

Review

The Sustainable Mobility Innovation Ecosystem: Proposing a Theory-Based Taxonomy

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Abstract

Sustainable mobility is undergoing a profound transformation driven by emerging technologies, increasingly stringent government regulations, and rising societal expectations, challenging traditional mobility models and fostering the emergence of new collaborative ecosystems. Actors from diverse sectors are converging to co-create innovative solutions that support a more sustainable mobility paradigm. Given the novelty of this phenomenon, this study proposes a theory-based taxonomy of innovation ecosystem initiatives for sustainable mobility. To this end, an exploratory literature review was conducted on 760 peer-reviewed articles published over the past twenty years, linking publications on innovation ecosystems with those on sustainable mobility. Topic analysis, performed using Latent Dirichlet Allocation (LDA), identified ten key themes. These themes were then grouped into three main categories during an expert roundtable: smart transportation systems, sustainable mobility planning, and logistics optimization. Furthermore, the analysis of author networks reveals a segmented and specialized collaborative structure, characterized by strong cohesion within thematic groups but limited connectivity between them. This fragmentation reinforces thematic concentration while limiting inter-domain interactions. Overall, the proposed taxonomy offers a structured framework for better understanding and supporting the design, coordination, and orchestration of innovation ecosystems in sustainable mobility.

Keywords: innovation ecosystem; sustainable mobility; smart mobility; taxonomy; Latent Dirichlet Allocation (LDA)



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1. Introduction

The use of advanced technologies is transforming many industrial and service processes, particularly in the mobility sector. Sustainable and smart mobility aims to provide integrated and optimal mobility by reducing human intervention in decision-making. New applications are emerging in this field, such as cyber-physical systems approaches for collaborative urban traffic management [1], data and service management technologies in intelligent transportation systems [2], the use of blockchain to ensure the security of data transfers within smart cities [3], and renewable energy transport technologies for

private vehicles [4]. Initiatives promoting sustainable mobility include the implementation of dedicated cycle lanes [5], the creation of car-free zones in the most congested areas [6], and government incentive programs for the purchase of electric vehicles [7].

Promoting innovation in the context of sustainable mobility is a major challenge, as it requires collaboration not only with suppliers and direct customers, but also with companies from many other industrial sectors and knowledge areas [8]. Innovation ecosystems (IEs) offer a suitable framework for orchestrating this collaboration [9]. IEs form when several actors with heterogeneous profiles have interdependencies that produce systemic outcomes governed by alignment structures [10–13]. The absence of this ecosystemic vision among members, or even the absence of one or more members playing a leadership role, particularly during the ecosystem's launch phase, can hinder its development and full potential [14]. Naturally, disruptive or radical innovations require strong integration between suppliers, complementors, and regulators, who will define the rules of the game. These relationships coexist and generate a constant flow of iterations and exchanges for which members may not yet be prepared [15].

Considering the Sustainable Mobility Innovation Ecosystem (hereafter referred to as SM-IE) as an emerging ecosystem, it is important to understand the typologies of the different theoretical perspectives used to analyze this ecosystem. SM-IE is an ecosystem that brings together all actors involved in the development, provision, use, management, orchestration, or regulation of sustainable mobility solutions—that is, solutions that meet essential transportation needs to ensure long-term ecological sustainability and promote intra- and intergenerational equity [16].

While some studies propose taxonomies, for example, to illustrate vehicle access regulations in urban areas applied within the framework of sustainable mobility strategies [17], or to understand the characteristics that shape mobility in the suburbs of large cities [18], these remain scattered and incomplete. The literature addresses various themes within the context of SM-IE, but no studies present a comprehensive list of the key theoretical perspectives needed to develop a theory-based taxonomy. Existing classification studies in sustainable mobility have generally focused on specific domains, such as urban transport policies, shared mobility, logistics, intelligent transport systems, or mobility planning. While these studies provide valuable insights into particular aspects of sustainable mobility, they do not adopt an innovation ecosystem perspective and therefore do not explain how the diverse actors, technologies, governance mechanisms, and operational practices collectively contribute to ecosystem formation and evolution. Furthermore, previous review studies have mainly mapped research trends and thematic areas without proposing an integrated theory-based framework capable of organizing the field from an ecosystem perspective. Therefore, a gap remains regarding the development of a comprehensive taxonomy that explains the structure of Sustainable Mobility Innovation Ecosystems as a whole.

Furthermore, despite the growing volume of research, the literature on SM-IE remains fragmented, encompassing numerous mobility initiatives, technologies, planning approaches, and stakeholder perspectives. Knowledge is thus dispersed across siloed research streams, making it difficult to achieve an integrated understanding of the field. To the best of our knowledge, no previous studies have comprehensively synthesized these diverse perspectives into a theoretical taxonomy of SM-IE, nor have any studies used thematic modeling based on latent Dirichlet analysis (LDA) to consolidate and structure this body of knowledge.

This study therefore aims to provide an answer to the following research question: What are the dominant theoretical perspectives within the Sustainable Mobility Innovation Ecosystem (SM-IE) literature, and how can they be synthesized into a theory-based taxonomy? To this end, 760 articles published between 2002 and 2022 in the Web of Science

database were analyzed. The LDA algorithm was used for topic modeling and then to structure the taxonomy. This resulted in a taxonomy divided into three categories: (i) smart transportation systems, (ii) sustainable mobility planning, and (iii) logistics optimization. A thorough understanding of SM-IE can be invaluable for driving the implementation, management, and orchestration of innovation ecosystems for sustainable mobility in different national contexts.

