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Managing battery risks in urban micromobility: ensuring compliance with the ADR Agreement in shared e-bike operations

**Zarządzanie ryzykiem związanym
z użytkowaniem baterii w mikromobilności:
Zapewnienie zgodności z umową
ADR w operacjach współdzielenia rowerów
elektrycznych**

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Abstract

The rapid expansion of shared electric bicycle (e-bike) systems has made them a vital component of modern urban micromobility, offering solutions to congestion, emissions, and accessibility. However, this development brings new risks – especially those associated with lithium-ion battery technology. This article examines the operational, environmental, and regulatory challenges posed by lithium-ion batteries in shared e-bike fleets, with a particular focus on compliance with the ADR Agreement governing the international transport of dangerous goods. By synthesizing findings from the scientific literature, technical standards, and safety guidelines, the study identifies critical issues related to battery degradation, thermal runaway, and end-of-life logistics. It assesses the readiness of current fleet management practices to meet ADR standards and proposes integrated recommendations for system operators and municipal authorities. These include engineering improvements, proactive maintenance, staff training, data-driven policy design, and public engagement. The paper argues that regulatory compliance, par-

ticularly with ADR, should not be seen as a constraint but as a strategic component of responsible and sustainable micromobility. Without such integration, the risks associated with battery failure and legal non-compliance could undermine both operational safety and public trust.

Keywords: micromobility, ADR Agreement, lithium-ion batteries, electric bicycles

Streszczenie

Dynamiczny rozwój systemów współdzielonych rowerów elektrycznych (e-bike sharing) uczynił je istotnym elementem miejskiej mikromobilności. Stały się one odpowiedzią na problemy zatłoczenia, emisji oraz ograniczonej dostępności transportu. Jednak wraz z tym rozwojem pojawiają się nowe zagrożenia – zwłaszcza te związane z technologią akumulatorów litowo-jonowych. Artykuł analizuje wyzwania operacyjne, środowiskowe i regulacyjne wynikające z zastosowania tych baterii we flotach współdzielonych, koncentrując się na zgodności z przepisami umowy ADR, regulującej międzynarodowy przewóz drogowy towarów niebezpiecznych. Na podstawie analizy literatury, norm technicznych i zaleceń bezpieczeństwa zidentyfikowano kluczowe problemy, takie jak degradacja baterii, zjawisko ucieczki termicznej oraz logistyka końca cyklu życia akumulatorów. Ocena obecnych praktyk zarządzania flotami wskazuje na potrzebę zwiększenia zgodności z ADR poprzez wdrożenie rozwiązań inżynierskich, systemowych i organizacyjnych. Zaproponowano zintegrowane rekomendacje dla operatorów i władz miejskich, obejmujące między innymi nadzór nad ładowaniem, szkolenia z zakresu ADR, politykę opartą na danych oraz edukację społeczną. Autor argumentuje, że zgodność z regulacjami – w szczególności z ADR – powinna być postrzegana nie jako bariera, ale jako strategiczny element odpowiedzialnej i zrównoważonej mikromobilności. Jej brak grozi nie tylko incydentami operacyjnymi, lecz także utratą zaufania społecznego do całego sektora

Słowa kluczowe: mikromobilność, umowa ADR, baterie litowo-jonowe, rowery elektryczne

Introduction

In the past decade, shared electric bicycle (e-bike sharing) systems have become one of the most dynamic components of urban micromobility. Their growing popularity stems not only from convenience and accessibility, but also from their perceived ability to reduce emissions, ease traffic congestion, and decrease dependence on internal

combustion transport. However, as this model of mobility expands, it brings with it new challenges that go beyond traditional infrastructure or social considerations. Of particular concern is the underlying energy technology – lithium-ion batteries – which power e-bikes and introduce significant operational, environmental, and regulatory risks, especially in relation to transport, charging, and disposal.

The primary aim of this article is to examine the compliance of lithium-ion battery technology used in e-bike sharing systems with the requirements of the ADR Agreement, the international legal framework governing the road transport of dangerous goods. This approach allows the issue to be framed not only in terms of user safety, but also in light of the legal responsibilities borne by operators and municipal authorities. The article seeks to assess to what extent current operational and logistical practices within shared micromobility align with ADR regulations, and what measures could enhance compliance without compromising operational flexibility.

