and assist in the recovery process. GPS cycling data can also be used to assess and map cycling conditions and patterns along routes. Bike environment monitoring studies show that GPS data can be used to assess bicycle riding conditions and assist in systematic monitoring of bicycle travel environments [25]. But its performance can be limited in dense urban environments, indoor parking lots, tunnels, or areas where there is poor satellite reception.

6.3 GPS Speed Data and Environment Classification

GPS-based speed and movement can be used to categorize bicycle environments, and can also infer unusual bicycle movement patterns. For instance, sudden movement at odd times, high-speed movement, or high-frequency changes in parking location may mean that the bike has been stolen or transported without permission. Public bicycle movements have been classified using speed data from GPS, and this has demonstrated that tracking data can be used to inform the interpretation of bicycle infrastructure and movement quality [26]. In a registration and tracking system, such analysis may be useful to improve the accuracy of alerts, but should be done with care to avoid spurious alarms and over-surveillance.

6.4 Travel Mode Detection and Context Recognition

GPS tracking systems can be more "smart" when location data are enhanced with context awareness. Travel mode recognition approaches can classify bike-riding from walking, driving or taking public transport using GPS trajectories, speed, acceleration and other mobility patterns. Bayesian-network-based models demonstrate that GPS tracks can be used to support travel mode recognition, which is useful for detecting whether a bicycle is being transported or used (being ridden) [27]. This can enhance theft prevention, but data processing, algorithm testing and privacy considerations are also needed.

6.5 Bluetooth, RFID, and NFC Implementation

Bluetooth Low Energy (BLE), RFID and NFC offer cheaper alternatives or supplements to GPS. Bluetooth beacons may be used to support proximity tracking using mobile phones or stationary receivers, and is suitable for campuses, parking lots and bike-share areas. BLE-based location fingerprinting studies demonstrate Bluetooth technology can enable indoor or short-range location, with varying accuracy based on the number of beacons and other factors [28]. NFC allows short-range identification via smartphone scanning or tags, and can be used to verify ownership, record service, and confirm bike transfers [29]. RFID can also be used for similar identification purposes, particularly when institutions want to quickly scan multiple bicycles.

6.6 Cost, Scalability, and Practical Deployment

When designing solutions, accuracy, cost, maintenance and impact on users must be considered. GPS provides better recovery prospects, but costs more and consumes more power. BLE can track proximity, but needs infrastructure. RFID and NFC are low-cost and robust, but do not support real-time tracking. Hence, scalable systems should be multifaceted: digital registration for all users, passive identification for low-cost confirmation, and active tracking for high-value bicycles, or fleets. This strategy increases equity and enables technological advancement where needed. Table 1 compares the characteristics of major tracking technologies.

Table 1. Comparison of Tracking Technologies for Bicycle Systems

Technology	Range	Cost	Accuracy	Power Requirement	Typical Use Case	Limitations
GPS	Global (outdoor)	High	High (outdoor)	High	Real-time tracking, theft recovery	Poor indoor performance, battery drain
GSM / Cellular	Wide (network-dependent)	Moderate–High	Moderate–High	High	Data transmission for GPS tracking	Requires network coverage, recurring cost
Bluetooth (BLE)	Short (10–100 m)	Low–Moderate	Moderate	Low	Proximity detection, indoor tracking	Limited range, requires nearby devices
RFID	Very short	Low	Low–Moderate	Very Low (passive)	Identification and verification	No real-time tracking
NFC	Very short (cm range)	Low	High (close range)	Very Low	Ownership verification, tagging	Requires manual scanning

Table 1 illustrates the variations in range, cost and power of different tracking technologies. GPS offers high accuracy and continuous tracking, but with higher costs and power consumption. On the other hand, RFID/NFC technologies are low-cost but cannot track continuously, and Bluetooth Low Energy (BLE) strikes a compromise for short-range tracking applications.

7. Comparative Analysis of Existing Systems

7.1 Academic and Operational Models

Bicycle registration and tracking systems can be compared and contrasted according to their purpose, technology, cost, scalability and user participation. Research and operational models are more concerned with system performance, efficiency in deployment, demand forecasting, redistribution, and performance than recovery of thefts. These studies are valuable because they demonstrate how bicycle systems work in a context of managing multiple users, locations and records. For bicycle registration and tracking systems, this implies that a system should be designed to not only store ownership information, but also facilitate search, update, spatial arrangement and management. Models for successful deployment and redistribution in public bicycle-sharing systems show that bicycle platforms need integrated planning of infrastructure, demand and resources [30].