The remainder of this article is divided into four sections. The following section presents the theoretical background, describing the concepts of innovation ecosystems and sustainable mobility. The third section explains the methodological approach adopted. The fourth section presents the results of the topic modeling analysis, the theoretical taxonomy and an author network analysis of the dataset. The fifth and final section concludes the article by summarizing its contributions and limitations and identifying avenues for future research.

2. Theoretical Background

2.1. Innovation Ecosystems

In business, economy and management studies, an ecosystem is an evolving term, initially understood as collaborative agreements between companies for the co-evolution of capabilities around innovations, whereby firms cooperate and compete simultaneously to support new products, satisfy customer needs, and foster subsequent rounds of innovation [10,13,19,20]. More recently, an IE has come to refer to combinations of resources such as products, services, capital, technologies, and intangible assets [9]. Actors can connect through formal relationships, such as supply chains, value chains, or alliances [11,15], or be linked by geographic location, such as within clusters or regional ecosystems [15], or even establish interdependencies between technology platforms [21]. Furthermore, there are knowledge ecosystems that emphasize research-based knowledge, and entrepreneurial ecosystems that prioritize value capture [11,21].

In general, IEs are organized around central entities [11,15] that define the objectives of each actor and the ecosystem as a whole, and ensure its smooth operation [11,22]. The challenge for these central entities (or ecosystem leaders, or hubs) is to create a governance structure adapted to orchestrating the ecosystem [10,23,24]. In addition to these entities, several other actors interact and share dynamic capabilities [25,26]. These include universities and research centers, industry associations, investors, funding bodies, governmental and political bodies, etc. [19,27]. These actors have specific roles within the ecosystem [23] and may come from different countries, sectors, and industries, and exhibit varied organizational structures (for-profit or non-profit, civil society organizations, public or private) and sizes [10]. Interactions between actors establish a network of relationships through which resources (human and financial) and information circulate [28] for the joint creation of value [11,29]. Key actors in the ecosystem must ensure the engagement of other stakeholders and that they are fairly compensated for their efforts and contributions to the IE [27]. Taxonomies in the field of IE research organize existing knowledge by identifying and classifying information from various sources [30–32]. In this context, five related approaches have been identified in the literature: (i) archetypes [33]; (ii) the ecosystem life cycle [13,34]; (iii) actor types and their roles [35,36]; (iv) relationship types (interactions and collaborations) [35,37,38]; and (v) the creation, sharing and capture of value [29,33,39]. Table 1 presents a summary of these categories.

The theory of IEs is particularly relevant to sustainable mobility, as their solutions rely on the coordinated action of technology providers, transport operators, regulators, infrastructure developers, users, and research organizations. The ecosystem approach thus

offers a suitable theoretical framework for understanding how these interdependent actors jointly design, implement, pilot, and deploy sustainable mobility solutions.

Table 1. Innovation ecosystem approaches found in the literature.

Taxonomy	Description	References
Archetypes	Three IE archetypes: (1) competence- and issue-driven, (2) place-driven, (3) hub- and chain-driven.	[33]
Ecosystem life cycle	Three phases, namely (1) formation, (2) growth and (3) maturity, with two models of network formation: (1) spontaneous or (2) planned.	[34]
	Four phases: (1) birth, (2) expansion, (3) leadership and (4) self-renewal.	[13]
Actors and roles	Four actors: (1) producer organizations, (2) primary consumers, (3) secondary consumers, and (4) support organizations.	[35]
	Four roles: (1) leadership, (2) direct value creation, (3) support for value creation, and (4) entrepreneurship.	[23]
	Four roles: (1) ‘Keystone’—facilitating access to resources for all actors in the ecosystem; (2) ‘Landlord’—attracting resources from the ecosystem;	[36]
	(3) ‘Dominant’—attracting resources and exercising hierarchical power in the ecosystem; and (4) ‘Niche players’—attracting and donating resources in a balanced way to the ecosystem (generally small and medium-sized organizations).	
Type of relationship	Six types: (1) competition, (2) predation, (3) parasitism, (4) mutualism, (5) commensalism and (6) consumerism.	[35]
	Three types of collaboration: (1) macroscopic (collaborating internationally), (2) medium or meso level (collaboration at national level) and (3) microscopic level (collaboration at regional level).	[37,38]
Value creation, sharing and capture	Four types: (1) ecosystem attractiveness, (2) efficient architecture and standardized platform design, (3) adequate management of industrial property (IP), (4) government intervention (availability of financing and regulatory policies).	[29]
	Four dimensions: (1) outputs, (2) strategies, (3) internal mechanisms, (4) inputs (IE characteristics).	[39]

2.2. Sustainable Mobility

Sustainable mobility [16,40] aims to oppose the conventional passenger transport system, designed to optimize costs and travel time, but which generates significant environmental impacts because it relies heavily on non-renewable energy sources and contributes significantly to global CO₂ emissions [40].