The secondary objectives of this study include:

- characterizing the risks associated with lithium-ion battery technology in urban environments;
- examining battery degradation mechanisms and their implications for operational safety;
- assessing the practical challenges of implementing ADR standards within shared fleet systems; and
- formulating recommendations for both operators and municipal authorities aimed at improving safety, compliance, and environmental responsibility.

The applied methodology is based on a comprehensive review of the academic literature, international legal documents (particularly the ADR Agreement), technical reports, and empirical data related to lithium-ion battery degradation and hazard potential. This is complemented by a critical synthesis of engineering, organizational, and regulatory measures that may serve as the foundation for a resilient and compliant operational model.

The choice of topic is driven by the growing scale of e-bike deployment in public spaces and the relatively low level of regulatory awareness – among both operators and municipal administrations. While micromobility is widely discussed in urban policy and planning, issues related to battery transport, safety, and end-of-life management are rarely examined in connection with legal frameworks such as ADR. This article seeks to bridge that gap by offering an integrated perspective on technology, regulation, and shared accountability in the governance of e-bike systems.

Historical overview of bike-sharing systems

Bike-sharing systems, as they are known today, have come a long way since their modest beginnings in the 1960s, becoming an integral component of urban mobility across many countries. The first generation of such initiatives was launched in Am-

sterdam in 1965 under the “White Bikes” project, which placed fifty bicycles – painted white – throughout the public space and made them freely available to residents without any form of security. The idea was rooted in the principle of unrestricted use; however, the lack of oversight and theft prevention mechanisms quickly led to the program’s failure. Nevertheless, the concept of shared access to bicycles gained attention and began to evolve.

The second generation of bike-sharing systems emerged in Copenhagen in 1995, featuring coin deposits, dedicated docking stations, and uniquely coloured and structured bikes. While this model significantly improved fleet control, the issue of user anonymity continued to facilitate theft. A true breakthrough came with the arrival of the third generation, built around modern information technologies. These systems, launched in cities like Rennes (France) in 1998 and expanded in Paris in 2007, introduced integrated docking stations, advanced user interfaces, and the ability to locate and reserve bicycles using magnetic cards, smartphones, or contactless smart cards. Thanks to this technological integration, bicycles became more accessible, and their use became intuitive and secure. In the United States, Washington, D.C. led the way, while Montreal pioneered the approach in Canada.

Today, the fourth generation of bike-sharing systems is emerging, integrating not only with public transportation networks but also with other forms of shared mobility, such as carsharing (Shaheen, Guzman, 2011: 23–24). Central to this evolution are intelligent solutions, including unified payment cards, solar-powered mobile stations, and economic incentives for users who assist in bicycle redistribution. These systems not only expand operational functionality but also support environmental and urban planning goals by reducing emissions and alleviating congestion in urban infrastructure. This thesis is echoed in the literature – Campbell (2024), for example, similarly concludes that “[...] Bicycle-sharing programs could therefore help support and increase the use of public transportation systems already in place in many cities [...]”.

As the technology matured and integration with public transport increased, bike-sharing systems began to generate tangible socio-economic benefits for cities. Research indicates that the presence of bicycle stations – commonly referred to as parking hubs – near commercial and service establishments can support local businesses. At the same time, the accessibility of shared bikes encourages individuals who previously did not consider cycling to adopt this form of mobility. This leads to a growing number of cyclists and, in the longer term, to the modernization of urban infrastructure that benefits not only riders but also pedestrians. Over time, other advantages of bike-sharing systems have also become more apparent – such as their potential to reduce congestion on roads and in parking facilities, and to strengthen public transport networks by serving as a “last-mile” solution. The result is improved air quality and a reduction in emissions from private transport, particularly in densely populated urban areas. Health benefits for users are equally significant – daily rides, even over short distances, have a positive impact on cardiovascular health and gen-

eral physical fitness. Interestingly, studies have shown that the visibility of cyclists in the urban space inspires others to adopt the practice, creating a positive feedback loop of behavioral change in urban mobility (Campbell, 2024).

