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SMART-CROWD: A System Architecture for Intelligent Assessment of Crowdsourcing Maturity in Urban Mobility Governance

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Abstract

Urban mobility has undergone a significant transformation in recent years, caused by rapid urbanization, environmental pressures, and technological innovation. Even though digital tools and mobility platforms are increasingly used to address transportation challenges, these challenges remain complex and multidimensional, concerning not only infrastructure, but also user behavior, institutional coordination, trust, and social acceptance. Crowdsourcing has proven effective in leveraging distributed knowledge and accelerating innovation in business and public sectors. However, its application in urban mobility contexts has not yet been sufficiently synthesized in a framework-oriented manner. To address this, the study first conducted a comprehensive literature review of existing crowdsourcing assessment frameworks and their applicability to mobility systems. The results show that current implementations in urban mobility often remain fragmented and limited to unidirectional data extraction, lacking comprehensive approaches that integrate technological, social, and organizational dimensions. In response to this, the authors developed the SMART-CROWD framework for assessing cities' maturity in using crowdsourcing across six dimensions: Strategy & Leadership (S), Methods & Tools (M), Engagement & Representativeness (A), Responsiveness & Impact (R), Technology & Data (T), and Civic Capital & Sustainability (CROWD). Each dimension includes measurable indicators, providing a structured basis of diagnosing disparities between technological capabilities and socio-institutional readiness. The SMART-CROWD framework is intended to support a transition from one-way data acquisition toward more scalable, reciprocal, and citizen-focused innovation ecosystems. This work contributes to the field of applied systems innovation by proposing a structured framework for assessing and guiding the use of distributed intelligence in smart urban mobility.

Keywords: crowdsourcing; crowdsourcing framework; open innovation; open innovation management; urban mobility; mobility management

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1. Introduction

Urban mobility, understood as the daily movement of societies to achieve various goals, due to rapid urbanization, environmental pressures, and the development of innovation, has undergone a significant transformation in recent years [1]. Digital tools, data analytics, and mobility platforms have become crucial in urban operations. The increasingly widespread use of technology is intended to address persistent transportation challenges,

from congestion and emissions, through accessibility gaps, to safety issues. However, these challenges are complex and multidimensional. They concern not only infrastructure but also user behavior, coordination between institutions, trust, and social acceptance [2].

Solving such complex problems requires access to diverse knowledge, rapid validation of ideas, and consideration of the perspectives of many different stakeholder groups. In these types of situations, crowdsourcing has long been used in the business sector as a method for leveraging distributed knowledge, accelerating innovation, and testing solutions in real conditions [3–6]. It has been successfully implemented in numerous initiatives. For example, platforms like OpenStreetMap and Zooniverse demonstrate how the distributed knowledge of citizens can be systematically integrated to create valuable data resources [7,8]. The numerous applications of crowdsourcing confirm that, from the perspective of systemic innovation, it serves as an adaptive element, supporting the evolution of systems by incorporating external resources, rapid concept validation, and building feedback loops between solution creators and users [7–9].

Since crowdsourcing is effective in supporting processes requiring the integration of diverse knowledge and rapid adaptation, the question arises how can it be used in the context of urban mobility and whether it can be an effective tool for supporting more responsive, inclusive, and sustainable transport systems. In response to this gap, the study conducted a thorough literature review of existing crowdsourcing assessment frameworks. The aim of this analysis was to verify whether available models are sufficient to address the complexity of contemporary mobility systems. However, the review results indicated a lack of comprehensive tools that combine technological, social, and organizational aspects. Consequently, based on the findings, a SMART-CROWD methodological framework was developed. This tool is intended to support the systematic assessment of cities' maturity in using crowdsourcing and to indicate directions for action relevant to building more effective and engaging transport ecosystems.

The article is organized as follows: After introducing the theoretical foundations and key challenges of urban mobility, the paper presents the review methodology and results, which provide the basis for the development of the SMART-CROWD framework. The final sections present an illustrative worked example, discuss limitations, and outline directions for future research.

2. Crowdsourcing in the Context of Open Innovation and Systemic Changes

Crowdsourcing, as a management and innovation concept, refers to the practice of leveraging knowledge, resources, or services provided by a large and distributed group of people, typically via digital platforms [5,10]. In public management and urban systems, crowdsourcing therefore means more than just data collection. It becomes a way to engage residents and other stakeholders in decision-making processes. To fully capture this potential in complex environments, it is useful to consider crowdsourcing through the lens of open innovation theory.

Open innovation theory assumes that value can be created by managing knowledge flows across organizational boundaries, including inbound, outbound, and coupled forms of collaboration with external actors [11,12]. In this context, crowdsourcing typically relies on open calls, task modularity, and mechanisms for aggregating and filtering distributed contributions [13–16]. What makes crowdsourcing particularly relevant from an open innovation perspective is its bidirectional character: mature systems do not merely extract knowledge from participants but also create value in return, thereby strengthening legitimacy, trust, and longer-term engagement [12,17–19]. Because managing such knowledge flows requires balancing technical tools, social engagement, and institutional coordination,

crowdsourcing should be viewed not only as a technical instrument but also as a capability that requires structured assessment [20–22].

3. Challenges of Modern Urban Mobility Systems

The effective use of crowdsourcing in urban mobility management requires first identifying areas in which traditional management systems show functional limitations. Although modern cities increasingly rely on advanced data collection infrastructures, institutional data often remain limited in timeliness, granularity, and operational responsiveness in dynamic urban environments [1,9]. From an open innovation perspective, this creates a need to complement institutional data with knowledge generated by system users, particularly where management needs exceed the informational capacity of formal monitoring systems [11,12,19,20,23]. The following analysis identifies the main areas in which these limitations are most visible and provides the context for the subsequent framework discussion.

One major group of challenges concerns real-time operational management. Stationary monitoring systems often fail to capture sudden congestion, incidents, roadway obstacles, near-miss safety events, or localized last-mile delivery barriers such as unloading constraints and access restrictions [24–28] As a result, traffic management centers and logistics operators may lack timely, user-level information needed for rapid and context-sensitive intervention.

A second challenge concerns the monitoring of infrastructure conditions and accessibility. Periodic audits, although methodologically standardized, do not fully capture the everyday experiences of users, particularly those with functional disabilities [29,30]. This creates a need for more continuous reporting of road surface degradation, accessibility barriers, and pedestrian obstacles, especially where delayed responses may reinforce transport exclusion [7,8,31,32].

A third set of challenges relates to strategic planning and public participation. Traditional consultation methods are often insufficient to capture representative resident perspectives on planned interventions, such as clean transport zones, bicycle infrastructure, or transport investment priorities [23,33–35]. This weakens the legitimacy of reforms and limits the capacity of institutions to incorporate distributed knowledge into long-term planning [2,36,37].

A further challenge concerns the relationship between managing institutions and system users. Operational indicators such as punctuality or ridership do not fully reflect subjective experiences of crowding, comfort, cleanliness, safety, or service quality [28,38–40]. At the same time, mobility governance involves multiple public and private actors, making coordination, interoperability, and trust increasingly important [2,39–41]. In this context, citizen involvement may contribute not only to better feedback but also to stronger engagement and more sustainable mobility behaviors [22,35].

Taken together, these challenges suggest that, across the analyzed dimensions of urban mobility management, traditional systems may be meaningfully complemented by crowdsourcing mechanisms. However, to use this potential in a deliberate and effective way, cities need tools that make it possible to assess whether a given crowdsourcing application fits the characteristics of a particular mobility domain and generates meaningful value for the wider system [1,20,42]. The following sections therefore examine whether such tools are sufficiently developed in the current body of scientific knowledge.

4. Methodology

Building on established recommendations for rigorous literature review design and adhering to PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

reporting principles, this study employed a systematic literature review supported by keyword-based bibliometric mapping and thematic content synthesis [43–45]. Unlike traditional narrative reviews, bibliometric methods add a quantitative layer by identifying relationships among documents and keywords, thereby supporting greater transparency in the mapping of thematic structures and reducing reliance on purely subjective interpretation [46]. In this study, co-word analysis was performed using author-provided keywords. This approach facilitated the mapping of core concepts and their interconnections within the research domain, making it possible to visualize thematic structures and conceptual relationships. Prior to the formal review, preliminary readings of seminal and highly cited studies were conducted to refine the search terms and support the conceptual delimitation of the review.

The review was designed as an iterative multi-stage search and screening procedure combining broad identification, query refinement, metadata cleaning, focused eligibility assessment, and bibliometric mapping. Scopus and Web of Science were selected as the primary bibliographic databases because they are widely used and complementary sources in bibliometric and review-based studies, offering broad coverage and partially different indexing profiles, which supports both recall and cross-database verification.

In the first stage, a broad identification search was designed to maximize sensitivity and capture the wider literature located at the intersection of mobility/transport and crowdsourcing research, without prematurely excluding studies that might address framework-related issues without consistently using the term "framework". In the second stage, the search space was refined by introducing the framework component to focus the corpus on studies offering conceptual, evaluative, architectural, or implementation-oriented structures relevant to the review objective. In the third stage, the search strategy was further narrowed to improve conceptual precision. The term "transport" was removed because it substantially broadened the retrieval to studies on logistics, freight systems, and technical transport processes that fell outside the conceptual focus of this review on crowdsourcing frameworks in urban mobility. In addition, the search was restricted to title, abstract, and keyword fields to improve topical specificity.

The database search was conducted using database-specific syntax adapted to the logic of each search stage. The search strings applied in the study were as follows:

Broad identification stage

Scopus: ((((ALL(mobility)) OR ALL(transport)) AND ALL(crowdsourcing)) OR ALL(crowdsourc*))

Web of Science: TS=((((mobility) OR (transport)) AND (crowdsourcing)) OR (crowdsourc*))

Refinement stage

Scopus: (((((ALL(mobility)) OR ALL(transport)) AND ALL(crowdsourcing)) OR ALL(crowdsourc*)) AND ALL(framework))

Web of Science: TS=(((((mobility) OR (transport)) AND (crowdsourcing)) OR (crowdsourc*)) AND (framework))

Final focused stage

Scopus: TITLE-ABS-KEY(mobility) AND (TITLE-ABS-KEY(crowdsourcing) OR TITLE-ABS-KEY(crowdsourc*)) AND TITLE-ABS-KEY(framework)

Web of Science: TS=(mobility AND (crowdsourcing OR crowdsourc*) AND framework)

The final focused search was executed on 20 May 2025. All retrieved records were exported from Scopus and Web of Science and merged into a single bibliographic dataset. Bibliographic preprocessing and science mapping were supported in RStudio version 2026.01 using the bibliometrix package, which is widely used for comprehensive bibliometric analysis and structured science-mapping workflows [47] (Aria and Cuccurullo, 2017). The dataset was processed to standardize metadata fields, harmonize author and source

information, and support duplicate detection. Duplicate records were identified primarily using DOI and, when DOI was unavailable or inconsistent, by cross-checking title, authors, publication year, and source title. Minor metadata discrepancies across databases were resolved manually.