To achieve sustainable mobility, structural and coordinated actions must be implemented with the support of civil society and regional governments [5,6]. These actions include public policies and appropriate transport planning, essential tools for promoting sustainable mobility [7], the planning of a multimodal urban network integrating the first and last mile with mass transit [40,41], electromobility (the transition of all modes of transport to electric powertrains), and low-mobility societies (the transition to car-free cities) [40] by encouraging walking and cycling [6]. In terms of technological developments, the academic literature presents at least two main categories of solutions under development: (1) smart mobility or intelligent transportation [42] and (2) green mobility [40]. On the one hand, smart mobility aims to use new technologies to make the mobility system for people and goods more efficient, safe, and clean [42,43], whether in mass public transport [40], rental and shared vehicles, taxis [44,45], or urban [46,47] or rural [48] air mobility. On the other hand, green mobility focuses primarily on providing existing modes of transport with the technological means to move away from fossil fuels and adopt more sustainable solutions. The use of zero-emission renewable energy sources in their propulsion engines,

also called decarbonization [49], is a major focus of green mobility. This latter approach is based on electromobility applications currently used in hybrid and electric vehicles [40], fuel cells [49,50], bioenergy, and renewable energies [51].

Furthermore, the literature review identified two main categories of articles: (1) articles addressing sustainable mobility as a whole, offering a more comprehensive view integrating the different perspectives of the mobility system, and (2) articles focusing on specific topics, addressing one or more perspectives of this system. Table 2 presents a description of these two approaches.

Table 2. Sustainable mobility approaches found in the literature.

Taxonomy	Description	References
Global-general topic of sustainable mobility	Four topics: (1) social, environmental and economic research, (2) planning, policy and management, (3) application and practice, (4) technology and (5) operations research.	[52]
	Nine topics: (1) sustainable transport indicators and performance model, (2) sustainable transport policy, (3) stakeholder involvement, (4) supply chain supply and logistics management, (5) environmental impact, (6) travel behavior, (7) new vehicle fuels, (8) strategic transport planning, (9) bicycles and public transport.	[53]
Specific topics	(1) Analyses on the actions and policies that can be implemented.	[7,54]
	(2) Characterization of the needs and interactions of actors involved in urban mobility.	[55]
	(3) Assessment of the impact of logistics expansion in urban and suburban areas.	[54]
	(4) Optimization of multi-constrained routing problems, and development of vehicle routing algorithms.	[56]
	(5) Shared mobility typology, including the different aspects of the car sharing service and the intersection of Digital Technology and Transport with Shared Economy. For the latter, the taxonomy considers market orientation (non-profit or for-profit) and the type of transaction (peer-to-peer, company–consumer or government–consumer).	[57,58]
	(6) Operational design and support domain of infrastructure for automated driving, which includes the user, vehicles and road infrastructure.	[59]

Finally, in addition to the technical, social, and economic obstacles that these new players in sustainable mobility must overcome [52], they must also learn to innovate in this sometimes poorly coordinated environment. Innovations in products, services, and business models related to sustainable mobility attract many new players who gravitate around these new solutions and seize various opportunities [60], thus forming an innovation ecosystem.

3. Research Methodology

This research combines quantitative and qualitative methods. The quantitative approach uses natural language processing (NLP) to extract knowledge from documents. The qualitative approach draws on grounded theory. This method is based on symbolic interactionism, according to which theoretical propositions emerge from data collected and systematically analyzed within the research framework [61]. Thus, this mixed-methods approach proposes a theoretical taxonomy of perspectives on symbolic and environmental interac-

tionism (SM-IE). This involves a descriptive literature review [62] that uses topic modeling to identify the main themes addressed and then propose the theory-based taxonomy.

Given the objectives of this research, the methodology for developing the proposed taxonomy follows the steps illustrated in Figure 1.

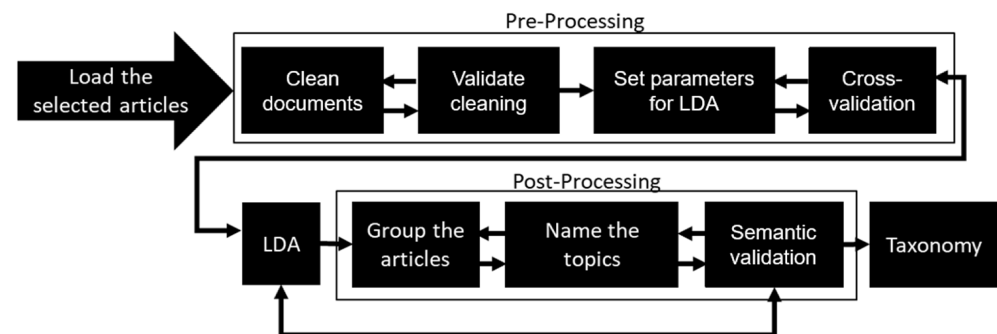


Figure 1. Methodological overview.

The research began with an inventory of peer-reviewed articles published in Web of Science (WoS) over a 20-year period. The WoS database was chosen because of its widespread availability and recognition by peer-reviewed journals. This study covers the period 2002–2022, which illustrates the emergence and consolidation of the sustainable transport ecosystem concept. This timeframe reflects both the methodological constraint necessary for systematic reproducibility and a desire to limit the influence of disruptions related to COVID-19, particularly by excluding reactive and ephemeral conceptualizations that emerged during the pandemic but were subsequently revised or abandoned [63], and which could bias the analysis. Given the usual academic publication cycle, the studies published up to 2022 mostly report on research conceived and conducted before or at the beginning of the pandemic, thus preserving a coherent representation of the foundational development of the field. In contrast, publications after 2022 increasingly reflect the structural changes and adaptations brought about by the pandemic [64,65]. The selected period thus corresponds to a phase in which the field reached a level of conceptual maturity under relatively stable conditions.