Over the course of several decades, bike-sharing systems have evolved from anarchic experiments into complex, integrated platforms for urban mobility. Yet the true breakthrough came with the widespread adoption of electric-assist technology, which significantly expanded both the user base and the reach and functionality of these systems. Today, electric bicycles – thanks to their ability to cover longer distances, reduce physical strain, and adapt to varied terrain – are increasingly displacing traditional bikes in shared fleets. E-bikes are not only a response to user needs, but also represent the next step in the evolution of sustainable urban transport. The current market is dominated by two operational models: docked systems, which rely on physical docking infrastructure, and dockless systems, which offer greater flexibility through GPS-based geolocation technology. Comparing the advantages, limitations, and spatial impacts of these two models offers critical insights into how system architecture influences operational efficiency, user safety, and alignment with sustainability goals.

Comparison of dockless vs. docked bike-sharing systems

The rapid development of dockless bike-sharing systems represents a response to the limitations faced by traditional station-based solutions. The most commonly cited barriers include difficulties in expanding infrastructure, limited availability of public space, reliance on subsidies, and low operational flexibility. A defining feature of dockless systems is the absence of physical docking stations – access to a bicycle is provided exclusively through a mobile application, using an integrated GPS module and internet connectivity. Once the ride is completed, the bike can be left in virtually any location, which on the one hand increases user freedom, but on the other hand shifts the responsibility for fleet positioning onto the users themselves. This model requires users to make an additional effort at the beginning of a journey – occasionally having to walk to the nearest available bike. However, the lack of obligation to end the ride at a designated location translates into convenience and time savings, especially in congested urban areas. In contrast to docked systems, where the number of parking spots near transport hubs is limited, the dockless model significantly reduces spatial and operational pressure in the vicinity of public transport stations. Moreover, expanding docked infrastructure requires considerable financial and organizational resources, whereas dockless systems can achieve comparable efficiency with a lower level of engagement from both public and private sectors. At the same time, the decentralized nature of dockless systems gives rise to significant regulatory challenges. The lack of control over parking locations leads to frequent violations of public space use – bicycles are often left in places not intended

for parking. It is also worth noting that many dockless systems are funded by private capital, primarily venture capital, allowing operators to bypass the lengthy approval procedures typically required for public systems. As a result, rapid expansion often occurs, along with duplication – understood as the presence of multiple operators that oversaturate the local market (Chen, Lierop, Ettema, 2020: 338–339).

In contrast to dockless systems, traditional docked models operate based on a physical docking infrastructure, which organizes both the availability of bikes and their positioning within the urban landscape. Each bicycle must be checked out and returned to a designated docking station, which imposes greater operational discipline but also ensures a higher degree of predictability and order in public space. This organizational structure also enables better control over fleet quality and more effective redistribution planning. Furthermore, the presence of fixed return points helps limit incidents of vandalism and improper parking. Docked systems are often closely integrated with public transit networks and serve as one of the pillars of sustainable mobility, especially in large urban centers. Thanks to the predictable location of stations, they can be better connected to multimodal transport hubs, facilitating last-mile travel and reducing the number of trips made by private cars (Moore et al., 2024: 944–946). These systems also have a smaller environmental footprint in terms of redistribution logistics – bikes are relocated over shorter distances between known locations, reducing the need for additional transport resources. Despite their advantages, docked systems are not without limitations. One of the most commonly raised concerns is their limited flexibility – users must end their journey at a location where a docking station is available, which can be problematic for atypical routes or urgent transport needs. Another key issue is spatial accessibility. Numerous studies have shown that docking stations are often located in areas with high employment and income levels, leading to inequality in access. This phenomenon is directly related to characteristics of the built environment: station placement decisions prioritize traffic density, bike infrastructure availability, and proximity to institutions, often resulting in a concentration of stations in central or affluent districts. Nevertheless, despite criticism and shortcomings, docked systems continue to play an important role in many cities – particularly where stable public-private partnerships exist and urban space is effectively managed. Their predictability, infrastructural permanence, and ease of operational oversight make them an attractive solution within transport strategies aimed at integration, order, and user safety (*Ibid.*, pp. 943–953).

The following synthesis combines insights from both the academic literature and critical empirical analysis – highlighting not only functional differences, but also underlying tensions between flexibility and control, efficiency and order, accessibility and exclusion.