Following metadata cleaning and deduplication, the remaining records were screened in two steps. First, titles and abstracts were assessed against the inclusion criteria. Records were excluded if they addressed non-mobility applications of crowdsourcing, focused on purely technical sensing without a crowdsourcing dimension, or discussed generic smart-city topics without a framework-oriented contribution. Second, full texts were evaluated against the final eligibility criteria. To ensure corpus consistency and comparability, the final analytical set was restricted to peer-reviewed journal articles. Only studies that clearly addressed crowdsourcing in urban mobility and provided a conceptual, evaluative, architectural, or implementation-oriented framework contribution were retained for the final synthesis. Records were also excluded at the full-text stage if source-type verification indicated that they were conference proceedings, workshop papers, editorials, commentaries, notes, brief communications, or similar non-article formats, or if they did not provide sufficient article-level detail for comparative framework analysis. Each bibliographic record retained in the final analytical corpus was then assessed using a standardized analytical template. For each publication, a structured content analysis was conducted covering three main components:

(1) Framework description, including objective, methods, input data, outcomes, and innovation;
(2) Framework typology, distinguishing implementation, evaluation, and descriptive frameworks;
(3) Relevance to mobility, understood in relation to traffic management, logistics, parking, and broader urban mobility functions.

The qualitative synthesis followed a thematic synthesis logic, enabling the structured interpretation of heterogeneous conceptual and implementation-oriented studies [48] (Thomas and Harden, 2008). To support coding consistency, the authors used a shared analytical template, iterative comparison of coded records, and joint resolution of ambiguous cases. Following the individual assessments, the findings were synthesized to identify the main categories, recurring methodological approaches, and key research gaps, including the limited integration of equity considerations, insufficient validation in real-world mobility systems, and the lack of standardized metrics for evaluating crowdsourcing effectiveness. In parallel, co-word analysis supported the identification of dominant themes and informed the subsequent development of the SMART-CROWD framework, including the derivation of its core analytical dimensions and their operationalization into an indicator structure.

5. Results: Crowdsourcing in Mobility Frameworks Analysis

The results of the systematic literature review provide an overview of the identified crowdsourcing frameworks in urban mobility and their main analytical characteristics. This section first presents the outcomes of the search and screening procedure and then discusses the retained studies in terms of framework description, typology, relevance to urban mobility, and critical gaps. The search and screening procedure yielded 42,388 records in total, including 25,242 from Scopus and 17,146 from Web of Science. After metadata standardization, duplicate removal, and preliminary exclusion of clearly out-of-scope records, 3646 records remained for formal screening. Subsequent screening reduced the set to 161 records eligible for full-text assessment, of which 93 peer-reviewed journal articles were retained for the final analytical corpus. The multi-stage search and screening process is summarized in Figure 1, while Table 1 presents the categories of full-text exclusions.

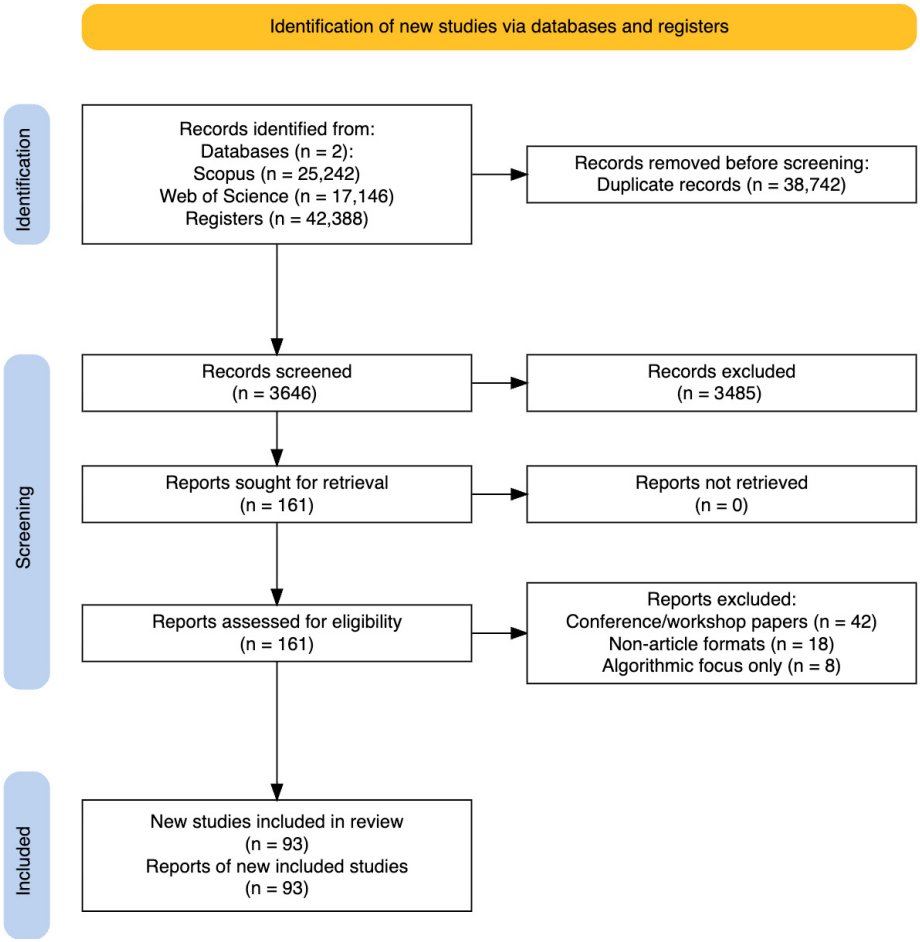

Figure 1. PRISMA flow diagram illustrating the study selection process. Source: Authors' own elaboration, based on [45].

Table 1. Summary of full-text exclusion reasons.

Exclusion Reason	Number of Records	Example
Conference proceedings or workshop papers	42	Indexed publications related to crowdsourcing and mobility but published in edited volumes or conference proceedings rather than peer-reviewed journals
Non-article formats or insufficient article-level detail	18	Editorials, commentaries, notes, brief communications, or records lacking sufficient detail for comparative framework analysis
Algorithmic optimization without framework contribution	8	Studies focused solely on prediction, routing, or optimization performance without conceptual, evaluative, or architectural framework development

Given the conceptual and heterogeneous nature of the frameworks, interpretive consistency was prioritized over formal inter-rater reliability metrics. Coding consistency was supported using a shared analytical template and iterative comparison of coded records. An illustrative example of the analytical coding is presented in Table 2, while the full synthesis of all 93 records is provided in Supplementary Materials.

Table 2. Example of literature review analysis results.

Authors	Article Title	Framework Objective	Framework Methods	Input Data	Outcomes	Distinctive Contribution
[49]	A cross-analysis framework for multi-source volunteered, crowdsourced, and authoritative geographic information: The case study of volunteered personal traces analysis against transport network data	To propose J-CO-QL, a declarative language for querying and manipulating geo-tagged JSON objects from diverse sources (VGI, crowdsourcing, authoritative data).	Development of J-CO-QL, a declarative query language; focus on cross-analysis.	Geo-tagged JSON objects, Volunteered Geographic Information (VGI), crowdsourced data, authoritative geographic information, personal traces, transport network data.	Enhanced capability for integrated querying and manipulation of heterogeneous geospatial data, facilitating comprehensive analysis.	Introduction of a dedicated declarative language (J-CO-QL) for seamless integration and querying of multi-source, geo-tagged data, addressing data heterogeneity challenges.
[50]	Can Computational Linguistic Be Used For WiFi Based Tracking System?	To examine the feasibility of CCG as an alternative to HMM in WiFi-based tracking, aiming for high room-level matching accuracy.	Computational Linguistic (CCG), Hidden Markov Models (HMM) for comparison.	WiFi signal data for tracking.	High room-level matching accuracy achieved (87.5% room level matching accuracy), demonstrating CCG's feasibility as an alternative and consistent good localization accuracy.	Investigating Computational Linguistic (CCG) as a novel approach for WiFi-based tracking, offering an alternative to traditional HMMs and capturing longer dependencies.
[51]	An Innovative Mobile Application for Booking Parking Spots	To introduce a crowdsourced mobile application for reporting and allocating available parking spots, with reliability assessment and visualization.	Mobile application development, crowdsourcing mechanism, probabilistic algorithm for credibility evaluation, visualization (coloring schemes).	Crowdsourced reports of available parking spots.	Facilitates reporting and allocation of free parking spots in real-time, improving urban parking management. Includes reliability assessment and visualization.	Development of a mobile application specifically for crowdsourced parking spot reporting and allocation, integrating reliability assessment and real-time distribution.
...	...	...	...	...	...	...

The following subsections present the results of the thematic analysis.

5.1. Framework Description Analysis

5.1.1. Framework Objectives

The analyzed frameworks exhibit a broad spectrum of objectives, ranging from operational optimization to security, planning, and evaluation. A dominant theme is the pursuit of greater efficiency within mobility systems, including traffic management, congestion reduction, resource allocation, and logistics coordination [26,52–56].

Another important group of objectives concerns privacy, security, and the reliable use of mobility data, particularly in relation to sensitive location information and secure data exchange across digital transport environments [54,55,57–59]. Several frameworks also focus on mapping, navigation, and localization functions, including map updating and positioning support in complex mobility environments [60,61].

Finally, a substantial group of studies addresses planning, evaluation, and engagement-oriented objectives. These include the assessment of public space quality, the evaluation of public transport policies and concepts, and the improvement of citizen participation and data quality through more structured feedback and incentive mechanisms [62–65].

5.1.2. Framework Methodologies

The analyzed frameworks employ diverse and often advanced methodologies, reflecting the interdisciplinary nature of research in crowdsourcing and mobility research. Optimization algorithms and machine learning are widely used, including deep learning, graph-based models, and reinforcement learning approaches applied to task such as movement analysis, service coordination, and ride-hailing services [40,66–68]. Game-theoretic approaches are also used for task allocation and incentive design, while simulation and modeling support the evaluation of citizen sensing applications, traffic systems, and logistics solutions [54,55,69–72].

In addition, several frameworks rely on data processing and integration techniques, including declarative query languages, data fusion, and contextual enrichment methods [49,73,74]. Blockchain-based solutions are also increasingly used in areas requiring secure coordination, authentication, and data exchange across mobility environments [59,75].

5.1.3. Utilized Input Data

The input data used in the analyzed frameworks is highly diverse, reflecting the versatility of crowdsourcing in urban mobility contexts. Location-based and geospatial data are predominant, including GPS traces, LiDAR data, WiFi-based positioning inputs, and geotagged social media content [31,60,68]. User-generated data also constitute a significant source, including crowdsourced reports, reviews and ratings, and volunteered geographic information [49,51,62]. In addition, many frameworks rely on smartphone, IoT, and vehicle sensor data, as well as operational and contextual datasets such as mobility service records, route information, and user behavioral patterns [67,72,76–78].