For the search, keywords related to the literature on innovation ecosystems and sustainable mobility were used. These keywords were combined to form the main query presented in Table 3.

The search was conducted in the “Subject” field of the Web of Science advanced search site for the aforementioned period, which identified 2245 articles. After applying filters, 760 articles were analyzed. To strengthen quality control during the selection phase, the first two authors independently reviewed all eligible documents. Any disagreements regarding inclusion and exclusion decisions were then discussed with the other members of the research team until a consensus was reached.

A topic modeling algorithm was applied to these documents. Topic models aim to detect groups of words with similar association patterns within a corpus, thus allowing these words to be grouped into relevant themes. These algorithms exploit the fact that words are not used randomly in texts, but rather according to specific combinations and frequencies. For example, in the field of economics and management, words like “research” and “development” are likely to appear more frequently together and be grouped into a common topic. By analyzing the co-occurrence of words in textual documents, it is possible to better understand the semantic content of specific sets of documents. Like other text exploration approaches, topic models aim to reveal deeper underlying semantic patterns by going beyond the surface lexicon of texts and exploiting authors’ consistent word usage.

Table 3. Search protocol and screening process to select the articles that were used in the review process.

	Attributes	Details	Number of Articles
Searching	Database	Web of Science Core Collection (done on 10 September 2022)	
	Main query	TS = ("green mobility" OR "green transport*" OR "sustainable mobility" OR "sustainable transport*" OR "renewable mobility" OR "renewable transport*" OR "smart mobility" OR "smart transport*" OR "intelligent mobility" OR "intelligent transport*" OR "mobility as a service" OR "transport* as a service" OR "mobility-as-a-service" OR "transport-as-a-service" OR "mobility service*" OR "transport* service*") AND TS = ("ecosystem*" OR "joint* creation" OR "joint value" OR "co-innovat*" OR "co-creat*" OR "co-evolut*" OR "co-specializat*" OR "coopetition*" OR "co-production*" OR "coordinat*" OR "collaborat*")	2245
Screening	Publication timeframe	1 January 2002 to 31 December 2022	2146
	Language	Only articles in English	2119
	Document types	Articles, reviews or early access (peer-reviewed documents only)	1299
	Title and/or abstract assessment	Removed articles that were not primarily intended to address, discuss, or answer research questions related to innovation ecosystem initiatives to promote sustainable mobility	863
	Full-text retrieval	Document in PDF format downloaded from the publisher's website	760

In this paper, we use an LDA model with Gibbs sampling. This model uses convergent iterative processes to compute the optimal probability distributions of words within topics and topics within documents. We chose this method because of the moderate size of our corpus and its proven effectiveness in several previous studies. The specifics of the LDA algorithm are well documented in [66]; for the sake of brevity, we do not repeat them here. Instead, we focus on the results produced by this model. The LDA model generates two matrices: the ϕ (phi) and β (beta) matrices. The ϕ matrix represents the probability distribution of words within each topic, thus characterizing topics by their lexical composition. The β matrix, on the other hand, provides the distribution of topics within each document, revealing the frequency with which each topic is represented. These matrices are essential to our analysis because they offer a comprehensive view of the thematic landscape of the dataset. The ϕ matrix allows us to understand the specific vocabulary that defines each topic, while the β matrix helps to quantify the presence and importance of these topics in different documents. This dual perspective is crucial for our quantitative assessment of thematic trends and patterns, which forms the basis of our subsequent analyses and interpretations. The optimal number of topics ($k = 10$) was determined through cross-validation and perplexity analysis, applying the Elbow method after testing several LDA models with different parameters.

The optimal number of topics was determined by a two-stage perplexity analysis using the Elbow method. Using the topicmodels package in R (version 4.2.1), 75% of the corpus was allocated to model training and 25% to testing. Perplexity was first estimated for a wide range of topic solutions (2, 3, 4, 5, 10, 20, 30, 40, 50, 75, 100, and 200 topics) to identify the likely optimal range. A second, more detailed analysis was then performed for 2, 4, 6, 8, 10, 12, 14, 16, 20, 30, 40, and 50 topics. The resulting curve suggests that the model's fit gains stabilize around ten topics. Finally, the solutions containing 9, 10, 11, and 12 topics were compared through qualitative semantic evaluation and expert discussion. The ten-topic solution offered the most coherent and interpretable representation of the

corpus and was therefore selected. The implementation of LDA used full-text documents, Gibbs sampling, 1000 iterations, a burn-in period of 200 iterations, $\alpha = 50/K$, and $\beta = 0.1$.