Tab. 1. Differences between dockless and docked systems

Comparison category	Dockless	Docked	Shared features
Service usage	No dependence on station location; flexible routes; easy integration with public transit; extended access range	User restricted to station locations; less flexible routes; shorter trips; integration with transit	Shift in transport behaviour toward public and active modes; peak usage during morning and afternoon
User experience & last mile	Greater flexibility; no need to end ride at a station; issues with parking and damaged bikes	Greater predictability; easier pickup and return; limited by station availability	Health and mood benefits through physical activity and environmental exposure
Accessibility & distribution	Bikes left wherever users end rides; large-scale redistribution required	Redistribution between stations on a smaller scale; often located in high-income areas	Accumulation of bikes in high-traffic locations; lower access for disadvantaged groups
Financing & implementation model	Often privately funded (venture capital); rapid deployment, risk of duplication and instability	Typically public-private partnerships; slower but more stable decision-making processes	–
Operational oversight & fleet control	Limited control over fleet location and condition; higher risk of vandalism and abandonment	Easier oversight through stations; better management of fleet quality and location	–
Impact on urban space	Low infrastructural footprint; higher pressure on public space if unregulated	Requires fixed infrastructure – limited scalability; greater potential for urban planning integration	–
Environmental footprint of logistics	Redistribution over large areas creates greater environmental impact	Shorter redistribution distances – lower environmental burden	–
Social equity & territorial access	Theoretically egalitarian, but practically chaotic; risk of underserved areas	Limited access for marginalized groups; dominance of central and affluent areas	–
Dependence on cycling infrastructure	Can operate in areas with weak infrastructure, but with higher risk of disorder and inefficiency	Functions best in cities with well-developed cycling infrastructure	–

Source: Author's own elaboration based on Chen, Lierop, Ettema, 2020: 338–340; Moore et al., 2024: 943–953.

The comparison of dockless and docked systems reveals that the differences between them extend far beyond infrastructure or operational design – reaching into the very foundations of governance models, financing structures, capacity for social integration, and even their impact on urban landscapes and the natural environment. While dockless systems embody the idea of “on-demand” mobility – fluid, decentralized, and immediate – docked systems offer stability, predictability, and a structured framework that better aligns with urban planning. The choice between the two

should not be viewed merely as a technological decision, but as a deliberate strategic choice in shaping urban and social development. Regardless of the model adopted, a growing common denominator is the prominence of electric bicycles – quiet, convenient, and environmentally friendly, yet technologically demanding. It is at this juncture that attention must shift from usage logic to the technological core of modern fleets: lithium-ion batteries. Their properties, performance, and operational risks now represent one of the most critical components in discussions about the safety and sustainability of shared micromobility systems. The following section of this article is therefore devoted to these issues: the characteristics, potential, and technological risks associated with lithium-ion batteries in the context of shared e-bike fleets.

Lithium-Ion battery technology in shared e-bike fleets: characteristics and inherent risks

Lithium-ion battery (Li-ion, LiB) technology currently represents one of the key components across numerous sectors of the modern economy – ranging from consumer electronics and energy storage systems to individual and shared transport. Its rapid development and broad availability have led to widespread adoption in everyday life, though this phenomenon often unfolds with limited public awareness regarding the risks associated with improper use or damage to such batteries. Although their operating principles resemble those of other electrochemical cell technologies, the chemical characteristics of Li-ion cells – particularly their high energy density and the presence of flammable electrolytes – make them prone to specific types of failure, including the so-called phenomenon of thermal runaway (Fleischmann et al., 2025: 1–3).

Thermal runaway is a violent and difficult-to-control exothermic process in which the heat generated cannot be effectively dissipated, leading to further temperature increase and structural degradation of the cell. This process may be triggered by mechanical damage, electrical overload, or overheating, and typically results in the release of flammable gases, flames, and – in extreme cases – explosions. Notably, the mechanisms leading to thermal runaway are usually categorized as electrical, thermal, or mechanical abuse, with each type capable of occurring independently or as a result of cascading failure (*Ibid.*, pp. 1–3).