5.1.4. Achieved Outcomes

The analysed crowdsourcing frameworks analyzed crowdsourcing frameworks generate a range of tangible outcomes related primarily to improved operational efficiency and system optimization. Reported benefits include enhanced traffic and logistics performance, more effective resource allocation, and improved coordination of mobility services [52,54,55,72]. In addition, many frameworks contribute to increased accuracy and reliability of mobility data and monitoring systems, strengthening predictive capabilities and supporting more informed operational decision-making [53,79].

Beyond operational improvements, the frameworks also support broader urban management and planning processes, including parking management, infrastructure assessment, and evaluation of public transport policies [51,63,80]. Some studies emphasize enhanced privacy protection and secure data exchange in mobility environments [57,58], while others introduce new analytical tools and system capabilities, such as advanced data integration methods or digital mobility representations [39,49].

5.1.5. Framework Innovativeness

The innovativeness of the analyzed frameworks manifests in several recurring forms. First, many studies introduce novel applications of existing technologies in crowdsourcing and mobility contexts, for example, by adapting computational, geospatial, or user-generated data techniques to new urban mobility problems [31,54,55]. Second, innovation often stems from combining methods drawn from different analytical traditions, such as

privacy-preserving techniques, AI-based optimization, and incentive-oriented or participatory mechanisms [57,65,67]. Third, some frameworks address specific research gaps, including privacy protection, cost-efficient data collection, and the balancing of operational efficiency with crowdsensing utility [58,67,81]. Finally, innovativeness is also reflected in the creation of dedicated tools and systems that expand the technical and analytical capabilities of crowdsourcing in mobility contexts [49,82,83].

5.2. Framework Typology

This section presents typological classification of the analyzed crowdsourcing frameworks into three categories: implementation, evaluation, and descriptive. This distinction helps to better understand the dominant orientations of research and development efforts within the domain of urban mobility and crowdsourcing.

5.2.1. Implementation Frameworks

Most of the analyzed frameworks fall under the implementation category, indicating a strong emphasis on developing and deploying practical systems, applications, and algorithms designed for real-world use. These frameworks typically involve the construction and demonstration of a functional system or a practical solution to a specific problem.

Implementation frameworks can be grouped into five main areas: mobile applications for urban services, optimization and task allocation systems, secure data distribution, mapping and localization, and traffic management and logistics. In the area of mobile urban services, implementation frameworks include applications for reporting and allocating available parking spaces in real time, often combined with reliability assessment mechanisms [51,84]. In optimization and task allocation, frameworks focus on fair workload distribution, spatio-temporal matching, and the coordination of service provision with crowdsensing functions [54,55,67,85]. Security-oriented implementation frameworks address scalable content sharing, trusted multi-operator coordination, and authentication in digitally connected mobility environments [54,55,59,75]. Other implementation frameworks support mapping and localization, including continuous map updating and indoor positioning based on crowdsourced mobility data [60,61]. In traffic management and logistics, implementation frameworks are used to support real-time detours, delivery planning, and dynamic roadway monitoring [26,53,72]. The prevalence of implementation frameworks suggests a field strongly oriented toward practical solution development, in which theoretical concepts are increasingly translated into deployable systems.

5.2.2. Evaluation Frameworks

A substantial number of frameworks are categorized as evaluation, reflecting a commitment to empirical testing, performance assessment, and comparative analysis. These frameworks are designed to measure the effectiveness, efficiency, or other performance metrics of crowdsourcing-based solutions, often involving simulations, benchmarks, or real-world experiments. They can be grouped into four broad areas: performance evaluation of crowdsourcing applications, assessment of policy and intervention effects, benchmarking of methodologies and technologies, and evaluation of broader concepts and schemes. In the first group, simulation-based frameworks are used to assess the operational effectiveness of crowdsourcing applications and the conditions required for their efficient functioning [71,86]. A second group evaluates the effects of mobility policies and urban interventions, including public space quality, public transport reforms, and bicycle infrastructure changes [62,63,87]. A third group focuses on benchmarking alternative methodologies and technologies, for example in indoor localization and transportation mode detection [54,55,68]. Finally, some evaluation frameworks assess broader organizational concepts and innovation schemes derived from collective intelligence and crowdsourcing

in transport and logistics contexts [64,87]. The growing presence of evaluation frameworks indicates a broader shift toward more empirically grounded crowdsourcing research. Such frameworks are important for assessing practical applicability and supporting the use of crowdsourcing in urban planning and mobility management.

5.2.3. Descriptive Frameworks

While fewer in number, descriptive frameworks remain important because they provide theoretical, architectural and analytical foundations for further development. Rather than focusing on direct implementation or empirical testing, they help define concepts, system architectures, analytical models, and research directions within crowdsourcing-based urban mobility studies.

The reviewed descriptive frameworks can be grouped into three broad areas. Some studies propose conceptual and analytical models that help structure emerging mobility problems and clarify the role of crowdsourcing in specific domains [49,88–92]. Second, other contributions focus on system architectures and technical blueprints, including mobility data infrastructures, digital twin concepts, and broader architectural reviews of crowdsourcing solutions [39,93,94]. Third, a number of descriptive studies take the form of literature reviews or requirement-oriented analyses, particularly in relation to privacy, security, and trust in mobile crowdsourcing environments [95,96]. The presence of descriptive works indicates that research on crowdsourcing in urban mobility is well-anchored theoretically. They make it possible not only to explore new paradigms, but also to define directions for further research and support the longer-term development of this interdisciplinary field.

5.3. Relevance to Urban Mobility Domains

The reviewed frameworks demonstrate a strong connection between crowdsourcing and urban mobility, highlighting its role in supporting data-driven and adaptive mobility management across multiple functional domains.

5.3.1. Traffic Management and Congestion Control

From the perspective of traffic management, crowdsourcing is increasingly used to support dynamic monitoring, congestion mitigation, and data-driven mobility optimization. Several frameworks use crowdsourced data from ride-sourcing fleets or navigation platforms to enable real-time monitoring of traffic conditions [53]. Hybrid approaches combining user-generated data with sensor-based monitoring are also applied to regulate traffic flow and reduce congestion [52]. Crowdsourcing solutions further support adaptive routing strategies in freight logistics, for example by enabling real-time detours around congested areas [72]. In addition, crowdsourced mobility data can serve as a cost-efficient complement to traditional traffic studies and planning analyses [97]. Overall, these approaches highlight the role of crowdsourcing in enabling more adaptive and responsive traffic management.

5.3.2. Parking Management

Optimizing parking availability remains a persistent challenge in urban mobility, and crowdsourcing is increasingly used to support real-time parking management solutions. One example is the mobile application introduced by Spanidis et al., which lies at the core of their framework for booking parking spots [51]. The system integrates user-generated reports to provide up-to-date information on parking availability, enriched with reliability assessment and intuitive visualization tools. In a similar vein, Christainas et al. proposed a crowdsourcing-based framework designed to report and allocate available parking spaces within urban environments [84]. Their solution also relies on data contributed

by users to ensure timely and accurate updates, supporting more efficient use of limited parking resources.

5.3.3. Logistics and Delivery Services

The analyzed frameworks show that crowdsourcing can improve both the efficiency and sustainability of logistics processes, particularly in last-mile delivery. User-generated data support more dynamic management of distribution networks and delivery routes. For example, Chen et al. proposed a probabilistic crowdsourcing model for just-in-time delivery planning based on taxi GPS data, demonstrating how existing mobility flows can support more flexible last-mile logistics [31]. In the area of sustainable logistics, Ghaderi et al. presented an integrated crowd-shipping concept as an alternative to traditional delivery models, highlighting the use of social resources in parcel distribution and its potential to reduce emissions and urban traffic through more efficient use of existing routes [56]. Also noteworthy is the framework proposed by Klumpp for assessing crowdsourcing in logistics, which provides an evaluation structure for analyzing its role in supply chains and its impact on logistics efficiency and service quality [87].

5.3.4. Public Transport Analysis and Planning

Public transport analysis and planning is another domain in which crowdsensing frameworks and user-generated data are increasingly applied. These approaches support a better understanding of system performance and facilitate service improvements. One application concerns the analysis of passenger occupancy patterns. For example, Lu et al. developed a framework using crowdsensing data to assess the effects of fare-free public transport policies on crowding levels [63]. Steiger et al. proposed the use of unstructured social media data to infer passenger flows and identify key transport nodes, supporting infrastructure planning and network management decisions [98]. The evaluation of innovative public transport concepts has also been addressed through criteria-based frameworks incorporating community-generated ideas [64]. Crowdsensing approaches further include the use of bus fleets as mobile sensing platforms. Ji et al. formulated a framework for deploying sensors along bus routes to monitor infrastructure and urban environmental conditions through drive-by sensing [92].

5.3.5. Ride-Hailing and Shared Mobility Services

Another topic of frameworks is those that use crowdsourcing to support the operation of ride-hailing services and other forms of shared mobility. These are solutions that cover both operational and strategic aspects of managing such systems.

Several studies focus on the coordination of service provision and data collection in ride-hailing systems. These include approaches that integrate crowdsensing with operational tasks, support fair task allocation, and enable simultaneous route planning and matching across multiple platforms [54,55,67,99].

Other frameworks address broader market and governance issues, including pricing strategies, equilibrium modeling for shared and autonomous mobility services, and micromobility management supported by citizen reporting of vehicle misuse or parking violations [89–91,100,101].

Additional solutions aim to improve service efficiency by reducing delays in shared mobility systems and supporting user-assisted relocation of shared vehicles [27,102].

5.3.6. Mapping, Navigation, and Location Services

Moving on to the next identified topic, which is frameworks supporting the creation, updating and improvement of mapping, navigation and localization systems in various urban and indoor environments. There are several solutions in the literature

that use crowdsourced data to improve accuracy, availability and dynamic response to environmental changes.

One example is the framework proposed by Kim et al., which uses crowdsourced data from multiple vehicles to continuously update high-definition (HD) maps [60]. This approach enables precise tracking of changes in road infrastructure, which is particularly important for autonomous vehicle systems.

In the field of indoor localization, Li et al. examined the use of computational linguistics (CCG) as an alternative to Hidden Markov models in WiFi-based localization, drawing on user-reported data to improve system performance [54,55]. Mansour et al. developed "Everywhere", a system for universal indoor localization based entirely on crowdsourced data [61]. Similarly, Laoudias et al. proposed a radio map fusion method adapted to different mobile devices, enabling broader use of crowdsourced location data [73].

Vela et al. addressed the problem of mapping routes accessible to people with limited mobility, using community-generated data on transport infrastructure availability to support route analysis and travel planning [103]. Gao et al. presented a framework for inferring social structures from sequential user location data, using movement patterns and variability as a crowdsourced resource relevant to both urban planning and large-scale mobility management [66]. Finally, Yu et al. introduced a Bi-LSTM-based framework for modeling movement uncertainty from crowdsourced trajectory data, supporting mobility forecasting, dynamic route planning, and traffic management [40].

5.3.7. Urban Planning and Public Engagement

A separate topic identified was the use of crowdsourcing in urban planning and citizen engagement in decision-making processes. The literature provides a number of solutions that use user-generated data to support participatory city management, assess its performance, and create more user-friendly environments for pedestrians and other mobility groups.

