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Review

Autonomous and Electric Vehicles in Urban Living Labs: Smart Mobility Strategies for the Future

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Abstract: The deployment of electric, connected, and autonomous vehicles on public roads presents a significant challenge that can be addressed through previously established frameworks developed globally for implementing these technologies as part of an urban living lab (ULL). This systematic review, based on records from four distinct databases, focuses on projects that have conducted deployments of self-driving technologies in streets within urban environments. The review describes relevant information about various initiatives, including a classification of the stages of development reached according to the urban area covered, safety considerations, and lessons learned for optimal deployment. On-board sensing technology, digital infrastructure, and energy and communication systems emerge as the essential components of a ULL with autonomous vehicles (AVs). A crucial goal for smart cities is ensuring the scalability of large-scale deployments of such ULLs for safe, clean, and future mobility experimentation. This can only be achieved through effective coordination among academia, government, industry, and society to guarantee the successful integration of multiple projects in a unique environment.

Keywords: urban living lab; smart mobility; autonomous vehicles; electric vehicles; intelligent transportation systems; sustainability; service

Citation: Mendoza-Armenta, A.A.; Félix-Herrán, L.C.; Silvestri, B.; Valderrama-Solano, A.C.; Tudon-Martínez, J.C.; Roccotelli, M.; Lozoya-Santos, J.d.J. Autonomous and Electric Vehicles in Urban Living Labs: Smart Mobility Strategies for the Future. *Energies* **2024**, *17*, 5399. https://doi.org/10.3390/en17215399

Academic Editor: Tek Tjing Lie

Received: 25 September 2024
Revised: 23 October 2024
Accepted: 28 October 2024
Published: 30 October 2024

1. Introduction

To develop a smart city, a high degree of coordination among the government, academic institutions, and industry is required to have a high impact on society with sustainable solutions [1]. This is often referred to as a triple-helix model, where public institutions, research organizations, and the private sector cooperate to develop urban sustainability [2]. Thus, research needs to be integrated with real-world applications, which are often rife with systemic obstacles. A good strategy to introduce these kinds of sustainable solutions is the urban living lab (ULL) concept: a specific urban site or district supported by multiple stakeholders who want to promote economic and social development through innovations with sustainable goals, converting them in the ideal place to test and evaluate a product or service that offers an environmental solution for urban spaces [2]. Examples of this approach are demonstrated in ULLs around the world, where their objectives are aligned with the testing and innovation of mobility services, offering sustainable alternatives for the future of transportation systems. These efforts are developed in collaboration with government departments, universities, vehicle manufacturers, and other technological enterprises [3–6].

Along with the smart city concept is smart mobility, one of the main axes supporting the optimization of cities. It refers to initiatives promoting cleaner, safer, and more efficient mobility where transport systems are concerned [1]. Sustainable mobility is consistent with the principle of sustainability, with minimal environmental and cost impacts, while still meeting existing transport needs [7]. Smart mobility encompasses a wide range of initiatives and programs aimed at optimizing sustainable transport systems. The most important and promising applications are related to connected and autonomous vehicles (CAVs) [8] in terms of their ability to process real-time road information, together with revolutionary traffic system management. Autonomous vehicles (AVs) and electric vehicles (EVs) promise to be more efficient, cleaner, and safer options, but regulations and policies are still in progress [9], placing government departments as one of the key intermediaries to develop such ULLs.

An interesting example emerging in this area is the Automated Mobility District (AMD), developed by the National Renewable Laboratory (NREL), which describes it as "a geographically confined district or campus-sized implementation of connected and automated vehicle technology for the purpose of publicly accessible mobility" [10]. An important issue discussed by the NREL is the optimization of traffic operations, which is essential for increasing safety and sustainable energy use if connected and electric AV fleets operate in dense urban environments [11]. At this point, several aspects play a crucial role in the effective introduction of AVs in urban areas: automated SAE International's classification levels [12], the types of vehicles, the routes or services deployed, and intelligent infrastructure supporting smart vehicles. Regardless of the number of differences between AMDs, a consistent characteristic is that they are specific areas with well-defined boundaries where the optimization of traffic operations has been achieved [10,11].

The current review aims to evaluate the latest smart mobility initiatives globally, only considering real-world deployments of self-driving technologies in specific urban areas. AV experimentation depends on socio-technical progress. Trials occur not only in AMDs or ULLs but also in various urban contexts. AV trials can be classified as on-road, testbeds, or precinct experimentation [13]. On-road deployments are projects or services with AVs operating in public spaces within a city, such as Waymo [14], which is quite different from testbeds, where new mobility technologies are tested on closed tracks. The level of maturity for each type of urban deployment is discussed in the Section 3, along with their interrelationships. However, a growing tendency toward future and clean mobility using electric, connected, and autonomous vehicles has gained traction without providing a summary of its larger, system-level integration, referred to in this investigation as a ULL.

With the vast amount of information covering smart city initiatives and the formulation of concepts to identify specific areas with integrated smart mobility projects, a question arises: How have ULLs been implemented when their purpose is related to innovation and automation in mobility? The current systemic review aims to answer this question by analyzing specific areas or districts with a high level of technological development that actively demonstrates what the future of mobility looks like, illustrating how to provide citizens with cleaner, safer, and more efficient transport solutions.

By reviewing ULL initiatives around the world using self-driving technology, this study serves to describe the process of implementing a ULL with AVs, outlining the stages involved and the factors influencing the feasibility of such initiatives. To a certain extent, it can be considered a guideline for success, since lessons from previous strategies are discussed. Other studies have already highlighted the potential of smart cities in the transport domain, identifying the policies, standards, and technology needed to enable a new mobility era [15,16], but only from a theoretical perspective.

2. Materials and Methods

This research followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. Only publications from Q1, Q2, and Q3 journals were used as the basis for further investigation. From the common topics and concepts addressed in the articles, reviews, and technical reports, further research was conducted to compile the most recognized global strategies, highlighting the future of mobility and contributing to scientific publications that communicate these advancements and findings.

To construct the database, three different combinations of keywords were applied using the Scopus database, considering common concepts and words aligned with the previously presented conceptual research question. The search schemes used to find the remaining studies are as follows:

- ALL (automation OR automated OR autonomous) AND ALL (electrification OR electric) AND ALL (transportation OR transport) AND ALL (mobility) AND ALL (smart OR future) AND ALL (vehicles) AND ALL (urban) AND ALL (laboratory OR district OR initiative OR center) AND ALL (test OR testing OR simulate OR innovate OR trialing) AND ALL (shared OR connected) AND ALL (sustainable OR sustainability OR clean) AND ALL (route OR circuit OR corridor) AND NOT TITLE-ABS-KEY (bike OR bicycle) AND NOT TITLE-ABS-KEY (metro OR subway OR train) AND NOT TITLE-ABS-KEY (airplane OR aerial OR airport).
- TITLE-ABS-KEY (automated AND mobility) AND TITLE-ABS-KEY (district OR city) AND TITLE-ABS-KEY (center OR lab OR corridor) AND TITLE-ABS-KEY (vehicle).
- TITLE-ABS-KEY (living AND lab) AND TITLE-ABS-KEY (smart AND mobility) AND TITLE-ABS-KEY (city OR district).

The first combination of keywords attempts to encompass a broad range of studies without exceeding the desired conceptual margin. This initial strategy provides us with a comprehensive collection of studies focusing on on-road smart mobility implementations. The search was conducted on 11 March 2024 and yielded a total of 459 studies. The second combination of keywords was restricted to the desired concepts found exclusively in the title, abstract, and keywords sections. This narrowed the search significantly to 25 documents, which were more representative of the purpose of this review. This refinement was performed on 8 April 2024. The last keyword combination was shorter than the others, maintaining the title, abstract, and keyword search strategy. However, the selected concepts are appropriate for describing initiatives or spaces taking action on smart mobility. This revised strategy was implemented on 22 April 2024, resulting in the discovery of 23 studies.

The search was delimited between 2019 and 2024; the Scopus database showed an increment in research studies published between those years when using the first combination of words, which considered a greater range of publications related to the desired concepts. However, it was necessary to apply exclusion criteria when performing a more in-depth analysis of the database.