In the context of shared e-bike systems, particular attention must be paid not only to the initiation of thermal runaway, but also to its propagation between individual cells within a battery pack. Studies have shown that in densely packed batteries – as is typical in light micromobility vehicles – this phenomenon can result in the rapid transfer of exothermic reactions from one cell to adjacent ones, regardless of the initial failure mechanism. Thermal propagation may be triggered by direct heat transfer, as well as by the impact of hot gases, flames, metal particles, or external electrical short circuits. This significantly complicates risk management and the design of ef-

fective safety measures (*Personal Light Electric Vehicle (PLEV) Battery Safety Research, Final Report*, 2025: 34–36).

Given the severe consequences posed by thermal runaway and its propagation within tightly packed e-bike battery modules, the development of effective and implementable safety mechanisms has become a key engineering challenge. The literature identifies a range of innovative solutions that can significantly reduce the risk of initiating or spreading exothermic reactions. Among the most promising are gas-based cooling systems using inert media such as nitrogen, compressed air, or argon. This technology effectively suppresses thermal propagation, although its limited cooling capacity and complex infrastructure restrict its applicability in compact battery systems typical of micromobility (Tau et al., 2024: 1100).

An alternative approach involves the use of phase change materials (PCMs) combined with structures designed to increase heat conduction surface area, such as spiderweb-like fins. These passive cooling systems allow for more uniform temperature distribution within the battery module, reducing localized overheating. However, they require adequate containment to prevent leakage of the material in its liquid phase and present greater design complexity (*Ibid.*, pp. 1100–1101).

Particular attention should also be given to solutions based on intelligent Battery Management Systems (BMS) integrated with machine learning algorithms. The use of predictive models such as XGBoost, neural networks, or adaptive reinforcement learning systems enables early detection of degradation trends, optimization of charging strategies, and active temperature management of battery packs under real-world conditions. The integration of artificial intelligence with BMS allows for the dynamic adjustment of battery operating parameters to match current environmental conditions, significantly increasing operational safety margins (*Ibid.*, pp. 1102–1103). It should be noted, however, that the effective deployment of intelligent systems requires large training datasets, and their accuracy depends on the quality of sensor integration in the field (i.e., the reliability of collected data).

All of these solutions – ranging from engineering to digital approaches – are aimed at reducing the risk of uncontrolled temperature rise and ensuring the structural integrity of battery packs in shared e-bike systems. It is important to recognize, however, that even under normal operating conditions and in the absence of thermal runaway incidents, lithium-ion batteries undergo gradual degradation. This inevitably leads to a decrease in usable capacity, an increase in internal resistance, and a decline in the chemical stability of the cells. In the context of fleet systems, where batteries are subjected to intensive use and frequent charging cycles, the ability to predict and manage battery end-of-life (EOL) becomes particularly critical – not only from a safety perspective but also in terms of operational efficiency and cost-effectiveness.

Lithium-ion batteries undergo gradual degradation, which leads to a decline in both their performance and capacity. The main causes of this degradation are so-called calendar aging and cyclic aging. These processes are difficult to study under

real-world conditions due to the long observation periods required; therefore, accelerated aging tests are gaining increasing relevance, such as (Menye, Camara, Dakyo, 2025: 7–9):

- HRAT (High-Rate Aging Tests) – accelerated aging tests under high load conditions;
- HTAT (High-Temperature Aging Tests) – aging tests conducted at elevated temperatures;
- or combinations of both, which allow for faster and more accurate assessment of how operating conditions affect battery health.

The end of battery life is typically defined as the point at which capacity drops to 80% of its original value. The literature outlines two main approaches for assessing the technical condition of a battery: the black-box approach and the white-box approach. The black-box model treats the cell as an opaque system that responds to external stressors such as temperature, current, or state of charge (SOC). The state of health (SOH) is evaluated based on observable symptoms such as capacity fade, power fade, or the occurrence of failure mechanisms like thermal runaway (TR) and short circuits (SC) (*Ibid.*, pp. 7–9).

In contrast, the white-box approach takes into account specific internal degradation mechanisms. Three primary degradation modes are distinguished (*Ibid.*):

1. **LLI – Loss of Lithium Inventory**

This occurs due to the growth and decomposition of electrode interface layers (CEI, SEI), electrolyte breakdown, or parasitic reactions. These processes lead to the permanent “trapping” of lithium ions that can no longer participate in charge and discharge cycles, thereby reducing both capacity and power output.