One of the areas where crowdsourcing has found wide application is sustainable urban mobility planning. In this respect, Bakogiannis et al. analyzed available technological tools supporting public participation in transport-related processes [104]. In their work, they proposed integrating a crowdsourcing platform as an element of citizen engagement. In turn, Anik et al. presented a framework focused on engaging young people in transport planning through social media and crowdsourcing mechanisms, showing how these tools can support social dialogue and build greater engagement in local issues [78].

In terms of assessing urban cohesion, Galpern et al. proposed a Bayesian beta-regression model for analyzing spatial connectivity in the city, based on GPS data reported voluntarily by users [105]. Their approach provides a quantitative indicator of urban cohesion that can be used both in research and in practical spatial planning.

In the area of applications supporting pedestrian mobility, Papageorgiou et al. identified key requirements for smart pedestrian applications while proposing a business model based on a social crowdsourcing platform [106]. Their solution aims not only to improve the quality of pedestrian movement, but also to promote walkability in the city. This is continued in the work of Ertz et al. who developed a framework for generating personalized walking routes based on user data and their active participation in content creation [107].

5.3.8. Other Applications with Indirect Mobility Relevance

Some crowdsourcing frameworks influence urban mobility indirectly by affecting environmental quality, safety, and broader urban living conditions that shape mobility patterns and infrastructure use. For example, Bocher et al. used the NoiseCapture application and smartphone-based crowdsourced data to map urban noise levels at a large

scale [76]. Although this study focused mainly on environmental quality, many noisy areas are caused by road traffic and public transport, which also makes this topic important from the perspective of urban mobility.

In a different approach, Panta et al. proposed a method for selective filtering of video footage from city cameras (CCTV), supported by, among others, crowdsourcing data [74]. Although the main goal was to analyze safety, the information obtained in this way can also be used in monitoring road traffic and supporting decisions in traffic management. In the context of integrating weather data, Quarati et al. presented a framework integrating data from different measurement sources, including weather stations, into a smart city application [108]. This direction was further extended by De Vita et al., who integrated federated machine learning with user-generated weather data to support more adaptive mobility management under changing climatic conditions [79]. Although these solutions are not directly focused on core transport operations, their influence on environmental quality, public safety, and urban data availability makes them indirectly important for effective mobility system performance. Together, they illustrate how diverse crowdsourcing applications contribute to the development of smarter and more resilient cities.

5.4. Critical Gaps in Frameworks

Based on the analysis of the crowdsourcing frameworks in urban mobility, several critical gaps can be identified, particularly when these frameworks are examined through the lens of open innovation. Based on the analysis of the crowdsourcing frameworks in urban mobility, several critical gaps can be identified, particularly when these frameworks are examined through the lens of open innovation. While crowdsourcing inherently involves external participation, the explicit adoption of open innovation principles remains limited across most of the reviewed works.

One notable observation is the minimal explicit reference to "open innovation" itself. Within the reviewed dataset, the term "open innovation" was directly referenced in only one instance [109]. This suggests a significant conceptual and strategic gap: although many frameworks use crowdsourcing, they rarely position it within a broader open innovation paradigm. As a result, the potential of external knowledge integration may remain constrained to data collection rather than broader co-creation.

Specifically, the critical gaps identified from an open innovation perspective include five main domains:

- Limited scope of external knowledge integration beyond data collection;
- Challenges in building trust and facilitating data sharing with external stakeholders;
- Insufficient interoperability and standardization for cross-organizational collaboration;
- Sustainability of engagement for continuous co-creation;
- Limited "opening up" of internal processes and platforms.

One of the most visible limitations concerns the restricted use of external knowledge beyond data collection. Crowdsourcing is widely applied to gather raw data, including GPS traces for traffic monitoring [53], parking spot availability [51], and environmental noise assessment [76]. However, its use rarely extends to ideation or co-creation of mobility solutions. In most cases, the crowd is treated primarily as a source of information rather than as an active participant in generating ideas or solving complex problems. Although some studies, such as Genitsaris et al., acknowledge collective intelligence, crowdsourcing, and co-creation in the assessment of public transport concepts, such deeper engagement remains the exception rather than the norm [64]. Closely related to this is the issue of challenges in building trust and facilitating data sharing with external stakeholders, which significantly hinders the openness and inclusiveness of innovation processes. Open innovation fundamentally relies on the willingness of diverse actors (citizens, private companies,

and public institutions) to share data and collaborate toward common goals. However, Nienaber et al. point out that distrust is often a decisive obstacle for public authorities trying to benefit from crowdsourcing and the sharing economy [37]. This lack of trust may stem from concerns about data misuse, unclear benefits, or skepticism toward the technology itself.

Although technical solutions have been proposed to enhance privacy and security [57,58,89–91], the socio-technical dimensions of trust remain underdeveloped, limiting the potential for truly open and participatory innovation ecosystems.

Another critical limitation is the insufficient interoperability and standardization for cross-organizational collaboration, which undermines the scalability and cumulative impact of crowdsourcing initiatives. A mature open innovation ecosystem requires seamless exchange of data, tools, and insights across platforms and institutions. Yet the analysis reveals a significant gap in standardized, interoperable frameworks for smart city applications. While certain efforts have been made to enable data integration [49,74], the absence of universal standards for data formats, APIs, and communication protocols results in fragmented systems that struggle to interoperate. This fragmentation prevents different crowdsourcing initiatives from connecting and building upon each other's contributions, limiting their ability to support broader, system-wide innovations that transcend individual projects or municipal departments.

Equally important is the lack of strategies for sustaining engagement in continuous co-creation, which limits the depth and continuity of innovation processes. However, while many frameworks explore mechanisms to motivate participation in data collection [65,70,110], there is limited evidence of deliberate approaches designed to maintain long-term user involvement in collaborative problem-solving or innovation activities. Most initiatives focus on transactional interactions, where users contribute data without being meaningfully involved in subsequent stages of idea development or implementation. The development of sustained communities of innovators or iterative co-creation cycles remains rare, indicating that the transition from one-time participation to ongoing collaboration has not yet become a central design principle in crowdsourcing-based open innovation. Without such continuity, the full potential of open innovation, particularly in terms of nurturing shared ownership and iterative improvement remains underdeveloped.

This misalignment between practice and theory provides the rationale for the development of the SMART-CROWD framework. Rather than proposing yet another technical solution, SMART-CROWD introduces a holistic maturity model that explicitly addresses each of these gaps through its six dimensions, ensuring that crowdsourcing evolves from fragmented sensing into embedded, governance-level co-creation. At the same time, the applicability of such a framework across different urban contexts may depend on local governance capacity, data availability, and the degree of institutional formalization of participatory processes.

Finally, there is an imbalance between the two directions of open innovation. While the collection of external data is relatively well established, much less attention is given to opening internal processes, tools, or platforms to external contributions. Many frameworks describe how cities or organizations gather data from citizens, but relatively few explain how internal datasets, analytical tools, or decision processes are made accessible for broader external use and collaboration. For example, Toole et al. developed an interactive visualization platform and an open-source toolbox for mobility analysis [111]. However, such examples remain relatively isolated rather than representative of a broader trend. This suggests that the two-way logic of open innovation has not yet been fully developed in the context of crowdsourced urban mobility.

Collectively, these five gaps reveal a systemic pattern: crowdsourcing in urban mobility is operationalized primarily as a one-way data acquisition tool rather than as a strategic, two-way co-innovation mechanism grounded in open innovation theory. The reviewed frameworks are strong in technical data collection, but weaker in reciprocity, trust, inclusivity, interoperability, and institutional openness elements essential for transforming citizen input into sustained, co-created urban value.

6. SMART-CROWD Framework: Comprehensive Methodology for Evaluating Crowdsourcing in Urban Mobility

Based on the reviewed crowdsourcing approaches and the gaps identified in the literature, the authors developed a structured framework for assessing crowdsourcing maturity in urban mobility. The SMART-CROWD framework is a collaborative self-assessment tool designed to assess and compare the maturity of cities in using crowdsourcing to address urban mobility challenges and support smart city development. It enables cities to diagnose their current position, define development priorities, and monitor progress over time.

The self-assessment process is intended to be conducted collaboratively by multidisciplinary teams comprising mobility planners, digital transformation units, public engagement officers, and data governance specialists. To improve inclusivity, the process may also incorporate input from external stakeholders such as NGOs, academic partners, or civic-tech communities.

The framework evaluates cities across six dimensions: Strategy & Leadership (S), Methods & Tools (M), Engagement & Representativeness (A), Responsiveness & Impact (R), Technology & Data (T), and Civic Capital & Sustainability (CROWD). The framework dimensions are conceptually aligned with the CalmMobility paradigm [2], which emphasizes equity, pacing, and affective alignment over speed and scale. The framework elements are presented in Figure 2.

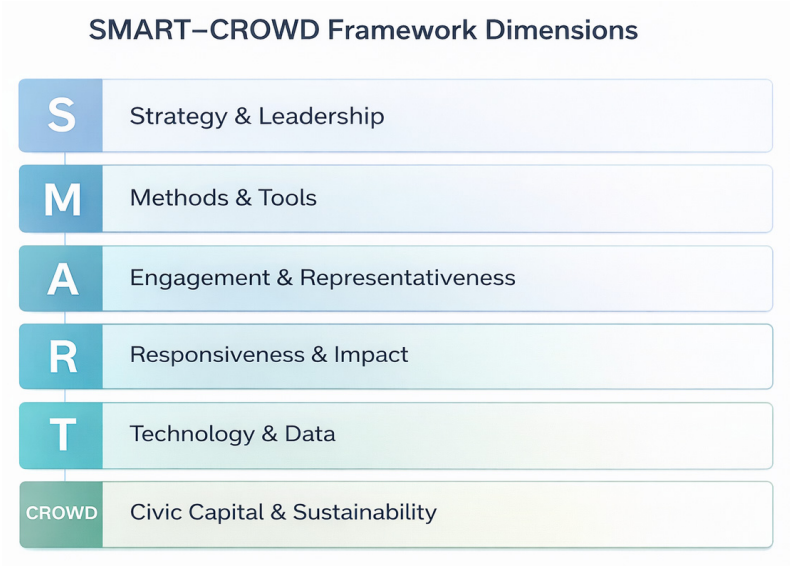

Figure 2. SMART-CROWD framework elements.

The SMART-CROWD framework assesses the maturity of crowdsourcing in urban mobility across six dimensions, each anchored in the broader logic of open innovation:

- (1st) Strategy & Leadership (S): This assesses the extent to which crowdsourcing is embedded in the city's strategic vision and governance structures. It emphasizes whether open innovation has been institutionalized as a guiding principle, recognizing the crowd not merely as data providers but as active contributors to policy and

service innovation. A key marker of maturity is the presence of a formal open innovation strategy, distinct from general digitalization plans, supported by policies that foster transparency, trust, and accountability in the integration of citizen-generated knowledge into decision-making.