Figure 1 shows the selection process in detail that led to the final number of studies included in this review. Database refinement was performed by limiting the search of publications to the English language (n = 392) and to the following document types: articles (n = 223), reviews (n = 128), book chapters (n = 26), and conference papers (n = 15). The reasons for exclusion are as follows:

1. Publications in languages that were not in English (n = 15).
2. Publications that were not an article, review, book chapter, or conference paper (n = 96).

Some of the records that were not analyzed due to language exclusion criteria were mostly written in Chinese. However, relevant initiatives from this country still appear in English publications. A careful analysis was performed on all the databases once the reports assessed for eligibility were identified. Due to the wide range of keywords considered in all the document sections in the first database, it was necessary to analyze the study to identify the purpose of the publication. If it was related to ULLs, any kind of self-driving technology, and cutting-edge technology for mobility being tested in real-world scenarios, it remained under consideration for the final studies included in the review. Taking into account these inclusion criteria, the final exclusion of records was performed as follows:

1. The publication was not related to automated land vehicles (*n* = 37).
2. The publication was more related to greenhouse emissions impact studies than new mobility strategies implementation (*n* = 28).
3. The publication was related to automated districts, but not implemented in a real-life scenario (*n* = 68).
4. The publication was related to social interests (*n* = 42).
5. The publication was related to public policies and regulatory frameworks (*n* = 27).

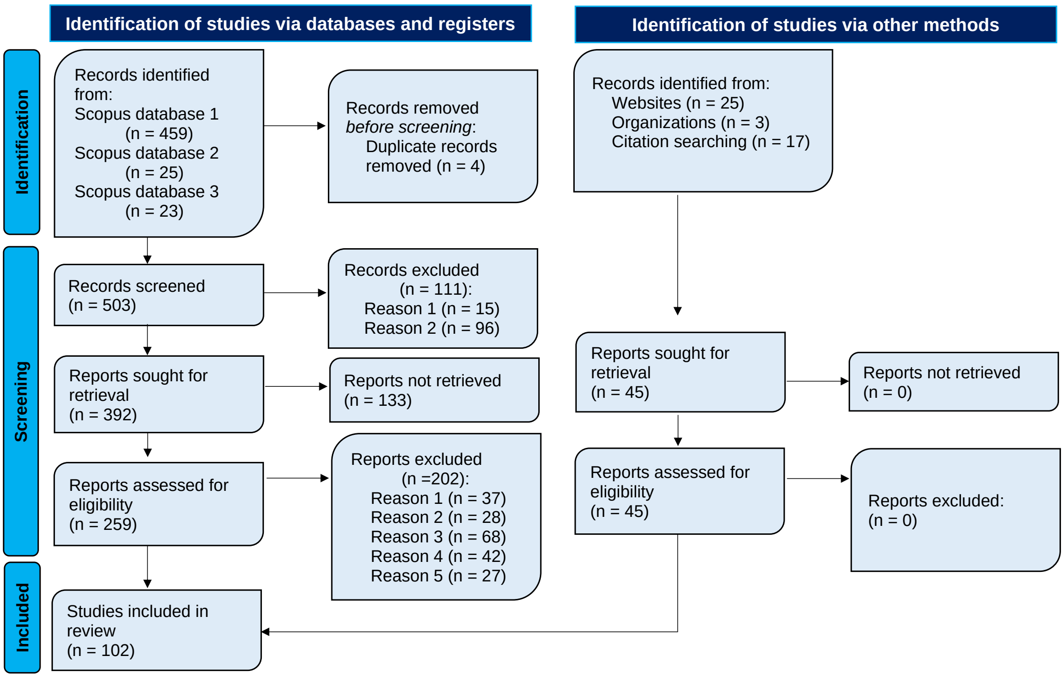

Figure 1. The methodology followed in a PRISMA flow diagram for reporting a systematic review [17].

This review includes 102 studies, of which 57 are from the Scopus database, comprising 49 articles and 8 conference papers. Additionally, 45 external studies were identified and included, 17 corresponding to paper publications, 3 to technical reports from public organizations, and 25 to references from official websites of ULL initiatives or government reports on technology growth and standardization.

3. Results

3.1. Summary

A total of 102 studies were included in this review, most of which are centered on real scenarios with some sort of technology or framework implemented to utilize AV technology. In this context, AV trials are strongly related to an urban ecosystem, as the system being tested interacts with urban infrastructure, socio-nature, and regulations [18]. Studies on smart cities have revealed a strong relationship between city development and cutting-edge information technology, regardless of the stage of experimentation [19]. City logistics face challenges at any stage of economic development. To address urban growth, traffic congestion, and environmental problems, developed countries constantly push initiatives involving AVs and EVs. However, developing countries often remain in the early stages due to internal constraints, leading to a lower distribution of technology and infrastructural adaptation [20]. Following these criteria, Table 1 presents the general characteristics of the studies applying some sort of implementation or initiative to promote the advancement of smart mobility.

Table 1. Records of AV deployments in real-life settings.

Study	Name of Initiative	Location	Classification	Purpose	Impact
[21]	Mcity	Ann Harbor, MI, USA	Testbed	To introduce AVs in community-based trip sharing.	The research center studies advanced mobility, showing that CAVs gain public acceptance. This has led to testing commute trip sharing and new mobility strategies, with large-scale implementation reducing vehicle usage by 92%.
[22]	Smart Nation	Singapore	Testbed	To transform transport services through technology.	The 2017 establishment of CETRAN made Singapore a leader in self-driving technology research and trials, contributing to international standards and large-scale deployments.
[23]	Florida-CAVI	Gainesville, FL, USA	Testbed	To field-deploy CAVs for testing and further development.	The Florida Department of Transportation developed the Florida-CAVI program to enhance traffic operations and document safety benefits for transportation automation. The I-STREET testbed facilitates data collection, analysis, and the distribution of CAVs in a safe demonstrative environment.
[24]	ADVI	Australia	Testbed	To support urban planning with AV technology.	Since 2015, Australia has stood out for AV trial announcements, contributing to international regulations and hosting conventions. AV deployments have sparked strong interest in policy development for Oceania's transition to shared mobility dynamics.
[25]	ITRL	Stockholm, Sweden	Testbed	To make a transition toward sustainable road transport.	The development of living labs and research platforms enables experimentation with automated vehicle solutions and smart mobility. The Automated Vehicle Traffic Control Tower serves as a testbed to explore connectivity, infrastructure, and sensing needs in AVs.
[26]	Innovation District	Las Vegas, NV, USA	Urban corridor	To demonstrate the first self-driving shuttle pilot project in the USA.	From November 2017 to October 2018, a self-driving shuttle bus operated in the Fremont Entertainment District, one of the first fully autonomous systems in real traffic conditions globally. The CAV gained significant public acceptance and project continuity.
[27]	CE-CERT	Riverside, CA, USA	Urban corridor	To evaluate CAVs' energy impacts.	An innovation corridor focused on sustainable mobility was developed. Using cooperative and automated driving technology can achieve a 4% reduction in total energy consumption compared to a scenario with 95.5% gasoline vehicles, 2% electric vehicles, and 2.5% plug-in hybrids.
[28]	Bay Street Innovation Corridor	Jacksonville, FL, USA	Urban corridor	To test and optimize CAVs.	Investigation for safer operations led to the creation of a testbed with CAVs that helped transform the transportation network, optimizing traffic operations and increasing safety within Downtown and South Downtown districts.
[29]	SURTRAC	Pittsburgh, PA, USA	Urban corridor	To create an adaptive traffic signal control system.	The project started as a pilot in June 2012 to manage traffic at fifty connected intersections. It achieved a 25% reduction in travel time and a 40% reduction in wait time compared to average traffic volumes.
[30,31]	Smart City Korea	Sejong, South Korea	Urban corridor	To develop a Cooperative Intelligent Transportation System.	The framework used in the autonomous bus field test proved to be a safe, comfortable, and efficient choice. It employed a cloud-based architecture for Sectionalized Speed Guidance, enhancing energy efficiency.
[32]	Babcock Ranch	Punta Gorda, FL, USA	Precinct	To gain insights into autonomous mobility on demand (AMoD).	The initiative developed an AMoD service to compare its benefits for city travel with conventional vehicles. The results revealed a high AV fleet efficiency, with 70% usage during operating hours. Although the service is no longer available, it inspired other self-driving projects in the state.