7.2 Station-Based and Location-Oriented Systems

Comparing bicycle systems based on stations is relevant because the systems rely on location, records, and user-system interactions. In these models, bicycles are interconnected with stations, users and user history. This is in contrast to private bicycle registration programs where bicycles can be left anywhere and proof of ownership is more problematic. But the bike-share systems demonstrate the benefits of controlled registration, asset identification and location-based management. A maximal covering location analysis of bicycle-node placement shows how effective a bike system is and how much it is supported by the placement of stations and service areas [31]. For a bicycle registration and tracking system, such location-based considerations can inform the placement of verification points, bicycle repair-shop registration offices, campus checkpoints and smart parking lots.

7.3 User Preference and Destination-Based Systems

Another interesting comparison is with systems that model user destination choices and travel patterns. Bike-share systems can use trip data to analyse users' origin and destination preferences, popular travel routes, and temporal usage patterns. While the main purpose of a bicycle registration system is not to understand destination choice preferences, this type of analysis can be used to prevent theft and recover stolen bikes. For instance, unexpected movement from a typical parking area, transfer to an unexpected neighbourhood, or frequent bicycle presence in resale markets could be signs of theft or sale. Analyses of destination choice preferences of Chicago Divvy system users reveal that bicycle use is influenced by spatial, temporal and user specific factors [32]. This indicates that a bicycle tracking system should consider the context of bicycle movement rather than the change of location.

7.4 Data-Driven Comparative Perspective

Big bicycle data offers a second standard for assessing registration and tracking. Big data systems can identify spatiotemporal characteristics, time of peak usage, typical travel routes, and suspicious travel patterns. This information is useful for tracking because it enables designers to identify normal movement versus anomalies. But data-rich systems also need to address issues of privacy, storage, and interpretation. If too much tracking data are gathered, the system may become invasive. If not enough data are gathered, recovery and verification may not be sufficiently robust. This study of large-scale bike sharing in Chicago reveals that bicycle use has spatiotemporal patterns that can inform predictive and analytical system design [33].

7.5 Comparative Strengths and Limitations

Low-cost paper-based systems are simple to set up but often don't support interoperability, speedy search and immediate recovery. Online registration systems enhance user access and record-keeping, but are contingent on user cooperation and data integrity. IoT-based tracking systems have better theft response, but come with increased costs, energy, maintenance, and privacy challenges. Crowdsourcing reporting systems may promote community participation, but may lack reliable verification and institutional credibility. On the other hand, bike-sharing systems generally have better control due to the centralisation of bicycle management, users, stations, and bike trips. Private bike systems are more difficult due to the decentralisation of ownership, the informality of parking, and user unpredictability. The characteristics of key system types are summarised in Table 2.

Table 2. Comparative Analysis of Bicycle Registration and Tracking Systems

System Type	Cost	Scalability	Usability	Tracking Capability	Key Limitations
Manual / Authority-Based	Low	Low	Moderate	None	Limited interoperability, slow updates, local scope
Web / Mobile-Based Registration	Low–Moderate	High	High	Limited (no real-time tracking)	Depends on user input accuracy, no active tracking
IoT-Based Tracking Systems	High	Moderate	Moderate	High (real-time tracking possible)	High cost, battery dependency, privacy concerns
Community / Crowdsourced Systems	Low	Moderate	Moderate	Low–Moderate	Reliability issues, inconsistent verification
Hybrid Systems (Recommended)	Moderate	High	High	High (optional tracking)	Requires integration and governance frameworks

Table 2 illustrates that there are different trade-offs in cost, ease-of-use, scalability and tracking performance across system types. Simple systems are affordable and user-friendly but lack sophistication, whereas IoT systems are scalable and offer good tracking abilities but have higher costs and operational complexity. Hybrid systems offer the best of both worlds by incorporating simple registration with optional tracking, and are therefore a more feasible option for practice.

7.6 Comparative Synthesis

The analysis reveals that the existing models do not completely meet the needs for a user-friendly bicycle registration and tracking system. Paper-based systems are user-friendly but lacks tracking. Online databases are scalable but require precise data from users. Tracking enhances chances of recovery but is expensive and a privacy concern. Bike-share models can provide insights into asset management, spatial analysis, and analytics, but not directly applied to private bikes. Thus, a successful system should draw on the advantages of several models: user-friendly digital registry, simple physical identification, optional smart tracking, location-based data analysis, and administrator access. This approach offers a better balance of ease of use, scaling, security and implementation.