- (2nd) Methods & Tools (M): This examines the diversity and openness of tools used by the city to engage external stakeholders. It considers whether platforms enable not only data submission but also bidirectional exchange, allowing contributors to interact with, iterate on, or improve proposed ideas. More mature cities tend to adopt interoperable systems that integrate with third-party platforms and support modular innovation through external input. The presence of co-creation environments such as innovation labs, online design platforms, or challenge-driven hackathons indicates stronger alignment with open innovation principles.
- (3rd) Engagement & Representativeness (A): This reflects the participatory logic of open innovation by emphasizing the inclusion of diverse and representative social groups rather than relying solely on institutional actors or already well-represented participants. This dimension captures the extent to which cities engage a broad cross-section of society, particularly underrepresented groups, and facilitate sustained, long-term participation. Because open innovation also depends on cross-sector collaboration, higher maturity is associated with the active involvement of academic institutions, civil society organizations, and private sector actors in ideation and testing phases.
- (4th) Responsiveness & Impact (R): This measures the city's ability to transform crowdsourced input into tangible outcomes and institutional change. It includes mechanisms for transparent communication with contributors, feedback loops that explain how ideas were used or why they were not, and metrics that track not only outputs (e.g., number of responses) but innovation outcomes, such as prototypes developed, services improved, or partnerships initiated. A higher level of maturity in this dimension is reflected in treating citizen participation as a meaningful governance resource rather than only as a consultative mechanism.
- (5th) Technology & Data (T): This evaluates whether a city's technical infrastructure supports openness through use of open data standards, APIs, and publication of anonymized datasets. Crucially, this dimension also assesses data quality assurance and bias mitigation mechanisms. It examines whether cities implement protocols to reconcile crowdsourced inputs with authoritative data sources (e.g., IoT sensors, official statistics) and whether they employ statistical methods to detect and correct demographic or geographic sampling biases. More mature systems are expected to provide confidence scores for data points and to report data quality metrics more transparently, so that technological sophistication extends beyond collection to include reliability and representativeness.
- (6th) Civic Capital & Sustainability (CROWD): This examines whether crowdsourcing initiatives build social trust, support sustainability transitions, and encourage responsible innovation. Cities are assessed on their engagement with NGOs and grassroots actors, alignment with SDGs, and ethical practices in the use of AI and data. Higher levels of maturity in this dimension are associated with stronger engagement with NGOs and grassroots actors, clearer alignment with the SDGs, and more explicit attention to ethical practices in the use of AI and data. In more advanced cases, cities may also support local open innovation ecosystems through incubators, living labs, public–private partnerships, and other forms of collaborative experimentation.

The six dimensions of the SMART-CROWD framework were designed to respond to the main gaps identified in the literature review. Specifically:

- Strategy & Leadership (S) addresses the lack of formal open innovation strategies that go beyond generic digitalization plans;
- Methods & Tools (M) and Technology & Data (T) respond to the limited interoperability and closed internal systems that hinder cross-organizational collaboration;
- Engagement & Representativeness (A) addresses the insufficient inclusion of underrepresented groups and the narrow demographic base of most crowdsourcing initiatives;
- Responsiveness & Impact (R) addresses the weak feedback mechanisms and absence of clear pathways from citizen input to institutional change;
- Civic Capital & Sustainability (CROWD) responds to gaps related to long-term engagement, ethical considerations, and alignment with broader societal goals such as equity and sustainability.

Taken together, these dimensions provide a structured basis for linking the shortcomings identified in the literature to key areas of maturity development in urban mobility crowdsourcing. Each dimension comprises five specific indicators (30 indicators total), which operationalize the dimension-level descriptors into measurable components. The complete list of indicators is presented in Table 3.

Table 3. SMART-CROWD Framework Indicators by Dimension.

Dimension	Indicator Code	Indicator Name
S: Strategy & Leadership	S.1	Formal Open Innovation Strategy
	S.2	Strategy for Building Trust & Transparency
	S.3	Dedicated Budget for Co-Creation
	S.4	Governance Model for External Collaboration
	S.5	Success Metrics & KPIs for Open Innovation
M: Methods & Tools	M.1	Bidirectional Communication Platforms
	M.2	Co-Creation & Problem-Solving Platforms
	M.3	Interoperability with Third-Party Tools
	M.4	Modular Innovation Architecture
	M.5	Tools for Idea Aggregation & Filtering
A: Engagement & Representativeness	A.1	Representativeness Monitoring
	A.2	Targeted Outreach to Underrepresented Groups
	A.3	Cross-Sector Collaboration Mechanisms
	A.4	Long-Term Engagement Strategies
	A.5	Inclusive Participation Mechanisms (Analog + Digital)
R: Responsiveness & Impact	R.1	Feedback Loop Transparency
	R.2	Mechanisms for Explaining Decision-Making
	R.3	Tracking of Idea Implementation Progress
	R.4	Innovation Outcome Metrics
	R.5	Celebration & Documentation of Co-Created Successes
T: Technology & Data	T.1	Open Data Publication Standards
	T.2	API Availability & Documentation
	T.3	Data Quality Assurance Mechanisms
	T.4	Bias Detection & Mitigation Protocols
	T.5	Shared Innovation Tools (Algorithm Repos, Simulation)
CROWD: Civic Capital & Sustainability	C.1	Partnership Frameworks with NGO_s/ Community Organizations
	C.2	Alignment with SDGs & Sustainability Metrics
	C.3	Ethical Frameworks for AI & Data Use
	C.4	Local Innovation Ecosystem Development
	C.5	Community Organizations' Ability to Initiate Projects

Among the thirty indicators, specific attention is drawn to indicators T.3 (Data Quality Assurance Mechanisms) and T.4 (Bias Detection & Mitigation Protocols) within the Technology dimension. These indicators were introduced to address well-recognized limitations of crowdsourced data by requiring cities to demonstrate not only data collection capacity, but also mechanisms for illustration, accuracy assessment, and representativeness monitoring. As a result, the framework evaluates the quality and reliability of citizen-generated intelligence, rather than merely its volume. While Table 3 defines the maturity logic at the dimension level, the operational assignment of scores requires additional indicator-level guidance to distinguish more consistently between adjacent maturity levels across different urban contexts. To support reproducibility and practical application, Table 4. presents exemplary indicator-level scoring rubrics for selected indicators across different dimensions. These rubrics show how the dimension-level maturity descriptors presented in Table 3 are operationalized for individual indicators by specifying threshold descriptions, qualitative distinctions between adjacent score levels, and suggested evidence sources. The complete set of indicator-level rubrics for all 30 indicators is provided in Supplementary Materials, enabling more detailed cross-city benchmarking and contextual adaptation while keeping the main text concise. This two-tier structure enables both high-level diagnostic assessment at the dimension level and granular, reproducible scoring at the indicator level. Cities applying the framework may use these rubrics as templates, adapting evidence sources to local administrative systems and data availability.

Table 4. Exemplary Indicator-Level Scoring Rubrics for SMART-CROWD Framework.

Dimension	Indicator	Score 1 (Initial)	Score 2 (Developing)	Score 3 (Defined)	Score 4 (Managed)	Score 5 (Optimizing)	Evidence Source
S: Strategy	S.2 Strategy for Building Trust & Transparency	No privacy policy or data protection measures for crowdsourced data.	General data privacy policy exists but lacks specific provisions for crowdsourcing; no public reporting on data use.	Dedicated transparency policy for crowdsourcing; annual public report on data use and impact; basic opt-out mechanisms.	Comprehensive transparency framework: quarterly impact reports, independent ethics oversight, clear data lineage documentation.	Real-time public data registry; bias audit results published; community co-design of transparency protocols; documented trust metrics improvement.	Privacy policies, public reports, ethics documentation, audit results, trust surveys.
A: Engagement	A.1 Representativeness Monitoring	No demographic data collected; participation limited to self-selected, digitally connected users.	Basic demographic data collected but participation skews >70% toward young, educated groups; no targeted outreach.	Systematic comparison with census data; targeted outreach to $\geq$2 underrepresented groups; participation diversity within $\pm$25% of population.	Dedicated channels for underserved groups; participation diversity within $\pm$15%; documented influence of diverse groups on decisions.	Co-designed engagement protocols with community organizations; participation demographics within $\pm$5% of census; longitudinal tracking of inclusion impact.	Participation analytics, census tables, outreach logs, demographic reports, co-design documentation.
T: Technology	T.3 Data Quality Assurance Mechanisms	No validation of crowdsourced data; raw data used without verification.	Basic automated checks (format validation, duplicate removal); manual review for critical data only.	Triangulation with $\geq$1 authoritative data source; documented accuracy rate $\geq$80%; basic bias detection protocols.	Advanced QA system: multi-source triangulation, ML-based anomaly detection, confidence scores for each data point, and public data quality dashboard.	Self-improving QA: community validation panels, adaptive bias correction, documented accuracy $\geq$95%, external audit of data quality processes.	Data quality reports, validation protocols, bias audit results, accuracy metrics, community feedback.

Table 4. *Cont.*

Dimension	Indicator	Score 1 (Initial)	Score 2 (Developing)	Score 3 (Defined)	Score 4 (Managed)	Score 5 (Optimizing)	Evidence Source
R: Responsiveness	R.1 Feedback Loop Transparency	No mechanism to inform participants about how input was used; "black box" decision-making.	Standardized automated responses acknowledging receipt; annual summary of general trends and actions taken.	Personalized responses with explanation of how specific input was used; public dashboard showing idea status.	Two-way feedback: real-time tracking of contribution journey, detailed justifications for rejected ideas, celebration of co-created successes.	Collaborative refinement loops: participants co-evaluate outcomes; transparent decision algorithms; documented trust and retention improvements.	Feedback logs, public dashboards, participant surveys, implementation reports.

Subsequently, each dimension is assessed on a five-point maturity scale:

1. Initial: Lack of formal processes or sporadic, unplanned activities.
2. Developing: Recognition of the need, fragmented actions, lack of coherent strategy.
3. Defined: Existing processes and strategies but requiring optimization and broader implementation.
4. Managed: Processes are well-defined, monitored, and regularly optimized.
5. Optimizing: Continuous improvement, innovativeness, proactive approach, and industry leadership.

Assessment scale for each dimension is presented in Table 5.

Table 5. SMART-CROWD assessment scale for each dimension.