Table 1. *Cont.*

Study	Name of Initiative	Location	Classification	Purpose	Impact
[33]	University District AV Transit Circulator	Houston, TX, USA	Precinct	To study AV technology and its potential in public transportation.	The Phoenix Motorcar Zeus 400 battery-electric paratransit shuttle bus, featuring a level 4 ADS, aims to provide first- and last-mile connections to METRO services as part of a pilot project running through 2024 and 2025. In June 2019, an EasyMile EZ 10 Gen-1 vehicle completed around 7500 trips on Texas Southern University's one-mile Tiger Walk.
[34]	Regional Transportation District's	Denver, CO, USA	Precinct	To serve three distinct routes with an automated shuttle.	The AV deployment operated on a one-mile loop in 2019, offering 600 free rides near the 61st & Peña commuter rail station, passing Panasonic's and EasyMile's offices. Although no further deployments were supported by the Regional Transportation District, the pilot provided valuable insights.
[35]	Milo project	Arlington, TX, USA	Precinct	To improve public awareness of AV technology.	Launched in August 2017, one of the first self-driving shuttle deployments in the USA operated in a parking lot between AT&T Stadium and Globe Life Park. The pilot program concluded after serving 740 passengers, inspiring further AV initiatives in the city and nationwide.
[36]	City of Mobility	Hamburg, Germany	Precinct	To be considered the mobility capital with sustainable initiatives.	Eight projects were launched to improve public transport's flexibility, efficiency, and sustainability. One featured an autonomous shuttle in Hamburg's Bergedorf district, which transported up to 12 passengers between stops and homes for three months in 2021.
[35,37]	ELA	Alberta, Canada	Precinct	To test the feasibility of autonomous shuttles in transportation systems.	In Alberta, different projects were developed. One ran between Calgary Zoo LRT Station and Telus Spark Science Centre for 33 days in 2018, serving about 4500 passengers. Another operated in Beaumont for six months in 2019, running fully autonomously in mixed traffic. Both were part of ELA's Electric Autonomous Shuttle pilot program with EasyMile.
[38]	TOPS Laboratory	Madison, WI, USA	Precinct	To improve traffic operations and safety.	With an interdisciplinary focus, initiatives span from database creation to AV implementation. Four concept routes have been designed to test connected and self-driving technologies.
[39]	SOLUTIONSPlus	Nanjing, China	Precinct	To co-develop innovative and integrated e-mobility solutions through living labs around the world.	The development of mobility alternatives in Nanjing is driven by its high population and role as a transportation hub. The city has significantly adopted EVs and tested a self-driving minibus on regional roads in October 2021.
[40]	Rivium Business Park and Central District	Capelle aan den IJssel, Netherlands	Precinct	To provide frequent and flexible transport with AVs.	The Rivium ParkShuttle is unique globally as the only permanent autonomous service in Europe. This cost-effective system autonomously navigates and generates revenue, solving last-mile transport between Kralingse Zoom metro station and Rivium business park.
[41]	Darwin SatCom Lab	Oxford, UK	Precinct	To test self-driving car technology.	Multiple labs for CAV research and development have advanced 5G and satellite communications. A partnership between university research institutions and industry led to a level 4 autonomous shuttle deployment in September 2022 along Norham Gardens, Parks Road, and part of Broad Street, setting the stage for another unit in 2024.
[3]	Smart Columbus	Columbus, OH, USA	ULL	To enable technological solutions to improve mobility, sustainability, and digitization in the city.	The introduction of safe, innovative solutions aims to boost EV adoption. Self-driving shuttles and connected vehicles address transportation gaps, with the Smart Circuit Shuttle providing over 16,000 rides in a year.

Table 1. *Cont.*

Study	Name of Initiative	Location	Classification	Purpose	Impact
[4]	Smart Mobility Living Lab	London, UK	ULL	To accelerate the creation of clean, efficient, and safe mobility solutions.	TRL conceived service offerings through testing, simulation, and innovation to cover all aspects of connected, automated, shared, and electric mobility. This includes testbeds for automation, connectivity, energy, logistics, communication, and decarbonization. The initiative involves multiple projects and global partners, providing shared research, standards development, safety frameworks, and consultancy services for the industry.
[42,43]	OVIN	Ontario, Canada	ULL	To drive and shape the future of the automotive and mobility sector.	Since 2017, Ontario has been developing programs with smart mobility technologies to enhance transportation. In Toronto, the Technology Pilot Zone tests connected, autonomous, and electric vehicles, making it a leader in AV research and industrial policy application.
[44]	Aveiro Tech City Living Lab	Aveiro, Portugal	ULL	To provide new solutions with efficient traffic management and intelligent transportation systems.	Development includes connected infrastructure with a multi-protocol network that classifies vehicles, detects peak traffic times, exchanges collision-avoidance information, and supports comprehensive network data management with third-party integration for self-driving technologies.
[45]	Beijing E-Town	Beijing, China	ULL	To promote collaborative innovation and development in intelligent transportation.	The technological hub has enabled AV testing on public roads and closed sites. The Yizhuang Base has offered nearly 10,000 h of testing for 284 AVs, adapting to various urban traffic scenarios.
[46]	Modena Automotive Smart Area	Modena, Italy	ULL	To develop a regional ecosystem with connected and autonomous mobility.	The living lab in R-Nord, spanning 3 km^2, features smart cameras, sensors, 5G antennas, servers, and a data center, facilitating innovations in sustainability and urban regeneration.
[47]	AV Living Lab	Ljubljana, Slovenia	ULL	To transform the future of mobility with real-life and new mobility solutions.	Diverse pilot programs and deployments promote car sharing, smart mobility plans, and insights into real interactions with self-driving technologies.

3.2. Data Distribution

The included studies have a notable presence in the European Union (EU). In the case of Europe, it is worth mentioning that most of the projects with real-world applications are related to the funding program Horizon Europe, formerly known as Horizon 2020. One of its pillars is based on global challenges and European industrial competitiveness, allowing the intervention of a cluster on climate, energy, and mobility to promote clean, safe, and accessible transport, as well as smart mobility [48]. The EU has made an incredible effort to support harmonization in research and innovation for Cooperative, Connected, and Automated Mobility (CCAM), providing a repository called Connected and Automated Driving (CAD). This repository includes terminologies, regulations, procedures, and action plans for future research, encompassing projects and demonstration activities with AVs across Europe [49].

In North America, ULLs with AVs have a strong presence in the USA. Most of the cities involved in early deployments, as reported in "The Automated Mobility District Implementation Catalog" [11], remain active with new projects or are searching for alternatives. The use of self-driving technology was typically within periods no longer than a year to verify public acceptance and test transport system efficiency. Projects developed in Ohio, Texas, Nevada, and Michigan are frequently documented in automated shuttle deployment studies [10,34,35].

From all the research included in this review, Figure 2 highlights only the studies that mention the implementation of future mobility strategies involving connected, electric, and autonomous vehicles. This does not necessarily mean that the ULL ecosystem is fully developed, but the research provides a framework for urban planning, simulation, experimental setup, or urban testing that could support ULLs' integration in future studies. Figure 3 provides further insights into the records found via databases and registers by classifying each study geographically and by the level of maturity in urban deployment contexts. Records identified through other methods were used to enrich the bibliography of this study and to complete Table 1 presented earlier, classifying them according to the definitions and characteristic criteria from previous ULL studies [2,50].