2. **LAM – Loss of Active Materials**

This refers to the loss of electrode active mass as a result of processes such as lithium dendrite formation, breakdown of binder materials, current collector corrosion, particle cracking, structural damage, and dissolution of transition metals. It primarily affects the positive electrode (cathode) and is exacerbated under high voltage and temperature conditions.

3. **CL – Conductivity Loss**

Loss of conductivity limits the ability to transport ions and electrons. It is caused by binder degradation, dendrite formation, and compromised separator integrity. As a result, internal resistance increases, leading to a further decrease in capacity.

The literature identifies a number of factors that significantly influence the rate of cell degradation, both from electrochemical and thermo-mechanical perspectives (*Ibid.*, pp. 10–31):

1. Current density and charge/discharge profiles are among the most important determinants. High current values lead to polarization effects, dendrite formation, and localized overheating, which significantly accelerate aging process-

- es. Asymmetric charging/discharging profiles (e.g., 1C/2C) have been shown to be more effective than symmetric ones (e.g., 2C/2C), increasing the number of possible cycles before reaching the EOL threshold (defined as 80% of nominal capacity).
2. The charging protocol also has a substantial impact. Standard constant current/constant voltage (CC-CV) methods can lead to local thermal overloads, whereas pulsed charging with relaxation phases (toff) supports a more uniform distribution of lithium ions and reduces the intensity of side reactions. Studies indicate that extending relaxation periods improves capacity retention and slows degradation.
 3. Voltage fluctuations within the battery pack also affect lifespan – extreme State of Charge (SOC) levels are particularly harmful. Very low SOC (0–10%) leads to cathode degradation (LLI), while high SOC (80–90%) intensifies parasitic reactions, resulting in Loss of Active Materials (LAM). A SOC range of 30–40% is considered most stable in terms of both capacity retention and internal resistance.
 4. Temperature is one of the most critical factors affecting LIB degradation. Exceeding the lower operational limit (e.g. $< -20^{\circ}\text{C}$) or temperatures above 55°C leads to accelerated degradation, increased internal resistance, and higher risk of thermal runaway. Temperature exerts its effects regardless of electrode chemistry and requires precise real-time thermal management.
 5. In addition, studies indicate the impact of ambient humidity, which, through condensation and corrosion, can compromise separator integrity, leading to increased resistance and faster capacity loss.

All these processes become particularly significant when lithium-ion batteries reach the end of their service life and must be transported – often in a damaged or unstable condition. In such cases, the provisions of the ADR Agreement, which governs the safe transport of dangerous goods (including lithium-ion batteries), gain critical importance. The next section of this paper will address these issues – focusing on classification, packaging requirements, and the responsibilities of transport chain participants – along with proposed improvements aimed at enhancing the operational compliance of shared systems with international safety regulations.

Lithium-Ion batteries as dangerous goods: application of the ADR agreement in the context of micromobility

The classification of lithium-ion batteries as dangerous goods unequivocally subjects their transport to international regulatory regimes, the most relevant of which in the European context is the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). This document, which governs the transboundary movement of hazardous materials, assigns lithium-ion batteries UN numbers 3480

(for standalone batteries) and 3481 (for batteries contained in or packed with equipment), classifying them under Class 9 – a category reserved for miscellaneous dangerous substances and articles not classified elsewhere (ADR, 2.2.9 and 3.2).

ADR requirements are detailed and stringent. They cover not only classification and labelling but also specific packaging, documentation, and handling instructions, all of which depend on the battery's type and condition. New or intact batteries, prototypes, units intended for reuse, and – most notably – those that are damaged, defective, or subject to recall (DDR) fall under different packaging instructions, such as P903, P908, P909, or P911, depending on the assessed risk and intended disposal route (ADR, 4.1.4). Damaged batteries pose a greater hazard due to their instability and susceptibility to thermal runaway, which is why they require the use of packaging that complies with strict standards – typically involving certified containers designed to mitigate the consequences of ignition or leakage during transport.