8. Integration with Emerging Technologies

8.1 IoT-Enabled Smart Mobility Integration

New technologies can make bicycle registration and tracking systems move from siloed databases to smart transport services. The Internet of Things facilitates the interaction between the bicycle, tag, sensor, parking location, user device and the administration system. In this context, a bicycle can be regarded as a digital object whose status, ownership and location can be updated via networked services. Sensing-as-a-service approaches for smart cities demonstrate how sensors can be used to gather and deliver urban data for a range of applications including transportation monitoring and urban planning [34].

8.2 NFC and Contactless Identification

Near Field Communication is a suitable, low-cost identification technology for bicycles because it enables short-distance, contactless communication via tags or chips. NFC can be used to confirm ownership, access maintenance history, confirm transfers, or check stolen-bike status using a smartphone in a bicycle registration system. The short range can be helpful to reduce unintentional access and support active verification. NFC is also appropriate for stores, law enforcement, college security staff, and bicycle repair shops that require quick identification of bicycles without the need for complicated devices [35].

8.3 Electric Bicycle and Smart Device Adoption

The rise of electric bicycles and smart cycling technologies opens up new prospects for embedded registration and tracking. Electric bicycles have batteries, controllers and other electronic components that make them more appropriate for integrated tracking modules compared to traditional bicycles. But registration and tracking requires useful, affordable, reliable and trusted services. Electric bicycle research suggests that pioneers experiment with technology based on perceived usefulness, environment concerns, and technology performance [36]. This suggests new tracking capabilities should be framed as valuable services, not surveillance.

8.4 Future Integration Potential

The future may integrate IoT sensors, NFC identification, mobile apps, cloud storage, and smart parking with a range of technologies to facilitate integrated registration, tracking and recovery. For instance, a bicycle could be registered on a mobile application, NFC identified at a bicycle repair shop, smart parking station, and automatically designated as stolen if lost. Machine learning may later assist anomaly detection, risk assessment and theft analysis, but functions like these need to be managed. So the best way to integrate is in a modular fashion: registration should be straightforward and inexpensive, while new technologies should be optional, scalable, privacy-enhancing, and "open" to institutional databases over time in a range of urban and institutional cycling environments. The integrated hybrid registration, monitoring and recovery process is shown in Figure 2.

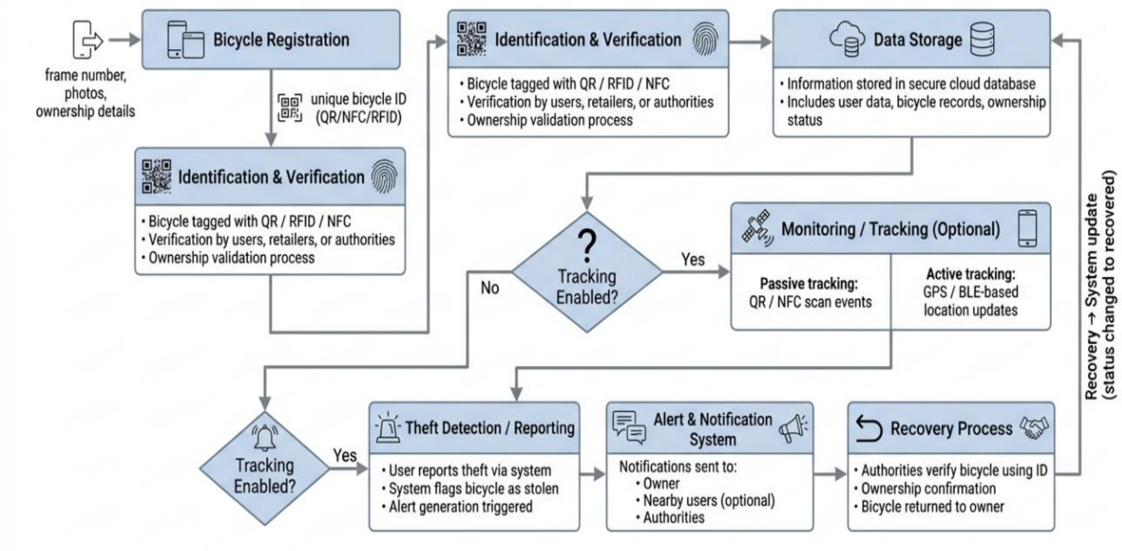

Figure 2. Hybrid workflow for bicycle registration, optional tracking, theft reporting, notification, and recovery.