After running the LDA, we began the post-processing phase. The main objective of this phase was to tag the topics. To do this, we examined the word distribution across topics and analyzed the titles and abstracts of the most representative articles for each topic. Representative articles are those most likely to address a specific topic. We evaluated our labeling results with domain experts, as recommended by previous studies [67,68]. The semantic validity of the identified topics was assessed by four external experts, including two specialists in innovation ecosystems and two specialists in sustainable mobility, each affiliated with different universities and countries. First, each expert independently reviewed the ten topics based on the highest-probability keywords, representative documents, and preliminary topic labels proposed by the research team. The experts were asked to evaluate: (i) the adequacy and clarity of the proposed topic labels, (ii) the semantic coherence of the topics, and (iii) the appropriateness of assigning topics to higher-level taxonomy categories.

To support a systematic assessment, a structured evaluation template was used to record the experts' comments, suggestions, and disagreements. Following the independent assessment phase, the experts participated in a joint discussion session with the research team. Cases of disagreement regarding topic labels or category assignments were reviewed collectively and supported by re-examination of representative articles and keyword distributions. Topic labels and category definitions were refined iteratively until consensus was reached among participants. The resulting taxonomy was subsequently reviewed by an additional specialist in transport transformation, who confirmed its overall coherence and practical relevance.

Based on the results obtained for each of the 10 topics, it was possible to identify the main research themes related to sustainable mobility and innovation ecosystems. After defining the headings for each topic, a hierarchical cluster analysis was used to create a dendrogram of the topics in relation to the documents. Analysis of the groups within this dendrogram led to a proposed taxonomy derived from the literature on SM-IE. This taxonomy was interpreted and validated by a transport transformation specialist. Furthermore, a social network analysis was conducted to examine collaborations between authors within the three identified categories.

4. Results and Discussion

4.1. Topic Definitions

This section presents the analysis of the 760 articles selected after the selection phase, using a topic modeling approach. Based on the analysis of the most frequent words and the interpretation of the titles, abstracts, and, in some cases, the full text of the most representative articles for each theme, titles were proposed for each topic. The definitions of these titles are shown in Table 4. The right-hand column indicates the probability of occurrence of the topic. For example, topic 8 is the most frequent, appearing in 112 articles (14.7%). Conversely, topic 3 has the lowest probability of occurrence (5.5%) in our database.

Topic 8 addresses the “public initiatives and policies” of local and regional authorities and public bodies regarding the strategic development of a long-term transport system [69] and new approaches to land-use planning and sustainable mobility [70,71]. It examines the governance structure of these authorities and the policy instruments that promote the orchestration and coordination of practices in support of sustainable urban development [72,73].

Table 4. Proposed titles for each topic.

Topic	Title	%
Topic 8	Public initiatives and policies	14.7%
Topic 7	Vehicular communication and security systems	12.1%
Topic 5	Integration and alternative means of transport	12.0%
Topic 9	Predictive models	11.4%
Topic 4	Intelligent transportation system	11.3%
Topic 6	Smart traffic control	10.3%
Topic 2	Optimizing passenger transportation	9.7%
Topic 10	Sustainable mobility system	6.7%
Topic 1	EV battery and smart grid integration	6.2%
Topic 3	Optimizing supply chain and logistics	5.5%

Topic 7 deals with “vehicular communication and security systems”. The wireless communication environment makes networks vulnerable to various cyberattacks that affect overall communication performance and traffic flow [74,75]. This topic presents solutions to mitigate these attacks and enhance network resilience, including new communication models that are alternatives to the conventional TCP/IP protocol [76–78]. These communication protocols are essential for promoting effective coordination and communication between vehicles, minimizing message collisions [79], and ensuring message integrity and sender authenticity [80].

Topic 5 (“integration and alternative means of transport”) presents research that deals with alternative and more sustainable modes of transport, such as the use of public mass transit [81], new mobility schemes built and promoted in collaboration with public health and urban planning professionals to increase walking and cycling [82,83], the importance of coordination between car-sharing operators and public transport agencies [84], the introduction of electric-assist bicycles as a substitute for cars [85], the strategy of bike sharing and access to reduced fares on various services [86], suggestions on how to integrate the elderly and disabled into public transport [87–89] and the discussion of transport and land-use policies that have made car use slower, less convenient and more expensive [90].

Topic 9 focuses on “predictive models.” To meet the requirements for vehicle safety and intelligence, it is necessary to develop technologies capable of identifying, detecting, and tracking obstacles (pedestrians, vehicles, and other objects on the roadway) and mitigating the adverse effects of visual-field blindness for safe driving [91–95]. These technologies are essential for the development of autonomous vehicles and driver assistance systems. Furthermore, this theme addresses the development of reliable object tracking methods, which are important for intelligent transport monitoring [96].

The “intelligent transportation system” (Topic 4) emerged with the development of 5G-ICN networks, the Internet of Things (IoT), and service-oriented architecture (SOA), among other technologies, which have enabled the virtualization, control, and real-time management of data to address the complexity of service logic execution while creating value for end users [97,98]. The interoperability of transportation service systems helps facilitate decision-making and improve the efficiency of these services [99]. Electromobility, for example, through the IoT, enables collaboration among various stakeholders, from manufacturers to energy market participants, to create advanced electric mobility services [100].

Faced with increasing congestion on urban roads and the development of autonomous and connected vehicles, new practices are needed to regulate traffic [101]. Thus, Topic 6 (“smart traffic control”) addresses practices aimed at optimizing vehicle speeds and coordinating traffic light synchronization on a main road [102–104]. In addition to these practices,

others are also examined to implement an integrated control strategy, such as the use and measurement of on-ramps, to improve traffic flow and service quality [101,105].