One of the most significant provisions of the ADR is Special Provision (SP) 376, which pertains to batteries that may violently disassemble, generate heat, or release toxic or flammable gases during transport. In such cases, unless a special exemption is granted by the competent national authority, the transport of such batteries is strictly prohibited (ADR, 3.3). Even in the case of batteries that do not present an immediate threat, SP376 mandates the use of reinforced packaging and, in some instances, the individual insulation of cells to prevent accidental activation. Determining whether a battery meets the criteria outlined in SP376 typically requires expert judgment – posing a considerable challenge in the field, particularly for personnel with limited training or operating under time constraints.

Responsibility for ADR compliance is distributed across all participants in the transport chain. The consignor, responsible for preparing the shipment, must ensure correct classification and safe packaging (ADR, 1.4.2.1.1). The carrier is obligated to verify the shipment's conformity with regulations and to carry the required documentation throughout transport (ADR, 1.4.2.2.1). The consignee, in turn, is responsible for receiving and further handling the goods without undue delay (ADR, 1.4.2.3.1). In the operational practice of dockless e-bike systems, however, these roles are often blurred. When a damaged battery must be retrieved from a public space – such as following a collision or an act of vandalism – and transported back to a service depot, the task may fall to a gig worker lacking ADR training, compliant packaging, or even formal consignor status. In such scenarios, the line between best practice and regulatory violation becomes dangerously thin.

Implementing ADR standards in the operational context of dockless fleets involves numerous logistical and economic challenges. Complying with packaging instructions such as P908 or P911 is not only technically complex but also costly. As a result, some operators – particularly those under budgetary pressure or managing geographically dispersed fleets – may feel incentivized to bypass full regulatory compliance. Manifestations of this include misclassification, procedural omissions,

or the use of non-compliant packaging. Such shortcuts increase the risk of incidents and constitute direct violations of the safety principles set forth by the ADR.

Ensuring adequate ADR knowledge among all personnel involved in battery logistics – not only technical and warehouse staff, but also mobile rebalancing teams and independent contractors – is a demanding task, especially in work models characterized by high turnover or decentralized structures. A lack of awareness or incorrect interpretation of regulatory details can result in inaccurate documentation, improper packaging, or unsafe handling of damaged batteries, particularly at the end of their service life.

In this context, ADR emerges as a fundamental pillar of safety that demands more than just technical compliance with packaging standards – it requires a systemic approach to staff training, process design, and compliance infrastructure. In practice, the safe handling of lithium-ion batteries within rapidly growing e-bike fleets – especially in densely populated urban centres – will depend less on the mere existence of regulations and more on the willingness of operators to treat them as a genuine tool for risk management. It is worth noting that in many cities, where decision-making processes often become mired in bureaucratic procedures, the very concept of ADR may be as unfamiliar as a battery that poses no risk of ignition.

Previous analyses have revealed that shared electric bicycle systems – regardless of their operational model – offer a number of important benefits for urban mobility, yet they also present significant challenges in the areas of safety, environmental responsibility, and integration with the urban fabric. In this context, the operation, charging, and transportation of lithium-ion batteries prove particularly sensitive, as their chemical properties and the risk of thermal runaway demand not only advanced technical solutions but also strict adherence to applicable regulations.

Battery safety cannot be treated as a secondary concern in operational planning – it is an integral part of it. As demonstrated, both the chemical composition of the cells and the way they are used, charged, and disposed of play a critical role in minimizing the risk of incidents and in building systems that are truly sustainable. Even the most advanced technology cannot replace procedural safeguards or relieve operators and local authorities of their responsibility to ensure compliance, transparency, and operational predictability.

Therefore, a collaborative and mutually accountable approach is essential – between those who design and maintain e-bike systems, and those who regulate and oversee them. The next section of this paper presents a set of integrated recommendations addressed to both system operators and municipal authorities. These are not intended as rigid prescriptions, but rather as proposed directions of action that may support the development of safer and more responsible shared micromobility systems.