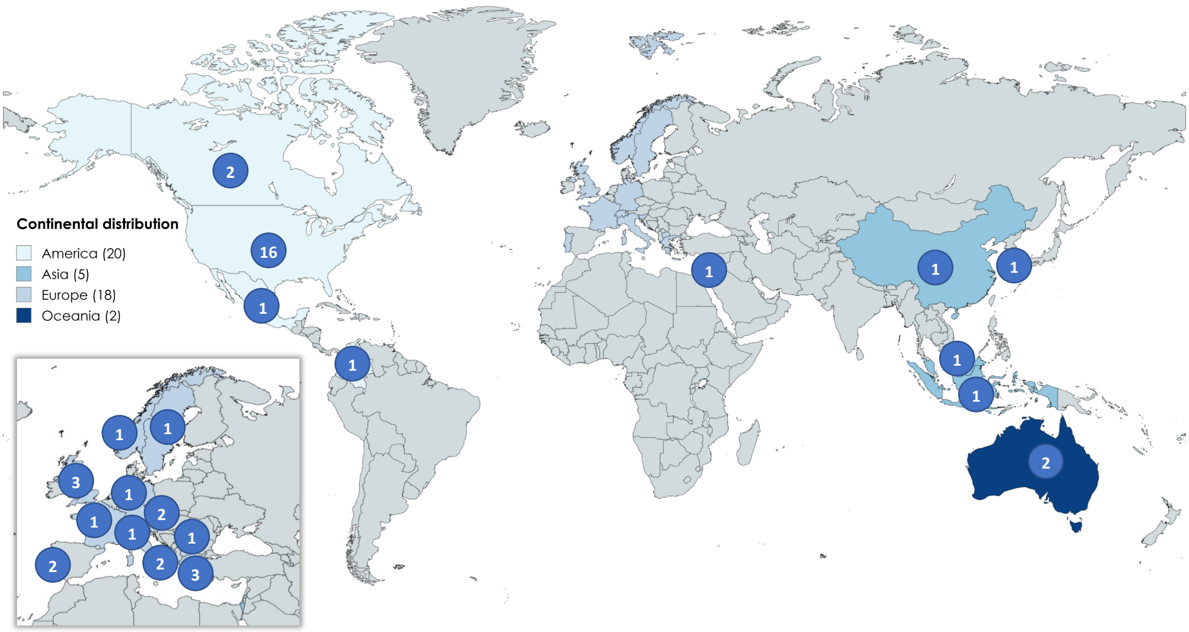

Figure 2. Worldwide records' distribution from the Scopus database with studies focusing on ULLs with the use of automated mobility in conceptual or experimental applications. Circled numbers indicate the total number of studies in each country, the sum of studies for each continent is also shown in the map's legend.

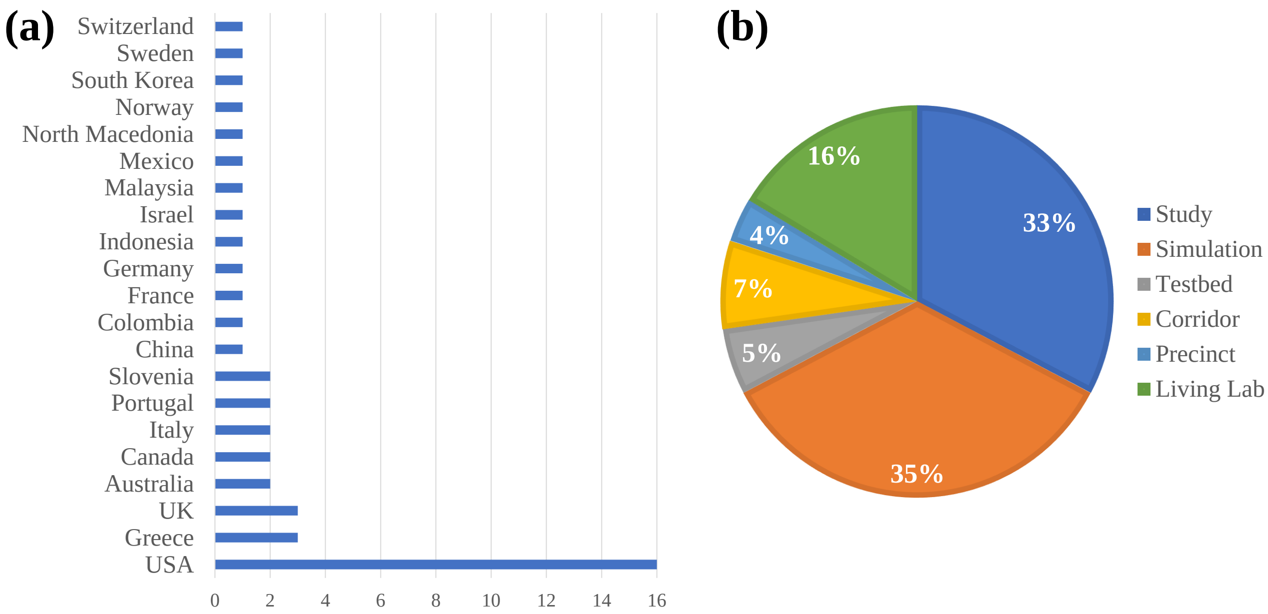

Figure 3. Records' classification for the Scopus database: the bar chart (**a**) shows the number of records found in each country, while the pie chart (**b**) displays the type of urban deployment for each record based on its own criteria.

Regardless of the continent where some cities are located, it is common to find studies on the concept of ULLs or actual deployments of technology to enhance mobility in communication, energy, and infrastructure without yet delving into the real-world implementation of AVs. This is the case for Latin American countries like Mexico and Colombia [1,51]. In Asia, a contrasting situation occurs, where some countries are actively implementing or studying the impact of urban deployments using self-driving technologies to improve mobility [30,52,53], while others use a living lab approach to address problems within the broader concept of a smart city [54]. This situation places China and Singapore as leaders on their continent, but special attention should be given to Japan, where the strong presence of Toyota Corporation and a dedicated institute for research in this area drive urban deployments related to battery-electric vehicles for autonomous mobility [55]. In Oceania, Australia and New Zealand are the representatives of such projects, promoting their adoption with the Australia & New Zealand Driverless Vehicle Initiative (ADVI) [13,24].

Considering that a ULL is an environment with multiple projects taking action in real-life settings, it is important to distinguish that proper implementation should include user involvement at any phase of development, as it aims to learn and experiment alongside the community [50]. In the context of EV and AV deployment, these characteristics rule out the majority of the records found in the database, but they help establish a reference framework for what can truly be considered a ULL with AVs. Describing the characteristics of a ULL can be extensive and vary depending on the projects and strategies of each ULL. Table 2 shows specific projects of the ULL initiatives described in Table 1 to understand the variety of action plans with AVs on public roads and how they serve specific purposes.

Table 2. Projects of AVs on public roads as part of ULL initiatives.

Flagship Project	Space	Service	Benefits for Community	Operating Years
'Smart Circuit and Leanden Leap from Smart Columbus https://smartcolumbus.com/projects/self-driving-shuttles (accessed on 20 August 2024)'	1.6-mile route around the Scioto Mile in downtown Columbus.	First-mile/last-mile mobility and food delivery service.	Service to 16,062 passengers.	2018–2021.

Table 2. *Cont.*

Flagship Project	Space	Service	Benefits for Community	Operating Years
'Area X.O from OVIN https://areaxo.com/smart-cities-and-infrastructure/ (accessed on 20 August 2024)'	1866-acre facility to develop, test, demonstrate, and implement smart city technologies.	Customized test cases and scenarios.	Open-source environment for data collection and Low-Speed Autonomous Shuttle deployment.	2019–present.
'GATEway from Smart Mobility Living Lab https://trl.co.uk/projects/gateway-project (accessed on 20 August 2024)'	3.4 km route around the Greenwich Peninsula.	Automated urban deliveries, remote teleoperation demonstrations, and automated vehicle systems for traveling.	Development and validation of new mobility solutions.	2016–2018.
'Smart Dynamic Area from Modena Automotive Smart Area http://www.automotiveacademy.unimore.it/site/home/masa.html (accessed on 20 August 2024)'	Smart Model Area through the city of Modena along a dedicated area for self-driving experimentation	ADAS testing.	Control and standardization in digital revolution for mobility.	2017–present.
'TRACE from AV Living Lab https://trace-horizon.eu/slovenian-pilot/ (accessed on 20 August 2024)'	11 km of roads.	Urban logistics and last-mile delivery.	Significantly reduce CO_2 emissions, cut down vehicle mileage, and improve the efficiency and reliability of delivery service.	2023–2026.
'Autonomous and Connected Mobility from Aveiro Tech City Living Lab https://www.navya.tech/en/first-deployement-in-portugal-of-a-navya-autonom-shuttle/ (accessed on 20 August 2024)'	Intra-urban route with three stops.	Autonomous shuttle testing using the V2X communication infrastructure of the zone.	Tech week to make citizens take part in technological and cultural activities.	2022.
'Yizhuang Base from Beijing E-Town http://www.beijingetown.com.cn/2023-05/15/c_886139.htm (accessed on 20 August 2024)'	Demonstration zone operated by Beijing Innovation Center for Mobility Intelligent (BICMI).	Testing for unmanned delivery vehicles.	290,000 km and nearly 10,000 h of closed test site.	2023–present.