Topic 2 deals with “optimizing passenger transportation.” Planning a reliable public transport service is linked to reducing costs and service times through effective vehicle journey time planning [106–108]. This planning involves seeking better coordination of systems to reduce intermodal passenger transfers, decrease waiting times, and improve the connectivity of transport network services [109,110]. Furthermore, the topic also addresses mobile application-based transportation systems, such as Uber and Didi, which have offered a new means of transportation to users [111].

Urban mobility plays a key role in the complex ecosystems of smart cities. Thus, Topic 10 (“sustainable mobility system”) aims to present a holistic approach to intelligent planning of the urban mobility system, involving a strategic decision-making process with broad participation from various stakeholders [112,113]. This theme addresses government transport policies, including sustainable development and eco-friendly transport practices [16], multimodal transport, cooperation policies and collaboration among mobility system actors [114], as well as the challenges of urbanization and transport infrastructure for the creation of a smart urban transport ecosystem [115].

Topic 1 (“EV battery and smart grid integration”) presents articles dealing with the development of technologies focused primarily on electric vehicles. The topics covered include methods for reducing electricity prices [116], energy efficiency [109], battery charging strategies, and refueling stations [117]. This topic also addresses the transport of renewable energy for passenger cars [4].

Finally, Topic 3 focuses on “optimizing supply chain and logistics.” Innovations benefit the supply chain and how its members, particularly logistics providers and distributors, make joint operational decisions [118]. This topic addresses, for example, the strategies that companies can adopt for the distribution of goods and merchandise throughout the chain, including the transport of empty containers [119] and the use of multimodal carriers [120]. Studies examine the role of logistics providers as orchestrators, financial service providers, and procurement support providers, working with buyers within supply chains and connecting buyers and manufacturers globally [121,122].

4.2. Towards a Theory-Based Taxonomy of SM-IE

Analysis of the 10 topics identified using the LDA technique led to the development of a theoretical taxonomy of initiatives within the SM-IE domain, thus establishing a new mobility paradigm. Topic modeling generated two dendrograms: (1) topics versus documents, and (2) topics versus the most frequent words for each topic. For semantic validation, a group of researchers specializing in innovation and mobility evaluated the results and found the grouping obtained from the themes versus documents dendrogram to be more coherent. Three categories were identified: (i) smart transport systems, (ii) sustainable mobility planning, and (iii) logistics optimization. These categories are illustrated in Figure 2.

The first category aims to develop technologies and innovations for the transportation system at the tactical level. These technologies promote system interoperability through the Internet of Things (IoT) [97] and target the development of autonomous vehicles [91], vehicle-to-vehicle communication and coordination [79], and traffic regulation [101]. They also seek to develop transportation using renewable energy [4,117]. The second category aims to develop strategic actions for smart and sustainable planning of the mobility system, primarily urban mobility [112]. These actions include policies encouraging alternative and more sustainable transportation [70,81]. Finally, the third category concerns resource optimization at the operational decision-making level for the various actors in the supply

chain [118]. These studies aim to establish a reliable public transportation service with reduced costs and operating times [106].