Dimension \ Score	1 Initial	2 Developing	3 Defined	4 Managed	5 Optimizing
S: Strategy & Leadership	No crowdsourcing initiatives; no formal strategy or governance	Ad hoc crowdsourcing projects without integration into strategic vision	General digital strategy mentions citizen engagement but lacks open innovation principles	Dedicated open innovation framework with clear governance model, resource allocation, and success metrics	Continuously updated open innovation strategy that positions the city as industry leader with measurable societal and innovation outcomes
M: Methods & Tools	No tools for crowdsourcing; traditional one-way communication channels only	Basic digital tools for data collection only, with no bidirectional capabilities	Some platforms enabling limited interaction but not integrated into cohesive ecosystem	Well-designed interoperable systems supporting multi-directional exchanges and cross-platform integration	Advanced co-creation environments with modular innovation architecture, enabling external actors to build upon city resources
A: Engagement & Representativeness	No systematic engagement: participation limited to digitally connected citizens	Basic attempts to reach diverse audiences through multiple channels but no representative sampling	Some efforts to reach underrepresented groups but without systematic inclusion strategies	Dedicated inclusion strategy with targeted outreach, representativeness monitoring, and active engagement of underrepresented communities	Proactive engagement of all citizen groups with specialized channels, systematic tracking of participation diversity, and documented influence on decisions
R: Responsiveness & Impact	No mechanisms to inform participants about how input was used	Basic automated notifications with minimal information on subsequent actions	Standardized template responses explain general processes but lack specific impact details	Personalized responses with clear explanation of specific input's impact; visible implementation of selected ideas	Two-way feedback loops with collaborative refinement of ideas; visible tracking of implementation progress and celebration of co-created successes

Table 5. *Cont.*

Dimension \ Score	1 Initial	2 Developing	3 Defined	4 Managed	5 Optimizing
T: Technology & Data	No publicly available mobility datasets; closed systems with no external access	Limited datasets published in non-machine-readable formats with minimal metadata	Basic datasets in standard formats (CSV, GeoJSON) but limited coverage and infrequent updates	Comprehensive, machine-readable datasets with complete metadata, regular updates, and clear licensing terms	Automated data publication with interlinked datasets, semantic descriptions, active developer community, and documented external innovations
CROWD: Civic Capital & Sustainability	No collaboration with NGOs or community organizations; no sustainability indicators	Occasional consultations with established organizations but no partnership framework	Regular meetings with selected NGOs but limited shared resources or co-decision making	Formal partnership agreements with defined roles, shared resources, joint decision-making processes, and regular evaluation	Long-term strategic partnerships with shared vision, distributed leadership, resource pooling, and community organizations initiating projects independently

A maturity assessment measure was developed for the analyzed area to support the identification of stronger and weaker dimensions within the framework. For each dimension, the overall score S_i is calculated as Equation (1)

$$S_i = \frac{\sum_{j=1}^{n} w_j \times x_j}{\sum_{j=1}^{n} w_j} \quad (1)$$

where

- w_j—Weight assigned to indicator j, $w_j \in$<0;1>.
- x_j—Score for indicator j, $x_j \in$<1;5>.
- n—Total number of indicators within the given dimension.

To ensure contextual relevance, weights (w_j) are not predefined but assigned by the city team during a facilitated internal workshop, based on local priorities, strategic goals (e.g., equity, decarbonization), and institutional capacity. For benchmarking purposes, equal weighting (w_j = 1) may also be applied across all indicators to enable neutral cross-city comparisons.

The final maturity score (M) for the city is the average of all six dimensions (2):

$$M = \frac{\sum_{i=1}^{6} S_i}{6} \quad (2)$$

In conceptual terms, the SMART-CROWD framework is intended to strengthen the role of open innovation in urban governance and mobility planning.

By incorporating open innovation considerations at multiple governance and operational levels, the framework provides a structured basis for assessing whether cities move beyond one-way consultation toward more collaborative problem-solving. Key distinguishing features of the framework include the following:

- Formal assessment of strategic openness through dedicated indicators and scoring;
- Stronger attention to shared responsibility and distributed ownership of innovation processes;
- Metrics extending beyond participation rates to capture value creation and co-created impact;
- Tools and processes supporting both external knowledge inflows and internal knowledge outflows;

- An institutionalization perspective consistent with city-as-a-platform thinking, where the municipality acts as an enabler of wider innovation ecosystems rather than the sole originator of change.

Through these mechanisms, the SMART-CROWD framework aligns crowdsourcing with core open innovation principles such as inclusiveness, reciprocity, experimentation, and broader knowledge exchange. In this sense, the main contribution of the study is threefold: first, it develops a systematic literature-based framework for assessing crowdsourcing maturity in urban mobility; second, it operationalizes this framework through dimensions, indicators, scoring logic, and rubrics; third, it demonstrates its practical interpretability through an illustrative worked example presented in the following section.

7. Illustrative Worked Example: City Maturity Assessment

While full empirical validation across multiple cities is beyond the scope of this study, this section presents a worked example intended to demonstrate the operational logic, transparency, and interpretability of the SMART-CROWD framework. Rather than serving as a measurement validation exercise, the example shows how the literature-derived dimensions, indicators, and scoring rubrics can be applied to a realistic urban mobility profile. City M represents a hypothetical yet plausible metropolitan context synthesizing conditions commonly described in the literature on digitally advanced urban mobility systems.

The City M assessment was based on structured desk research, secondary-source analysis, and the analytical judgment of the authors applied to the proposed dimensions and indicators. To support scoring consistency, the indicators were interpreted using the scoring rubrics defined in Table 4 and Supplementary Materials, and the final assessments were discussed iteratively by the authors to ensure coherence between the qualitative city profile and the assigned maturity levels.

The profile of City M reflects a large, digitally advanced metropolitan context with a population exceeding 25 million residents. The city features a comprehensive mobility ecosystem integrating traditional public transit, multiple shared mobility services (car sharing, bike sharing, scooter sharing), ride-hailing platforms, and pedestrian infrastructure, all coordinated through digital platforms and Mobility as a Service (MaaS) system. Supported by major investments in IoT sensor networks, artificial intelligence infrastructure, and data analytics, City M maintains real-time monitoring systems for traffic, environmental conditions, and infrastructure status.

The city has implemented various crowdsourcing initiatives across its mobility landscape, including large-scale traffic monitoring platforms, participatory accessibility mapping, public transport feedback systems, and academic collaborations in mobility research. Despite these technological capabilities, many of these initiatives operate in relative isolation from each other, with limited integration into broader urban governance frameworks. Although data collection is sophisticated, the city continues to face challenges related to data quality, representativeness of participation, and the translation of citizen input into tangible policy change. Engagement with traditionally underserved groups, including elderly residents, non-digital natives, and lower-income communities, also remains fragmented and is often limited to one-way data collection rather than collaborative innovation.

To support the application of the framework, City M was first assessed at the indicator level using the scoring rubrics presented in Table 4 and Supplementary Materials. The complete indicator-level scoring sheet, including brief justifications for all 30 indicators, is provided in Supplementary Materials. The aggregated dimension-level maturity results are presented in Table 6.

Table 6. SMART-CROWD maturity assessment scores for City M.

Dimension	Score (1–5)	Justification
S: Strategy & Leadership	3	City M has recognized the value of crowdsourcing in mobility management but lacks a formal open innovation strategy that explicitly connects these efforts to broader urban governance. While digital transformation initiatives exist, they are often siloed within specific departments without integrated leadership across mobility planning, public engagement, and technology governance. The city has begun developing policies around data privacy and citizen engagement but has not yet institutionalized open innovation as a guiding principle across its mobility planning processes.
M: Methods & Tools	4	The city excels in deploying diverse technological tools for mobility data collection and analysis, including real-time traffic monitoring platforms, participatory mapping applications, and multi-channel feedback systems. It has implemented several co-creation environments such as innovation labs and hackathons focused on mobility challenges. However, these tools often operate in isolation without standardization or interoperability between departments and external stakeholders, limiting their collective impact and scalability.
A: Engagement & Representativeness	2	Despite advanced technological infrastructure, City M struggles with inclusive participation. Most crowdsourcing initiatives attract digitally connected, tech-savvy residents while underrepresented groups (elderly populations, non-English speakers, lower-income communities) have limited engagement opportunities. The city has recognized this gap but has not yet developed systematic strategies or dedicated resources to ensure representative participation across its diverse population. Cross-sector collaboration exists with academic institutions but remains limited with community organizations and civil society groups.
R: Responsiveness & Impact	3	City M has established basic mechanisms for collecting citizen feedback but lacks transparent systems for explaining how this inputs influence decision-making processes. While the city can effectively monitor and visualize crowdsourced data, it has not developed robust frameworks for translating this information into tangible outcomes, policy changes, or service improvements. Performance metrics focus primarily on quantitative outputs (number of participants, data points collected) rather than innovation outcomes such as new services developed, partnerships initiated, or systemic improvements implemented.
T: Technology & Data	4	The city demonstrates advanced capabilities in data collection, processing, and visualization, with comprehensive IoT infrastructure and sophisticated analytics platforms. It publishes significant datasets through open data portals and has begun implementing APIs for third-party developers. However, these efforts remain primarily focused on transparency rather than active enablement of external innovation. While data quality and processing capabilities are strong, the city has limited shared tools, algorithm repositories, or simulation environments that would allow external stakeholders to build directly on city-generated data and technologies.

Table 6. *Cont.*

Dimension	Score (1–5)	Justification
CROWD: Civic Capital & Sustainability	3	City M has established partnerships with academic institutions and some private sector organizations for mobility innovation and has begun aligning certain initiatives with sustainability goals. However, engagement with grassroots organizations and community groups remains limited, and ethical frameworks for AI and data use are still emerging rather than fully institutionalized. The city has invested in some innovation infrastructure (incubators, living labs) but these efforts lack coordination and systematic connection to broader urban governance structures, limiting their long-term sustainability and impact.

The final maturity score for the City M is calculated as follows:

$$M = \frac{(3+4+2+3+4+3)}{6} = 3.17$$

This score positions City M between the "Defined" (3) and "Managed" (4) maturity levels, indicating that the city has established systematic approaches to crowdsourcing but still has substantial room for improvement. City M performs strongest in Methods & Tools (4) and Technology & Data (4), reflecting its technological sophistication and robust digital infrastructure. However, the dimension-level results also reveal notable weaknesses in Engagement & Representativeness (2), particularly with regard to inclusion of underserved groups and broader community partnerships. Moderate scores in Strategy & Leadership (3), Responsiveness & Impact (3), and Civic Capital & Sustainability (3) indicate partially established processes that remain insufficiently integrated, inclusive, or institutionally embedded. The indicator-level assessment also reveals important internal variation within stronger dimensions. For example, while Technology & Data performs well overall, the lower score for T.4 (Bias Detection & Mitigation Protocols) shows that even technologically advanced cities may lack sufficiently developed mechanisms for reconciling crowdsourced inputs with authoritative data sources or correcting for sampling bias. This distinction illustrates the value of combining dimension-level diagnosis with more granular indicator-level scoring.

Figure 3 visualizes City M's maturity profile using a radar chart, highlighting the imbalance between technological capabilities and socio-technical dimensions such as civic engagement and transparency.

The illustrative assessment of City M reveals a maturity profile that is technologically advanced yet socio-institutionally uneven. The city demonstrates notable strengths in its digital infrastructure and innovation capacity. It has developed sophisticated bidirectional platforms that enable two-way exchanges between authorities and citizens (scoring high on Indicator M.1), and it provides shared innovation tools such as open APIs, simulation environments, and data repositories (Indicators T.1 and T.2), which allow external actors to build upon municipal resources. However, even within strong dimensions, specific gaps remain. For instance, while co-creation platforms are advanced (M.2), interoperability between them remains limited (Indicator M.3 scored 3), creating data silos that hinder scalability. Furthermore, City M fosters cross-sector collaboration with academic institutions and selected industry partners and has invested in physical and organizational infrastructure for innovation, including incubators and living labs. These efforts also suggest a visible institutional commitment to innovation, although not yet in a fully integrated or strategically coordinated form.