Figure 2 shows the hybrid flow of the proposed system. It starts with bicycle registration and ID assignment, followed by identification and verification using QR, RFID or NFC technologies. In the case of tracking, the system can be based on passive scans or active GPS/BLE updates. In case of theft reporting or detection of suspicious behaviour, notifications are issued to the owner, police, and potentially other users. During the recovery phase, bicycle identification, ownership confirmation and status update are performed.

9. Discussion

The effectiveness of bicycle registration and tracking systems are still limited by technical, operational, social and ethical issues. Operational challenges include the relationship between digital records and the physical world. Even when bicycle ownership data is stored securely, tracking can be hampered when bicycles are stored in uncontrolled and unsecured places. Therefore, bicycle parking should be considered an integral part of the bicycle registration system, rather than a separate urban planning issue. Structured parking areas can enhance visibility, control and trust, which are all important in the theft prevention and recovery process [37]. So, future systems should connect online registration systems to bicycle parking sites, repair stores, university campuses, municipal offices and other verification sites.

Uptake is also a concern as most registration schemes rely on user engagement. People might not register if registration takes too long, is expensive, invasive or benefits are unclear. Other factors that might influence participation include age, income, travel purpose, infrastructure, urban form, and IT literacy. Because bicycle use is context dependent, registration and tracking systems should not be standalone apps [38]. Rather, they should align with local travel patterns, be affordable and easy to use by people with varying technology skills.

Security and privacy issues are also crucial. Tracking features can help recover stolen bikes, but can also reveal travel patterns, parking practices, home addresses, work addresses and lifestyle patterns. If the user concerns are related to potential misuse of location data, they may opt-out of tracking or avoid use of the system altogether. Naturalistic studies demonstrate that cycling behaviour is complex, and dependent on traffic, infrastructure, and the environment [39]. So, data tracking should be used judiciously and regulated by privacy-by-design approaches, consent-based tracking, minimal period of data retention, and controlled user access and control.

There are some gaps in the existing research. The literature typically examines bike-sharing schemes, cycling routes or general cycling modes, rather than private bicycle registration and ownership verification. We also lack evidence about the success of such systems in schools, universities, residential and workplaces, and developing cities. There are few cost-sensitive solutions, particularly for users who may not afford GPS devices. And more testing is needed to understand how the system will work as it relies on timely registration, reporting and ongoing user participation.

Policy and research should focus on hybrid systems that include easy digital registration, passive identification and active tracking (optional). This will facilitate standardised ownership transfer, stolen-bicycle reporting, recovery confirmation, and appropriate data sharing between cyclists, retailers, insurers, cities, and police forces. Workplaces and work-related facilities, bicycle parking, and supportive infrastructure can all impact cycling behaviours, so registration systems should be linked with mobility policies and urban planning initiatives [40]. In general, future bicycle registration and tracking systems should be scalable, privacy-aware, accessible, interoperable, and technically robust while delivering public value and ensuring user trust over time.

10. Conclusion

This review discussed the design needs of an easy-to-use system of bicycle registration and tracking by incorporating the views of cycling behavior, system architecture, usability, security, tracking technologies, comparison of system models, and emerging mobility applications. As demonstrated in the discussions, a good system cannot be based on digital registration and tracking hardware only. Rather, it must work as a socio-technical platform that includes bicycle identity, confirmed owner-ship, user engagement and safe data stewardship, checked recovery support. The review points out that adoption is all about usability. Registration procedures should be easy, convenient, and credible and tracking capabilities should be transparent and privacy-sensitive. GPS, Bluetooth, RFID, NFC, cloud databases and IoT integration are technical aspects which can enhance the ability of the system but these features should be valued by taking into consideration affordability, reliability, interoperability and user control. The integration of a basic digital registration, passive identification as well as optional active tracking seems to be the most appropriate hybrid model to be offered to various users and institutionalized circumstances. All in all, bike-tracking and registration systems have the potential to help in deterring bicycle theft, owning, recovery, and urban mobility sustainability. The implementation of the future must focus on standardization, privacy-by-design, low cost implementation, and cooperation between cyclists, retailers, municipalities, campuses and law-enforcement agencies. They also endorse responsible data management in the future smart mobility ecosystems. Such systems can be made viable, scalable and socially acceptable tools in the modern cycling environments by balancing technical strength with human-centered design.

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