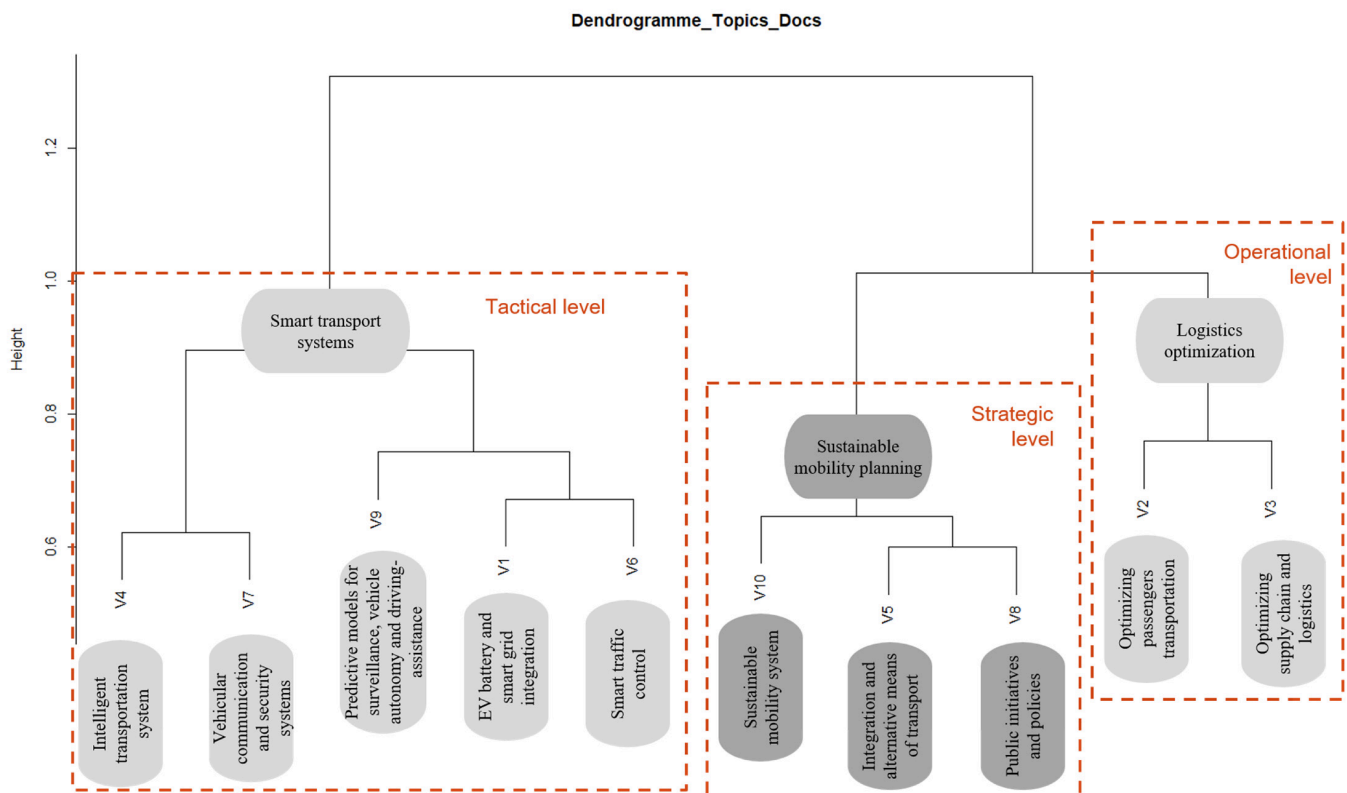


Figure 2. Theory-based taxonomy of SM-IE.

Together, these three categories reveal complementary levels of action within sustainable mobility infrastructure. Sustainable mobility planning focuses primarily on strategic decisions, governance structures, and long-term policy directions. Intelligent transportation systems operate mainly at the tactical level through technologies and coordination mechanisms that enable the delivery of mobility services. Logistics optimization focuses on operational decisions related to resource allocation, service delivery, and efficiency. Together, these categories illustrate the interaction of strategic, tactical, and operational issues within innovation ecosystems for sustainable mobility.

4.3. Analysis of the Collaboration Network

To understand collaborations between authors within the three categories mentioned, a social network analysis was conducted. The 760 articles analyzed include a total of 2637 authors who worked individually or collaboratively. This analysis identified the number of authors who worked in multiple categories of the taxonomy. Only 40 authors (1% of the total) contributed to two or three categories. Most of them (25 authors) focused their research on categories 1 (smart transport systems) and 3 (logistics optimization). This demonstrates that researchers concentrated their efforts on a single category, primarily category 1 (56.2%). Table 5 presents the number of authors and their respective percentages for each category of the proposed taxonomy.

Among the 2637 authors, 5041 relationships were identified. These authors were grouped into 598 working groups. As shown in Table 6, groups composed of three authors were the most numerous (22.2% of the groups, or 133 groups). Only one group comprised 36 authors. The network analysis indicators are summarized in Table 7.

Table 5. Number of authors for each category of the proposed taxonomy.

Category	Number of Authors	Percentage
Category 1	1482	56.2%
Category 2	743	28.2%
Category 3	372	14.1%
Categories 1 and 2	12	0.5%
Categories 1 and 3	25	0.9%
Categories 2 and 3	1	0.0%
Categories 1, 2, and 3	2	0.1%
Total authors	2637	

Table 6. Number of authors for each group.

Group Number	Number of Authors	%	Group Number	Number of Authors	%	Group Number	Number of Authors	%
1	37	6.19%	9	4	0.67%	17	2	0.33%
2	106	17.73%	10	5	0.84%	19	3	0.50%
3	133	22.24%	11	6	1.00%	23	1	0.17%
4	112	18.73%	12	2	0.33%	24	1	0.17%
5	84	14.05%	13	4	0.67%	30	1	0.17%
6	48	8.03%	14	2	0.33%	31	1	0.17%
7	26	4.35%	16	1	0.17%	36	1	0.17%
8	18	3.01%						

Table 7. Summary of network analysis indicators.

Indicator	Value	Interpretation
Authors (nodes)	2637	Total number of authors identified in the corpus
Collaborative relationships (edges)	5041	Co-authorship links
Connected components	598	Highly fragmented collaboration structure
Largest connected component	36 authors	Absence of a dominant collaboration cluster
Network density	0.00145	Very low overall connectivity
Average degree	3.82	Authors collaborated with approximately four co-authors on average
Modularity	High	Strong community formation and specialization
Betweenness centrality	Low overall	Limited number of bridge authors connecting communities
Thematic specialization	98.5% of authors belong to a single category	Low interdisciplinarity across themes

The analysis of author collaborations, based on the data presented, reveals a structure characterized by strong modularity and weak integration among researchers. Collaborations occur primarily within a single article, forming well-defined groups where authors are closely linked to one another but maintain few external connections with other groups. This pattern indicates a fragmented network, typical of scientific fields where partnerships are established on an ad hoc basis and project-specifically. Furthermore, most authors are associated with a specific category, suggesting weak individual interdisciplinarity. Although some researchers appear in multiple articles or groups, they tend to remain focused on a single category. This reinforces the notion of thematic specialization and limited interdisciplinary engagement between different fields of knowledge. Moreover, the network exhibits low centrality of intermediation, indicating a scarcity of actors playing a significant “bridge” role between different categories. Consequently, the circulation of knowledge tends to remain confined to specific groups, hindering the dissemination of ideas between different fields. In summary, these results suggest that the analyzed collaborative network is segmented and specialized, with strong internal cohesion within groups but weak overall

connectivity. This model risks limiting interdisciplinary innovation while reinforcing the in-depth and specialized nature of research within each group.