3.3. Trends and Technological Advancements

Smart mobility implies the introduction of multiple technologies. In developing an autonomous and electric vehicle, several factors play crucial roles. However, to introduce it into an ecosystem where it can be connected and exchange information while interacting with real traffic, more considerations arise. Over the years, specific frameworks and standards have been proposed to indicate which types of technology are related to an automated driving system (ADS) and where the line of advancements is pointing. Nevertheless, it depends on the purpose of each city or district implementing these kinds of initiatives.

In Figure 4, the convergence of multiple technologies in a ULL is highlighted. Specific combinations result in the application of cutting-edge technologies across various sectors. The main idea is to demonstrate how ULLs implementing AV projects depend on the appropriate technological integration of three systems (transport, communication, and infrastructure) that continuously interact during the implementation of services or testing purposes with self-driving technologies. Physical components acting as sensors in the vehicle and in urban spaces have wireless communication with servers that create the roadway digital infrastructure [56].

Regarding transportation technology testing, hardware components are crucial for sustaining innovation in transportation. Their application, along with control algorithms, supports the development of ADSs and intelligent transportation systems (ITSs). The AMD Implementation Catalog incorporates a total of 10 sites, describing them as early deployment districts with AV technology. For instance, the University District AV Transit Circulator in Houston, Texas, and the Regional Transportation District's in Denver, Colorado, explore first-mile/last-mile solutions with an ADS. The Innovation District in Las Vegas, Nevada, explores some of the hardware components, including LiDAR sensors, cameras at the front and rear of the vehicle, inertial motor units (IMUs), and a global positioning system (GPS), providing fixed points of location in all operating sites [10,11]. The Center for Environmental Research and Technology (CE-CERT) has been developing on-board intelligent systems through a dedicated research group focused on innovation in transport, particularly through the application of sensors such as LiDARs, cameras, and radars, as previously mentioned. Additionally, if wireless communication devices are equipped to enable vehicle communication, the result is CAVs [27]. Similarly, the Integrated Transport Research Lab (ITRL) is considered a hub for innovation in intelligent transportation systems, developing large-scale automated platforms and testing the first 5G network in Sweden [25].

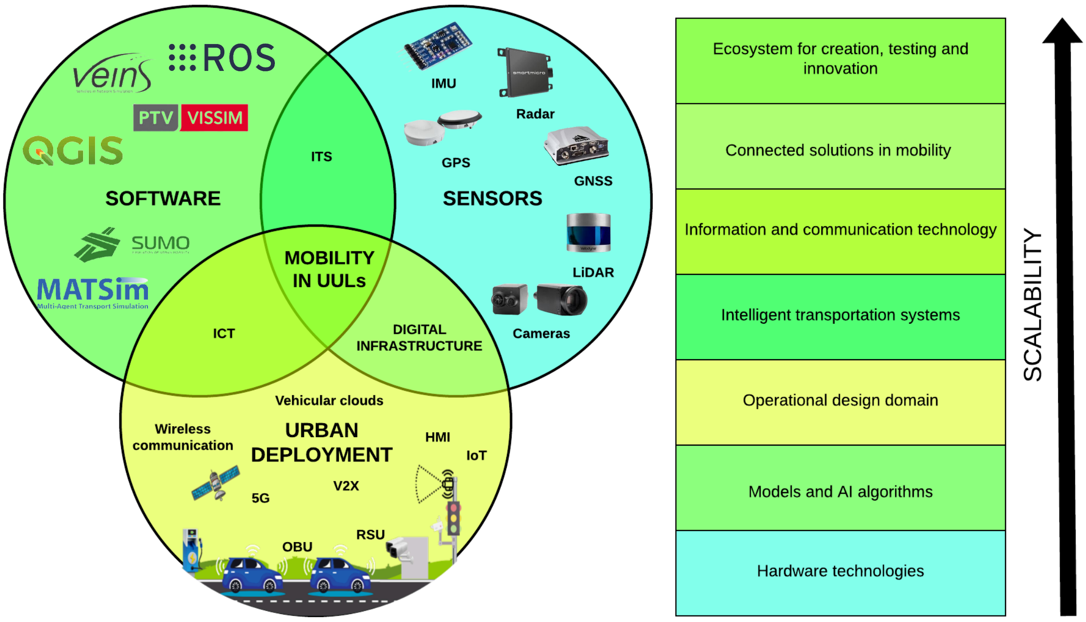

Figure 4. Interaction of technologies to support testing of connected, electric, and autonomous vehicles in a ULL environment.

Digital technologies play a crucial role in the innovation of products and services. Specifically, 5G networks enhance CAV functionality, extend coverage, and provide high-definition georeferencing [57]. A revision with evidence from the Smart Columbus projects identified high-tech and innovations as playing a crucial role in the growth of smart cities. An interesting initiative described as an emerging technology is the Connected Electric Autonomous Vehicle (CEAV), a testbed in specific areas of Ohio to evaluate the adoption of AV technology [58]. In 2019, Smart Columbus published a final report of the CEAV Test Plan, along with another called the CEAV Operational Concept for the Smart Columbus Demonstration Program, identifying real-time data transmission and software capabilities in the vehicles as crucial features to reach level 4 automation. The Smart Nation initiative in Singapore has a general vision of service digitization, but the government has ensured transformation in every possible area, evolving into a digital government, economy, and society [22]. As part of this, Nanyang Technological University developed a Mobility-as-a-Service (MaaS) testbed to provide an integrated mobility solution. This includes not only public transport digitization but also the deployment of an autonomous shuttle service between the university residence halls and the use of dynamic routing technology [59].

The promotion of autonomous EVs goes toward the development of smart cities, directly contributing to smart mobility strategies. Implementing this type of technology in

ULLs requires various procedures and extensive validation before the public can interact with an autonomous EV on public roads. At this point, simulation tools play a crucial role in gaining insights into traffic patterns, travel demand modes, and other mobility contexts of the study area [60]. The simulation of traffic models is essential, as it opens the investigation to any country trying to contribute to the field of AVs' impact. Using the MATSim software, a study was able to evaluate traffic congestion in the Jerusalem Metropolitan Area by introducing shared AVs, making them an attractive option for public transportation in the city [61].

Based on the high-quality requirements to test CAVs, simulation environments serve as a faster means of experimentation prior to a physical testbed implementation if appropriate control algorithms and vehicle dynamics are introduced in the simulation [62]. The Information and Decision Science Lab's Scaled Smart Digital City is a 1:25-scaled robotic testbed to investigate CAVs' impact on safety and transportation efficiency and is capable of replicating real-world traffic conditions [63,64]. It also implements digital simulations to complement the results of its model. Additionally, simulations allow for the interpretation of results related to energy consumption, optimal speed range, and pollutant emissions within the vehicle-to-everything (V2X) proof of concept for CAVs using eco-drive controllers [65,66].