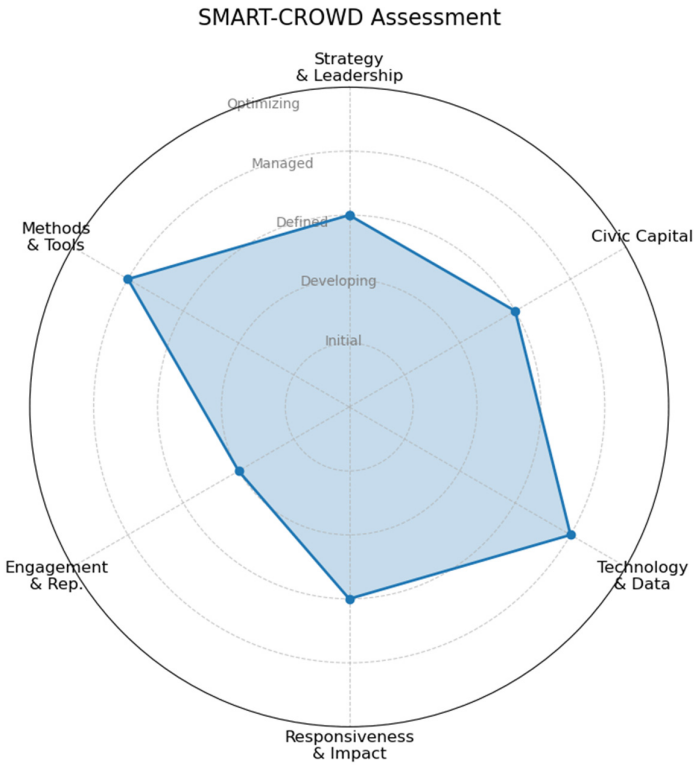

Figure 3. City M's SMART-CROWD profile.

However, the assessment also uncovers critical gaps that limit the city's ability to fully realize open innovation in practice. Most notably, mechanisms for inclusive engagement remain significantly underdeveloped. Detailed indicator analysis reveals that Indicator A.2 (Targeted Outreach) scored only 1, indicating no systematic strategy for reaching underrepresented groups, while A.1 (Representativeness Monitoring) scored 2 due to reliance on self-selected digital samples. While digital participation channels are robust, they largely exclude elderly residents, non-digital natives, and other marginalized groups who lack access to or familiarity with online platforms. This results in a skewed representation of citizen input and weakens the participatory potential associated with open innovation. Additionally, although the city collects substantial feedback from residents, it offers limited transparency about how this input translates into concrete decisions or policy changes. This is reflected in Indicator R.2 (Mechanisms for Explaining Decision-Making), which scored 2, signaling that users rarely receive clear justifications for why ideas are accepted or rejected. As a result, trust and sustained engagement remain limited. Community partnerships with grassroots organizations and NGOs are similarly weak, reflecting a top-down rather than co-creative approach to urban problem-solving. Finally, while privacy-preserving technologies are in place, the city lacks comprehensive communication strategies that build public trust and explain how personal data is protected and used.

These findings suggest that City M functions effectively as a technology provider but has not yet developed into a more fully collaborative innovation partner. Its crowdsourcing initiatives remain largely transactional and data-centric, rather than relational, inclusive, and co-creative. Importantly, the diagnostic logic of the SMART-CROWD framework makes it possible not only to identify general weaknesses, but also to translate them into more concrete, dimension-specific intervention directions.

In the case of City M, the most critical gaps concern social inclusiveness, demographic representativeness, transparency and feedback, sustained civic engagement, institutional embedding of open innovation, accessibility of participation channels, and the visibility of ethics and data governance practices. Rather than treating these as isolated weaknesses,

the framework allows them to be interpreted as an interrelated improvement agenda in which deficits in inclusion, feedback, and institutional support reinforce one another.

To make this diagnostic logic more operational, the results were translated into an illustrative improvement pathway for City M, presented in Table 7. The purpose of this pathway is not to provide a validated implementation plan, but to show how low-scoring dimensions can be linked to plausible interventions, indicative implementation horizons, and expected directions of institutional and operational development. In this way, the framework supports a more structured transition from diagnosis to action.

Table 7. Illustrative Improvement Pathway for City M Based on Diagnostic Gaps.

Dimension/Diagnostic Gap	Current Score	Priority Intervention	Indicative Timeline	Expected Direction of Improvement
Social Inclusiveness—limited participation from underrepresented groups	2	Introduce targeted outreach measures for underrepresented communities and strengthen community-based participation channels	Short to medium term	Improved inclusiveness and broader representation in participation processes
Demographic Representativeness—participant structure does not sufficiently reflect population diversity	2	Diversify recruitment and engagement mechanisms to reach groups that are less visible in digital participation ecosystems	Medium term	Better alignment between participation profiles and the broader urban population
Transparency and Feedback—weak feedback loops between contributors and city institutions	2	Establish structured feedback mechanisms and communicate how citizen contributions influence decisions and interventions	Short term	Greater transparency, stronger responsiveness, and improved contributor trust
Sustained Civic Engagement—low continuity of participation over time	2	Develop retention-oriented engagement practices, including recurring communication and long-term participant support	Medium term	Stronger repeat engagement and more stable civic participation over time
Institutional Support for Open Innovation—limited formal anchoring of crowdsourcing in governance structures	2	Integrate open innovation more explicitly into mobility governance through dedicated coordination, planning, and resource allocation	Medium to long term	Stronger institutional embedding of crowdsourcing within mobility governance
Accessibility and Inclusion Channels—excessive reliance on digital-only participation pathways	2	Expand accessible and non-digital participation channels for residents facing digital, linguistic, or social barriers	Medium term	Greater accessibility and more equitable participation opportunities
Ethics and Data Governance—insufficient visibility of ethical safeguards and accountability mechanisms	2	Introduce clearer ethical oversight, data governance rules, and public communication on responsible data use	Medium term	Improved accountability, legitimacy, and public confidence in participatory data use

The value of the framework lies not only in identifying weak dimensions, but also in linking sequenced and context-sensitive improvement directions. In particular, the low scores observed in inclusion, representativeness, transparency, and institutional support suggest that technological capacity alone is insufficient to ensure mature crowdsourc-

ing governance. Instead, progress requires coordinated changes in outreach practices, feedback systems, governance arrangements, and accountability mechanisms. The value of the framework therefore lies not only in identifying weak dimensions, but also in revealing how these weaknesses can be translated into sequenced and context-sensitive improvement directions.

This illustrative application also highlights the practical interpretability of the SMART-CROWD framework. Rather than remaining at the level of abstract benchmarking, the framework can support more fine-grained reflection on dimension-specific strengths and weaknesses. By diagnosing between technological capacities and socio-institutional weaknesses at the level of individual indicators (or example, between stronger data publication practices -T.1 and weaker shared tools -T.5), SMART-CROWD can help identify context-sensitive areas for institutional and organizational improvement in urban mobility governance.

In practical terms, the intervention pathway suggests that cities move beyond ad hoc participation measures and embed inclusive crowdsourcing more systematically in formal procedures, assigned responsibilities, and cross-departmental coordination. For example, inclusive engagement protocols may specify which groups are at risk of exclusion, which outreach channels should complement digital platforms, how participation diversity can be monitored, and how feedback to contributors should be communicated and documented. Likewise, transparency-related interventions require not only communication tools, but also organizational routines for explaining why citizen inputs were accepted, modified, or rejected. In this way, the framework supports not only diagnosis, but also the identification of institutional adjustments that may enable more structured improvement.

8. Discussion

The SMART-CROWD framework offers a structured approach to assessing the maturity of crowdsourcing initiatives in urban mobility. By addressing the key gaps identified in the existing literature, the framework integrates open innovation principles more explicitly than most existing crowdsourcing approaches. This section discusses its potential implementation pathways, analytical contribution, and broader relevance for innovation-oriented smart city governance.

The practical value of the SMART-CROWD framework lies in its multidimensional assessment approach, which can support implementation by urban authorities and mobility service providers. Cities can operationalize this framework through the phased implementation pathway illustrated in Figure 4.

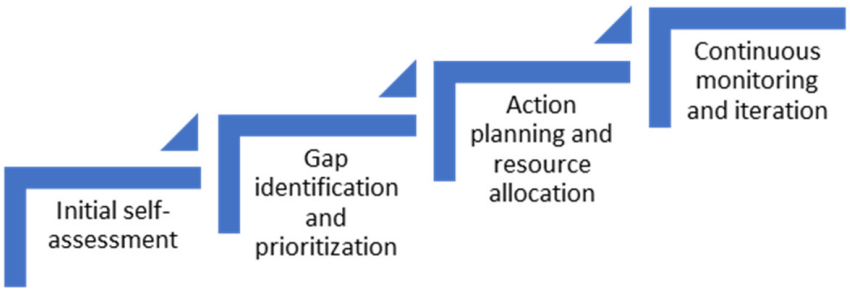

Figure 4. SMART-CROWD framework phased approach.

The first phase concerns initial self-assessment. The process begins with an assessment based on framework's six dimensions (Strategy & Leadership, Methods & Tools, Engagement & Representativeness, Responsiveness & Impact, Technology & Data, and Civic Capital & Sustainable Development). For each indicator, city departments or project teams can assign a maturity score from 1 (initial) to 5 (optimizing). This scoring provides a

baseline picture of current capabilities and helps identify relative strength and weakness. The weighted scoring system supports a more structured and transparent assessment of the city's crowdsourcing maturity.

The second phase concerns gap identification and prioritization. Lower scores in specific indicators or dimensions may point to areas requiring attention. For instance, a low score in "Strategic Open Innovation Framework" (S dimension) may indicate the need to formalize open innovation strategies, while a low score in "Availability of Co-creation and Problem-Solving Platforms" (M dimension) may suggest the need for more dedicated digital infrastructure. In this way, framework can support prioritization of interventions in line with local needs and strategic objectives.

The third phase concerns action planning and resource allocation. Based on the identified gaps, cities can formulate more targeted action plans. The framework may also inform resource allocation by indicating areas that require greater institutional or financial support, such as long-term engagement and co-creation initiatives (S dimension). This may help direct resources are directed towards more coherent improvements rather than fragmented ad hoc efforts.

The fourth phase concerns continuous monitoring and iteration. The SMART-CROWD Framework is intended to be iterative, with regular re-assessments (e.g., annually or bi-annually) making it possible to track progress, review the effects of implemented changes, and adjust strategies when needed. Such repeated assessment is important in the context of changing urban conditions, evolving technologies, and shifting forms of participation.

8.1. The Framework's Contribution to Open Innovation Development

The SMART-CROWD famework's main contribution lies in its explicit integration of open innovation principles, which responds to several shortcomings identified in the existing literature on crowdsourcing in urban mobility.