Tab. 2. Recommendations for electric bike system operators

Recommendation	Explanation
Safety begins with the battery	Selecting chemically stable cells – such as lithium iron phosphate (LFP) – can significantly reduce the risk of fire, even at the expense of lower energy density. However, chemistry alone is not sufficient. Battery packs should be resistant to moisture, impacts, and external tampering, and should be equipped with advanced Battery Management Systems (BMS) that monitor temperature, voltage, and overloads while signaling early signs of degradation.
Charging infrastructure under full supervision	Centralized charging hubs must meet stringent fire safety standards: physical separation between units, adequate ventilation, and suppression systems adapted to lithium-ion battery fires. In decentralized models, where charging occurs off-site, every individual involved – regardless of formal employment status – must receive appropriate training.
Proactive operational approach	Regular technical inspections of e-bikes and their batteries, rapid response to damage reports, and clear procedures for isolating and transporting compromised components are essential for safe operation. Equally important is educating users about safe riding practices and responsible parking.
End-of-life battery management (EOL)	Operators should ensure full traceability of battery lifecycles and partner with certified recycling entities. Where feasible, second-life applications (e.g., stationary energy storage) should be considered to reduce pressure on disposal systems.
Training and ADR compliance culture	Every employee who handles batteries – from technicians to van drivers – should receive basic training in ADR requirements and be able to identify high-risk situations. Where possible, clear documentation procedures should be implemented and appropriate packaging, labeling, and transport tools provided.

Source: Author's own elaboration.

Tab. 3. Recommendations for municipal authorities and regulators

Recommendation	Explanation
Safety standards as a condition for operation	Operating permits should require compliance with technical standards such as EN 15194, UN 38.3, and ADR – with particular emphasis on procedures for handling damaged batteries. Cities should require end-of-life (EOL) management plans and evidence of cooperation with responsible recycling partners and safety advisors for dangerous goods (commonly DGSA).
Infrastructure supporting order and safety	The development of designated parking zones, safe bicycle lanes, and charging points that meet safety standards is a key element of integrating micromobility into the urban ecosystem. Such investments increase operational predictability and order.
Collaboration with emergency services	Cities should cooperate with fire and emergency response units in developing procedures for dealing with lithium-ion battery fires. Training in fire suppression methods and risk assessment should become part of the municipal emergency preparedness strategy.
Public education and engagement	Public awareness campaigns should raise citizens' knowledge of safe e-bike use, how to report damage, and the risks associated with improper battery handling. A well-informed public becomes a co-creator of safety.
Adaptive data-driven policy	Authorities should require operators to enter into data-sharing agreements covering battery failures, safety incidents, and vehicle distribution patterns. Only on this basis can regulations be dynamically adjusted to evolving technological and social realities.

Source: Author's own elaboration.

Concluding remarks

Shared electric bike systems are becoming a permanent feature of the urban landscape, supporting the goals of sustainable transport, reducing emissions, and offering a new standard of everyday mobility. However, their rapid development reveals less obvious tensions – between accessibility and control, efficiency and safety, flexibility and legal compliance. At the core of these tensions lies the technology of lithium-ion batteries, whose practical utility is closely tied to the risks of degradation, thermal runaway, and operational failures. As demonstrated, both the chemical characteristics of the cells and the conditions of their use significantly affect the durability, safety, and predictability of battery behaviour – particularly under conditions of intensive and decentralized fleet operation. Technical solutions offer tangible opportunities to mitigate risks, but their effectiveness depends on proper implementation and their integration into robust operational procedures. In this context, the ADR Agreement is not merely a set of regulations governing the transport of dangerous goods, but a practical risk management instrument – especially with regard to the end-of-life phase of batteries. Requirements concerning classification, packaging, labelling, and the responsibilities of transport chain participants should not be viewed as bureaucratic burdens, but rather as an integral part of the safety strategy for micromobility fleets. Much, however, depends on the awareness and determination of both operators and local authorities. In contexts where regulations are treated superficially and operational structures fail to incorporate ADR requirements, the risk of serious incidents increases – incidents that could undermine public trust in the entire sector. Conversely, where technical, regulatory, and organizational knowledge is integrated, e-bike sharing becomes a model not only of convenience, but of responsibility. The development of these systems, therefore, requires not just technological innovation, but also a culture of compliance and managerial maturity. It is this very culture that will ultimately determine whether municipal e-bike fleets become a true component of sustainable transformation – or merely another flashpoint in the broader tension between speed of implementation and depth of accountability.

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