When AVs are mentioned, EVs are often included in the concept, although they are not strictly related. Initiatives aiming for a positive impact on the environment often bring together e-mobility and self-driving technology on a large scale. In a living lab, innovations for a sustainable urban concept vary depending on the mobility approach taken, but ultimately, they serve the goal of emission reduction [67]. For example, initiatives in Nanjing focus on the development of new energy vehicles to reduce the impact of greenhouse gas emissions and improve traffic capacity for efficient road control using high technologies [39]. Europe has been considering commercial customers' requirements for CAV development. The Smart Mobility Living Lab in London offers assistance with research in a real-world testbed and its digital twin, allowing the validation of the performance of physical systems and components in virtual environments, simplifying the process before real-world testing is implemented [4]. Germany is another country characterized by strong projects related to automated mobility in living labs. The Hamburg Electric Autonomous Transportation (HEAT) project developed an autonomous shuttle to transport up to 10 passengers in mixed traffic conditions [36]. Additionally, the RealLabHH in Hamburg's Bergedorf district implemented an on-demand service with shuttle vehicles operating in automated mode within predefined areas. An on-board human–machine interface (HMI) displayed a street map, traffic surroundings, and a control panel [68].

3.4. Support Network

The network of a ULL is characterized by alliances that include universities, the government, and industry partners. For example, Transdev Group, a company operating public transport, has been involved in two different projects with AVs in Florida. May Mobility, a company focusing on autonomous technology, has participated in both the Smart Columbus and RAPID projects in Arlington, Texas, to deploy AVs in those districts [10]. Most of the initiatives in the USA are characterized by strong government support, sometimes with the help of federal departments, but also by universities procuring the latest advancements and conducting in-depth investigations. Notable universities include the University of Houston, the University of Michigan, and the University of Florida, to name a few [11].

The Smart Columbus initiative is supported by the U.S. Department of Transportation. Specifically, in the CEAV project, they relied on EasyMile's product system [11]. A large group of partners and stakeholders are involved in this initiative, with the City of Columbus, Michael Baker International (infrastructure USA-based company), and The Ohio State University playing crucial roles in testing responsibilities [58]. In Riverside, California, the investigation of shared, electric, connected, and automated operation levels, along with its data collection plan, is sustained through the collaboration of various state universities and the U.S. Department of Transportation, with matching funds from various sources [27].

Figure 5 denotes how the integration of multiple stakeholders plays a crucial role in these kinds of initiatives. Academia, industry, public bodies, and users make the execution of projects possible. This type of unique collaboration in Sweden's research labs has enabled the merging of inputs from all sectors [25]. Navya and EasyMile are two vehicle manufacturers that are deeply involved in projects with ULLs in Hamburg, Germany, providing them with low-speed autonomous shuttles [68]. To understand the necessary level of synergy in a ULL, the Smart Mobility Living Lab in London, one of the greatest initiatives around the world, needs government support via the Centre for Connected and Autonomous Vehicles and InnovateUK, along with a consortium including TRL, Cisco, DG Cities, and other partners [4]. Such strong partnering and networking have allowed it to become the most advanced center in CAV technology development.

Initiatives that are part of consolidated national growth plans can be directly managed by the government. Such is the case with the Smart Nation Group, a division of the Singapore government within the Prime Minister's Office and overseen by the Ministry of Communications and Information [22]. Specific projects developed within the Smart Nation vision can work independently and expand their network. For example, the MaaS testbed at Nanyang Technological University required an alliance with JTC and SMRT corporations, as well as mobility partners like Continental and 2getthere, to create a ULL [59]. This is what is called a multi-stakeholder ecosystem. There are other cases where initiatives are driven by international programs to achieve sustainable development goals. One example is SOLUTIONSplus, which works with the UN Environment and the International Energy Agency [39]. However, the ULLs that are part of this initiative can grow independently, depending on local support or additional projects involving self-driving technology; such is the case in Nanjing and Hamburg [68,69].

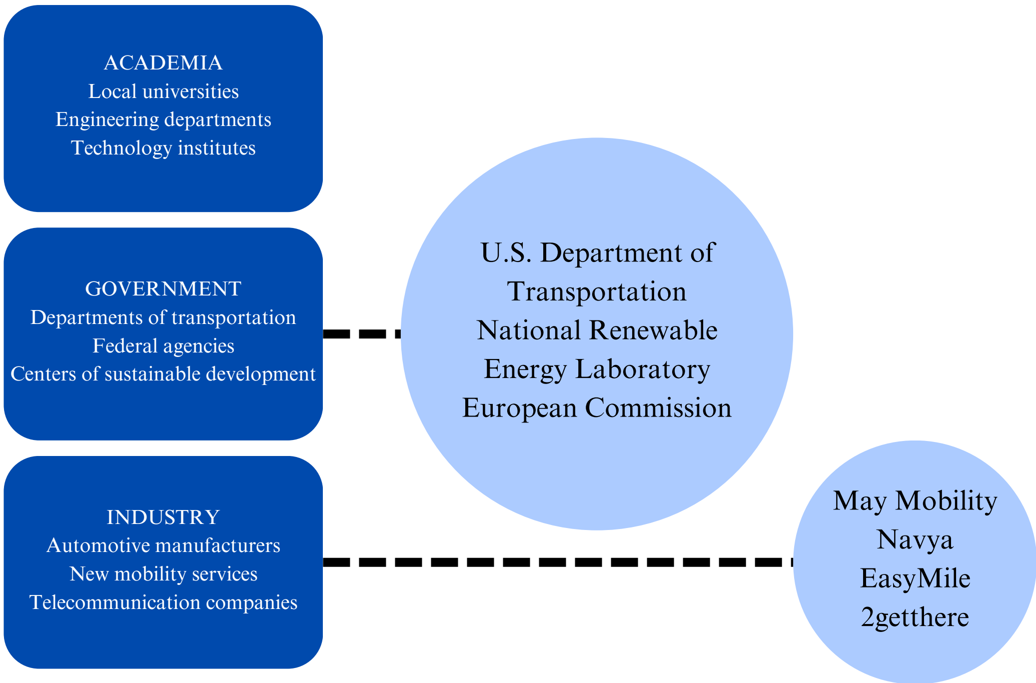

Figure 5. Principal stakeholders found in the literature.

3.5. Contributions

ULLs with AVs have a broad impact on sectors related to smart mobility, providing societal benefits, improvements in vehicle energy consumption, enhanced traffic control, and safer operations. These contributions are evident in any urban deployment of AVs, but the discussion about how the integration of automated mobility solutions within a unified ecosystem like a ULL creates a greater impact remains unexplored. On-road self-driving technologies have proven to be a viable solution for first-mile/last-mile mobility challenges. In general, the public describes the experience positively, and initiatives in Texas, Ohio, and Florida offer more inclusive transportation alternatives, allowing wheelchair users easy access to the vehicles. Additionally, zero-emission strategies using EVs have accumulated millions of miles while the service is active [11].

In Figure 6, it is stated how the level of development for each initiative can potentially impact technology, infrastructure, policies, and society for smart mobility strategies. Independent deployments are referenced as on-road trials of AVs, with Google's Waymo pioneering automated ride-hailing services since 2018 with great success [70]. Vehicle manufacturers, digital mobility companies, and other tech enterprises lead on-road tests to disrupt transport services and support ADS development, bringing cutting-edge technology with vehicle performance at any legally authorized location. However, these efforts are usually associated with motivations centered on constructing new business models in the private sector [13]. The initiatives presented in Table 1 have a positive effect on traffic operations, energy consumption, and safe mobility, with quantitative results demonstrating the significance of each type of urban deployment. Although all have a strong impact on specific issues, a qualitative analysis suggests that the potential of ULLs is greater, as they represent an ecosystem where such initiatives could be part of a supported network as they are continuously implemented, improved, and scaled up.