An important gap in prior research is the predominant focus on crowdsourcing as a data acquisition tool for example real-time traffic data [53]; parking spot availability [51]; environmental noise data [76]. While valuable, this approach often overlooks the crowd's potential as a source of ideas and solutions [11]. SMART-CROWD responds to this issue by introducing indicators such as "Availability of Co-creation and Problem-Solving Platforms" (M dimension) and "Active Involvement of External Experts and Communities in Innovation Processes" (A dimension). This may encourage cities to move beyond passive data collection towards broader engagement in problem-solving and co-creation, treating citizens not only as a data providers, but also as a potential contributors to innovation.

The lack of explicit framing of crowdsourcing within a broader open innovation paradigm was another notable limitation in many analyzed frameworks; only Suh et al., explicitly mentioned it. SMART-CROWD addresses this gap by introducing a "Strategic Open Innovation Framework" indicator (S dimension) [109]. This may encourages cities to formalize how external knowledge and participation contribute to their broader innovation strategy for urban mobility, so that crowdsourcing is treated less as an is isolated tactic and more as a part of a wider innovation approach.

Open innovation depends on trust and willingness to share [112]. Distrust towards public authorities [37] may therefore limit the quality and continuity of participation. SMART-CROWD address this issue through indicators such as "Strategy for Building Trust and Transparency in Data and Innovation Processes" (S dimension) and "Mechanisms for Transparent Feedback on Data Use and Decisions Made" (R dimension). By promoting clear communication about how citizen input is used, and how decisions are made, the framework may support the development of social capital needed for more sustained external engagement.

Fragmentation resulting from the lack of standardized and interoperable frameworks was also identified as an important gap. While some frameworks addressed data integration [49] SMART-CROWD extends this perspective by including indicators such as "Availability of Open Data and Open-Source Tools" and "Application of Open Data Standards and APIs for Interoperability" (T dimension). These elements may support a more connected innovation ecosystem by making it easier for external developers and researchers to build on city data and tools [113]. In addition, the "Development of an Open Innovation Ecosystem in Mobility" (CROWD dimension) highlights the role of local innovation hubs and partnerships. Moreover, unlike many frameworks that treat crowdsourced data as inherently valid, SMART-CROWD incorporates criteria related to data quality assurance and bias mitigation (T dimension). This is an important feature of the framework, as it acknowledges that crowdsourced data may be noisy and may require validation against other sources before being used in urban governance.

Unlike many analyzed frameworks that focus on specific technical solutions, such as privacy protection [57,58,91], traffic optimization [60,67], SMART-CROWD provides a more holistic assessment structure. It combines technical aspects with socio-economic and ethical considerations, including "Assessment of Ethical Aspects of Crowdsourcing and AI" (CROWD dimension). In this way, the framework reflects not only efficiency-oriented concerns, but also broader issues of equity, responsibility, and alignment with societal values, which are important for the long-term sustainability of smart city initiatives [114].

8.2. Distinctive Features Relative to Previously Analyzed Frameworks

The SMART-CROWD framework differs from the previously analyzed frameworks in several important respects:

(1) Broader analytical scope: While individual frameworks in the literature address specific areas, for example WiFi tracking [54,55], package delivery [31], or objectivity analysis [65], relatively few provide an integrated, multi-dimensional assessment across strategy, methods, engagement, impact, technology, and civic capital. In this respect, SMART-CROWD brings these dimensions together within a single assessment structure.

(2) Stronger integration of open innovation considerations: Many previously analyzed frameworks, including those using crowdsourcing, treated it primarily as a data collection mechanism. By contrast, SMART-CROWD incorporates open innovation more explicitly into its assessment logic, including the role of external ideas, actors, and collaborative processes in urban mobility governance.

(3) Diagnostic and operational potential: Unlike purely descriptive or analytical approaches, SMART-CROWD is structured in a way that may support diagnostic use. Its maturity scale and detailed indicators can help cities identify weaker areas and consider more targeted improvements, although the practical robustness of this application still requires broader empirical testing.

(4) Attention to socio-technical aspects: Many existing frameworks focus primarily on technical dimensions. SMART-CROWD, while including technological issues, also gives substantial attention to socio-technical factors such as trust, inclusivity, and long-term citizen engagement, recognizing that these human dimensions are important for real-world implementation and impact [71].

The SMART-CROWD Framework should be understood as a structured literature-based and diagnostic contribution rather than as a fully validated empirical instrument. Its main value lies in integrating strategic, technical, participatory, and governance-related dimensions within a single assessment structure, operationalized through indicators and scoring rubrics and illustrated through a worked example. In this sense, it may support

future comparative research and context-sensitive practical application, while still requiring broader empirical testing across different urban settings.

8.3. Limitations

The SMART-CROWD framework, while designed to provide a comprehensive assessment perspective, has several limitations that should be acknowledged when interpreting its current scope and applicability. First, the present study is primarily conceptual and synthesis oriented. Although the framework is illustrated through the "City M" example, this application should be understood as an exploratory demonstration of the framework's diagnostic logic rather than as empirical validation. The assessment relied on structured desk research, secondary-source analysis, and the analytical interpretation of the authors. Accordingly, the study contributes a systematically developed and operationalized assessment framework, while its empirical validation remains a task for future research.

Second, the framework has not yet been tested comparatively across multiple real-world cities. As a result, its ability to discriminate between different institutional, technological, participatory, and governance contexts requires further verification. Future studies should therefore extend its application through multi-city analyses, expert-based validation, and structured comparative case research.

Third, formal inter-rater reliability metrics were not calculated. This reflects the current objective of the study, which is to introduce and illustrate the framework rather than to conduct full measurement validation. Coding consistency was supported through shared scoring rubrics, iterative comparison of interpretations, and joint resolution of ambiguous cases. Nevertheless, future applications should test the robustness of the scoring approach using independent evaluators and formal agreement procedures.

Another limitation concerns data availability and quality. Some of the more advanced indicators, particularly those related to long-term civic engagement, demographic representativeness, open innovation outcomes, and institutional resource sharing, require evidence that may not be routinely collected or publicly reported by cities. In such situations, assessments may rely partly on proxy indicators or informed estimation rather than complete empirical datasets.

A further practical limitation relates to the resource intensity of implementation. Conducting a comprehensive assessment across all six dimensions requires administrative coordination, analytical capacity, and access to sufficiently detailed documentation. This may pose challenges for smaller municipalities or for cities with limited institutional or data-management capacities.

Despite these limitations, the SMART-CROWD framework offers value as a structured diagnostic and strategic tool. Its main contribution lies in integrating crowdsourcing and open innovation considerations within a coherent assessment logic, while also providing a basis for future empirical refinement, comparative validation, and context-sensitive application in real-world urban mobility governance.

9. Conclusions

Urban mobility governance increasingly requires approaches that go beyond purely technology-centered solutions and account for inclusivity, adaptability, and institutional capacity. In this context, crowdsourcing can be understood as one mechanism through which open innovation may inform mobility planning and operations. At the same time, its effective use requires a structured basis for assessment and improvement.

The literature review showed that existing crowdsourcing frameworks in urban mobility are diverse in their objectives, methodologies, and applications, but they often focus more strongly on technical or operational functions than on the broader governance logic

of open innovation [115–141]. Much of the reviewed literature emphasized efficiency, optimization, and data processing, while giving less attention to co-creation, long-term participation, and institutional embedding, and strategic openness. Direct references to open innovation were also relatively rare, suggesting that crowdsourcing is often used in practice without being explicitly framed as a mechanism for collaborative problem-solving and external knowledge integration.

To respond to these gaps, we developed the SMART-CROWD framework as a six-dimensional structure for assessing crowdsourcing and open innovation maturity in urban mobility. Compared to many earlier approaches, the framework brings together strategic, participatory, technological, and governance-related dimensions within a single assessment logic. It also incorporates indicators related to open innovation strategy, co-creation capacity, transparency, interoperability, and data governance.

The illustrative application to City M suggests that even technologically advanced cities may exhibit asymmetries, with stronger performance in Methods & Tools and Technology & Data than in Engagement & Representativeness and Responsiveness & Impact. This example shows how the framework can be used to identify imbalances in crowdsourcing maturity and to indicate possible areas for further development. By translating gaps identified in the literature into measurable dimensions, SMART-CROWD can support self-assessment and more structured reflection on improvement pathways in urban mobility governance.

From a practical governance perspective, the findings suggest that cities should not treat crowdsourcing merely as a technical data acquisition mechanism, but as an institutional capability requiring deliberate design, coordination, and accountability. More specifically, the framework points to several priority directions for practice. First, cities should formalize inclusive engagement protocols that specify which communities are at risk of underrepresentation, which outreach channels are to be used beyond digital platforms, and how participation diversity will be monitored over time. Second, crowdsourcing initiatives should be supported by structured feedback routines so that contributors can see how their inputs are assessed, incorporated, modified, or declined. Third, open innovation in mobility should be embedded more explicitly in governance structures through dedicated coordination roles, clearer cross-departmental responsibilities, and stronger alignment between participatory inputs and formal planning processes. Fourth, cities should strengthen transparency, ethics, and data governance procedures, including clearer communication on data use, privacy protection, and the reconciliation of crowdsourced inputs with authoritative sources where feasible. Finally, the analysis suggests that long-term crowdsourcing maturity depends not only on participation volume, but also on institutional continuity, trust-building capacity, and the ability to sustain repeated engagement over time. These recommendations should be understood as framework-derived strategic directions rather than universally fixed prescriptions, but they indicate how the diagnostic logic of SMART-CROWD can be translated into more operational and context-sensitive action. Their relevance and feasibility may vary depending on local governance arrangements, administrative capacity, data availability, and the maturity of participatory institutions.

Ultimately, the SMART-CROWD framework may help cities reflect more systematically on how crowdsourcing is designed, governed, and embedded in mobility policy. In this sense, it can support the identification of stronger and weaker areas and indicate where strategic, organizational, and participatory adjustments are needed to make crowdsourcing more equitable, credible, and effective. This is consistent with broader smart city and sustainability goals, including SDG 11 and SDG 13.

Future research should include broader benchmarking studies applying the SMART-CROWD framework across diverse urban contexts in order to identify maturity patterns,

institutional drivers, and possible relationships with urban outcomes. Comparative analyses could also examine how different weighting schemes influence strategic priorities in crowdsourcing for mobility. Such work may help strengthen the empirical grounding and practical applicability of the framework in urban governance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/asi9040077/s1, Table S1: Example of literature review analysis results; Table S2: Scoring Rubrics for Strategy & Leadership (S) Dimension; Table S3: Scoring Rubrics for Methods & Tools (M) Dimension; Table S4: Scoring Rubrics for Engagement & Representativeness (A) Dimension; Table S5: Scoring Rubrics for Responsiveness & Impact (R) Dimension; Table S6: Scoring Rubrics for Technology & Data (T) Dimension; Table S7. Scoring Rubrics for Civic Capital & Sustainable Development (CROWD) Dimension; Table S8. Estimated Indicator-Level Scores for City M (Illustrative Assessment).

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