These results support the proposed taxonomy. The limited number of authors working across multiple categories suggests that the three dimensions identified by the taxonomy correspond to relatively distinct research communities. While specialization contributes to the deepening of knowledge, closer interactions between categories could foster broader learning and innovation within the ecosystem.

5. Conclusions

Given the novelty of the SM-IE phenomenon, the main objective of this study was to develop a theory-based taxonomy of SM-IE to establish this new mobility paradigm. To this end, a literature review was conducted, and 760 articles were analyzed using the LDA algorithm for topic modeling. A taxonomy was thus proposed (Figure 2), composed of three categories: (i) smart transport systems, (ii) sustainable mobility planning, and (iii) logistics optimization.

The proposed taxonomy made it possible to identify the technologies, resources, and knowledge present in the ecosystem, thereby enabling the analysis of the actions adopted by the actors in this ecosystem at three levels: strategic, tactical, and operational. The taxonomy presents the relationships between the different actors in the ecosystem, including the role of: (i) the government in developing policies that promote sustainable mobility; (ii) companies involved in technological developments at various stages of the value chain, such as infrastructure and vehicle development, information flow management, and the provision of logistics and transportation services; and (iii) society, which benefits from these products and services, whether as users of public transportation or purchasers of technologies for private transportation. In this sense, and drawing on a comprehensive study on innovation ecosystems, the taxonomy presented in this study identifies and classifies the key elements that must collaborate for the proper functioning and orchestration of the ecosystem. By enabling the characterization of actions at three levels, as well as the analysis of actors' actions, it provides an ecosystemic approach to sustainable mobility.

The theoretical contributions of this research are threefold. First, this study advances IE theory by extending its application to the emerging domain of sustainable mobility. While IE research has traditionally focused on digital technologies, manufacturing industries, and entrepreneurial contexts, limited attention has been given to sustainable mobility as an ecosystemic phenomenon requiring coordination among heterogeneous actors, technologies, infrastructures, and regulatory bodies.

Second, the study contributes to the sustainable mobility literature by moving beyond descriptive reviews and domain-specific taxonomies. Existing classification efforts typically focus on individual dimensions of mobility, such as transport policies, shared mobility services, logistics systems, or intelligent transport technologies. In contrast, the proposed taxonomy integrates these fragmented perspectives into a unified framework grounded in innovation ecosystem theory.

Third, the taxonomy provides a novel conceptual structure that links sustainable mobility initiatives across three interconnected levels: strategic (sustainable mobility planning), tactical (smart transport systems), and operational (logistics optimization). Rather than merely grouping topics, the taxonomy explains how distinct streams of research contribute to the functioning and orchestration of Sustainable Mobility Innovation Ecosystems. As such, it offers a foundation for cumulative theory development and future empirical studies on ecosystem governance, orchestration, actor interactions, and ecosystem evolution within sustainable mobility contexts.

In terms of practical applications, given the unique dynamics of IEs and the need for appropriate management to enable them to reach their full potential, this taxonomy can help ecosystem actors understand their roles and better align their strategies, particularly those responsible for orchestration. It can also help policymakers and public authorities identify these initiatives in their respective regions and simultaneously design public policies that foster the emergence and maturation of these ecosystems, as well as increased interaction between the three levels (tactical, strategic, and operational). Finally, it allows for self-assessment of emerging SM-IE by providing the key building blocks of this type of ecosystem.

From a managerial perspective, the taxonomy offers a structured framework for ecosystem orchestration and strategic decision-making. Managers, policymakers, transport operators, and technology providers can use this framework to identify ecosystem components that require additional resources, governance mechanisms, or collaborative efforts. By distinguishing between strategic, tactical, and operational levels, the taxonomy helps align the actions of different actors and supports the design of more integrated sustainable mobility initiatives. One limitation of this study is that it was restricted to peer-reviewed articles published in English in the Web of Science database, and only for the year 2022. While thematic modeling is designed to analyze English-language texts, the research could be expanded by exploring other knowledge sources in several other languages. Another limitation is that the proposed taxonomy has only been validated by a few experts and the researchers themselves and has not yet been presented to stakeholders in this ecosystem.

A further limitation is that this study did not explicitly distinguish between developed and developing countries. Consequently, potential differences in institutional contexts, infrastructure, and ecosystem configurations across geographical contexts were not examined. Furthermore, although electric mobility is among the identified themes, this study did not specifically examine electric vehicle adoption ecosystems, which can involve different actors, governance models, business models, and motivations. Future research could explore these dimensions and examine their links with the broader Sustainable Mobility Innovation Ecosystem.

For future work, it is suggested that the collaborations between the authors and their relationships to these three categories be analyzed so to assess their level of integration. This integration is essential for maintaining a sustainable mobility ecosystem, thus justifying the need for further research. It is also suggested that the proposed taxonomy be validated with external stakeholders, as participants in the ecosystem. This will allow for the development of a taxonomy that is relevant to the various actors within the ecosystem.

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