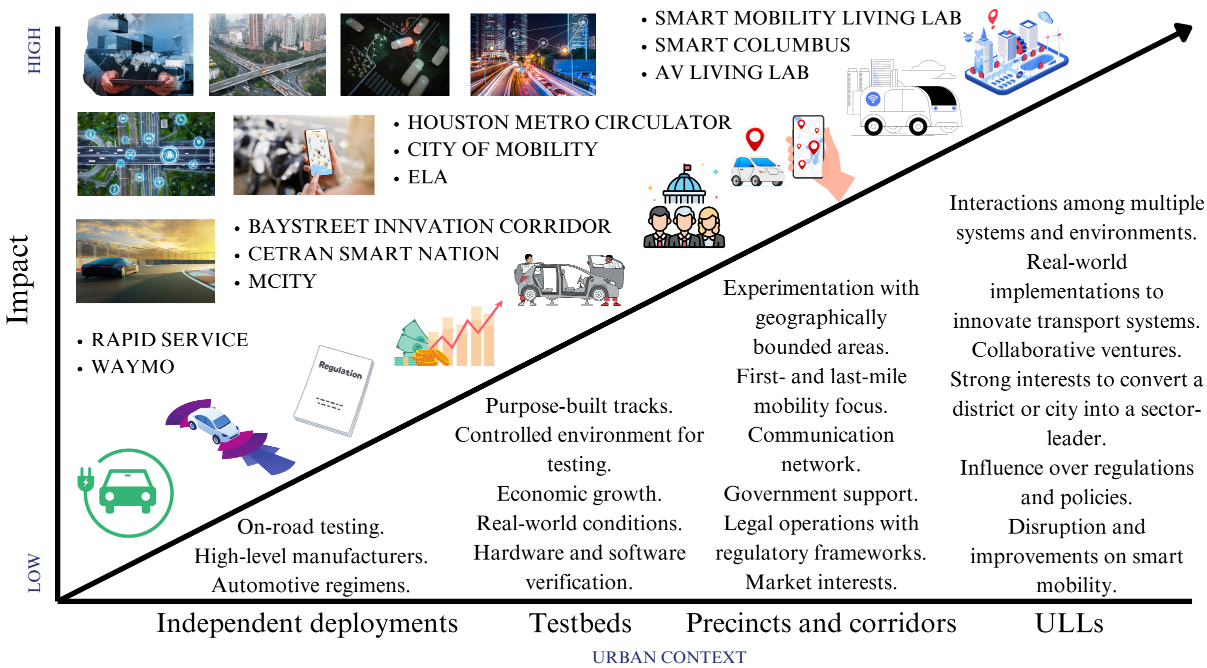

Figure 6. Overall impact on the deployment of electric and autonomous vehicles in different urban contexts.

Diverse cities in the USA are characterized by the presence of AVs in some form of implementation. Waymo One is the first service of autonomous trips providing a sustainable, efficient, and safe option for transportation in San Francisco, Phoenix, Los Angeles, and Austin [14]. San Francisco is a city with high-cost parking areas; a study with data on San Francisco's downtown central business district demonstrated more efficient use of parking spaces and a traffic congestion reduction when AVs performed drop-off and pick-up mobility services in the area [71]. The adoption of AVs for shared mobility services has been envisioned by companies with on-demand transportation services (Uber, Lyft, DiDi) to consider automation in vehicles as a viable option. Nevertheless, a study with data on preferences for shared AV services in New York revealed that ride-pooling options are usually avoided [72].

Testbeds are controlled environments where AVs can be deployed for testing purposes, featuring necessary urban elements to simulate real conditions within closed areas. Although testbeds represent a preliminary stage of implementation before deployment on public roads, research and development play a crucial role in preconfiguring technology for real conditions. These initiatives typically involve collaboration between academic institutions and the automotive industry [13]. The Mcity initiative provides a full-scale outdoor laboratory to test the performance and safety of CAVs, V2X communication, 5G networks, and state-of-the-art instrumentation and sensors for automation. This public–private partnership, led by the University of Michigan, brings innovation to mobility [73]. The Centre of Excellence for Testing & Research of Autonomous Vehicles—NTU (CETRAN) in Singapore has been open since 2017. While it does not develop new technologies, it applies research in collaboration with Nanyang Technological University to ensure the correct operation of ADSs according to international standards [74]. The NTU-JTC-SMRT MaaS Testbed of Smart Nation highlights specific points of success and valuable contributions. Firstly, the digitization of transport allows data to be shared in real time with the government. Secondly, it opens a new market with a proven business model and regulatory readiness. Finally, the ULL approach is centered on users, enabling continuous feedback and adaptations in subsequent iterations [59]. A study in China revealed that gender, age, educational background, income level, and frequency of use are factors in determining the level of acceptance of self-driving technologies [69].

Real-world data collection, simulation studies in shared mobility scenarios, experiments, and early deployments with CAV technologies conducted in Riverside estimated better energy efficiency in ride-hailing services using EVs. They also predicted a prevalence of shared AV fleets of 60% over the use of private cars in scenarios with dominant and high levels of penetration of these technologies [27]. Self-driving technology is not just limited to passenger mobility services: the freight transport system also represents a large scale of operations. A significant number of automated technology implementations in Sweden are related to driverless trucks. Some studies indicate a cost reduction of around 30–40% per ton-kilometer, amounting to SEK billions per year, with the introduction of driverless trucks in logistic hubs [75]. The introduction of CAVs impacts multiple areas, particularly in the emissions of greenhouse gases and other pollutants. Using the California Statewide Travel Demand Model framework, it was found that, in general, CAV penetration could increase vehicle miles traveled. For this reason, it is important to take action in implementing zero-emission vehicle (ZEV) policies. An analysis of dynamic shared-ride systems within an Internet of Things (IoT) network demonstrated that CO_2 emissions could be reduced by 15.16% to 19.13% if one-tenth of the riders adopted ride-sharing services with AVs in Sunway, Subang Jaya, Malaysia [53].

A more extensive implementation occurs in precincts or urban corridors, where similar synergies are sustained but with projects having a longer scope, predominantly focusing on first- and last-mile mobility solutions in public areas such as business parks, university campuses, or other geographically bounded urban zones [13]. Regulations and policies play crucial roles in the successful real-world implementation of AVs in precinct tests and urban corridors. Government agencies are involved in ensuring legal operations and providing resources for logistics, infrastructure, and funding. The ELA project has deployed up to 11 autonomous shuttle services across Canada, each varying in route, passenger capacity, and operational days. These deployments have significantly advanced autonomous shuttle technology, supported by various universities and government departments of transportation in each city [37]. The Innovation Corridor in Jacksonville has implemented projects to enhance IoT devices' value, expand mobility options with autonomous shuttles, and develop smart infrastructure, succeeding through partnerships among academia, industry, and government [76].

ULLs implementing AVs enable testing across various self-driving systems, offering comprehensive technical, legal, and societal solutions. This collaborative venture resembles precincts or urban corridors but operates at a higher level, transforming transportation systems and services to promote economic growth through disruptive innovations in mobility [13]. A ULL functioning with AVs integrates built environments and real-world trials of mobility services across diverse areas within the same district, representing the pinnacle of urban development and a precursor to city-wide implementation. This vision aligns with initiatives like Smart Columbus, whose diverse projects, applications, and programs shape future modes of transportation and public acceptance of smart mobility [3]. The Smart Mobility Lab in London has played a significant role in advancing CAV trials by establishing a safety case framework. Close collaboration with the government facilitates policy and legislation development, underscoring public and private sector interests in enhancing mobility [4].

The operation of Smart Columbus impacts the community by enhancing human services. Principal examples include enabling technologies for trip and mobility assistance with AVs and managing a food delivery service [58]. On the other hand, Europe has the Rivium Business Park and the Central District in Ijssel, Netherlands, where they are developing cutting-edge vehicle technology capable of moving up to 22 passengers using completely automated systems in mixed traffic conditions [10]. It is common to find that some applications and studies of AVs are about automation in delivery services and dispatching operations, supported by an increase in efficiency in last-mile operations with a reduction in waiting times [77].

The diversity of projects in London can be attributed to its Smart Mobility Living Lab, which is built for both the private and public sectors. This has resulted in collaborative projects like GATEway, ENDEAVOUR, ATLAS, and DRIVEN [4]. Considering urban development, intelligent transportation systems could meet the demands for transport and logistic services. However, stakeholders should understand the requirements in a simplified manner to grasp the global technological challenges in the urbanization, automation, and digitization of mobility services [78].

3.6. Challenges and Lessons Learned

AV adoption is complicated due to the numerous factors involved, but identifying socio-demographic variables and travel behaviors provides valuable information to delineate urban planning and policy adoption in real-world experimental settings. Long-distance trips are demonstrated to be less likely if AVs are adopted [79]. Figure 7 illustrates important factors in creating a ULL ecosystem for future smart mobility using shared, electric, connected, and automated vehicles. It shows that this process involves an integrated approach to specific issues that must be addressed to ensure cleaner, safer, and more efficient mobility, as well as gaining acceptance within the district where it is being developed.

The operational design domain (ODD) plays a crucial role in ADSs since it allows vehicles to operate autonomously in a designated area. In this context, multiple conditions can limit the maneuvers and features of the vehicles. Common causes of problems related to the ODD include mixed traffic flow, extreme weather conditions like heavy rainfall, and system constraints in detecting objects [10]. In the Netherlands, to achieve complete AV operation, Regional Transportation Districts rely on smart traffic signals [11].

During the testing of self-driving shuttles in the Smart Circuit of downtown Columbus, researchers encountered problems maintaining passenger safety conditions in the vehicle and other limitations in operational concept development [11]. However, the project found an alternative use for the AVs in the Linden community, providing an autonomous food delivery service for low-income families [58]. Studies from Riverside developed an innovative modeling suite framework to quantify the impact of new mobility technologies on traffic operations. While this framework is only useful for constrained system settings, it serves as an example of initiatives promoting CAV deployment in a sustainable energy direction, increasing confidence in this technology, and supporting further in-depth studies in distinct real-world applications [27].

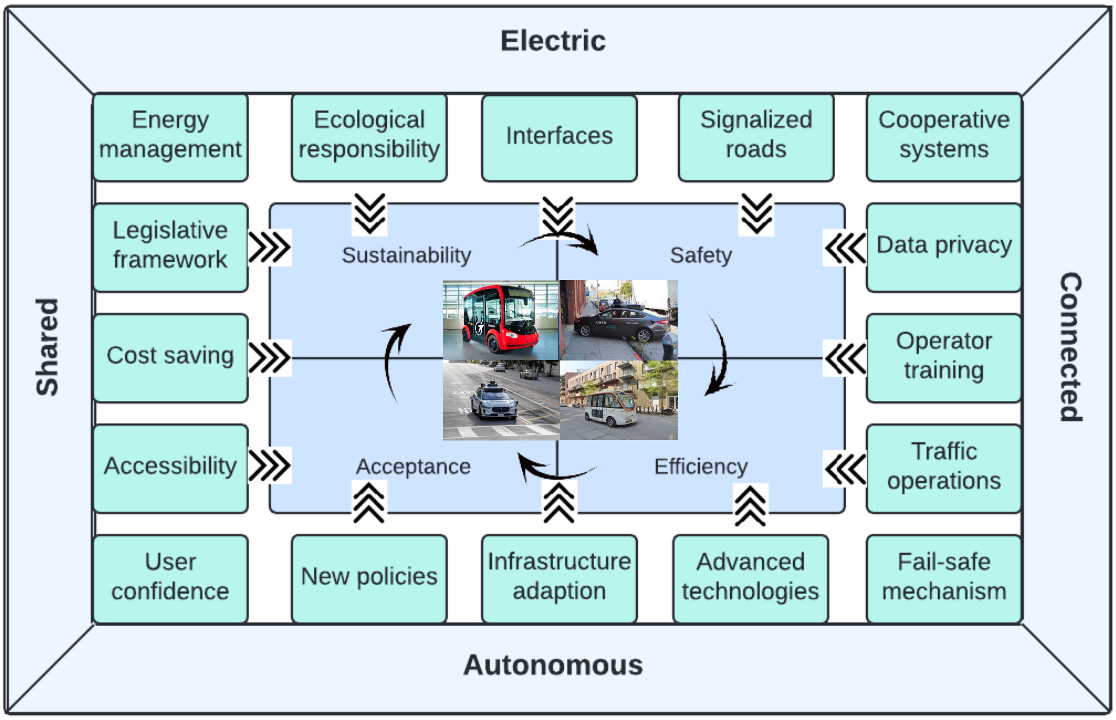

Figure 7. Important factors to address for the successful testing deployment of shared, electric, connected, and autonomous vehicles with positive effects on the pillars of the ULL ecosystem. All images from Wikimedia Commons, licensed under CC BY 4.0.

A project summary published in 2018 by the ITRL discussed the impact of AVs on transport systems, indicating that automation leads to an increase in vehicle kilometers traveled with reduced marginal costs. This can translate to greater energy consumption and higher emissions. However, to avoid this sustainability imbalance, policy instruments act as a regulating tool [75]. On the other hand, regulations should cover a wide range of considerations. In terms of safety, qualified operators and supervised interactions with AVs are essential to ensuring a safe experience. The operation of autonomous shuttles in Hamburg in 2021 provided information about the operators' perspectives on these technologies. The study concluded that a multimodal approach is necessary, incorporating auditory signals, visual cues, and accessible buttons with vehicle mechanism feedback [68].

Every initiative can gain different insights from CAV technology deployed in ULLs, but the roles and responsibilities in these kinds of services are among the most valuable aspects. AVs are an innovative concept that requires a controlled environment, continuous monitoring, a well-trained team to operate the vehicles, maintenance at charging or mobility stations, and safety marshals during operation; this has been shown to increase user confidence and comfort [59]. It is a fact that AVs require greater public acceptance, as society currently has a low level of trust in self-driving technologies. As secure and practical research on AVs continues to emerge, social acceptance should broaden [69]. Public acceptance of automation in transport may be low in some countries, even when opinions about AVs and their technological development are positive. This underscores the importance of a legislative framework and the adaptation of laws to support broad deployments and increase public awareness of the benefits of AVs [80].

Information and communications technology (ICT) is one of the most relevant aspects to implement in urban connected environments with an ITS, a key configuration in living labs using CAVs. In contrast to Europe, Asia, and North America, African and Latin American countries do not present active ULL initiatives using AVs. However, in Popayan, a medium-sized city in Colombia, a fleet management and control system was developed and tested to identify the appropriate requirements, technological components, and communication protocols in the ITS architecture for improvements in their transit services [51]. Connected vehicle algorithms and their evaluation have been proven to improve safety and mobility efficiency in corridors with signalized intersections [81]. Similarly, the Campus City project in Monterrey, Mexico, presents an analysis of an ecosystem of innovation within a pedagogic framework. It highlights the relevance of stakeholders to provide a first approximation of energy requirements and explains how a living lab relies on advanced data, information, and telecommunication systems to offer smart mobility solutions [1].

Consciousness about the increasing popularity of AVs is a reality in countries in the Middle East. In China, a case study of larger-size instances like districts to optimize vehicle routing algorithms has led to cost-saving solutions for the operation of shared autonomous electric vehicles (SAEVs) [52].

Numerous large-scale projects have been developed in the UK for CAV-related infrastructure development since 2014, emphasizing V2X systems and traffic control without an in-depth exploration of the concept of vehicular clouds. Oxford is characterized by the presence of CAVs, which led to a case study in this city to develop design principles in physical and virtual infrastructure [82]. Its application could expand ITS strategies and help manage parking facilities to successfully introduce CAVs into current urban environments. MERGE Greenwich and GATEWay projects are excellent examples of initiatives in the UK contributing to building this environment in the Smart Mobility Living Lab in London, where IoT constitutes the ecosystem communication to transform the infrastructures and materials of mobility [13].

4. Discussion

The key challenges in integrating various technologies to support the testing of connected, electric, and autonomous vehicles in ULL environments are related to the factors identified in this study. In particular, the interaction of CAVs with other actors in the urban environment is currently a crucial factor. Indeed, the various technologies developed, implemented, and adopted aim to control the interaction of all devices inside and outside CAVs. In most cases, especially in a ULL environment, where there is high interaction of CAVs with other road actors, it is necessary to use appropriate infrastructure to effectively develop an approach to future smart mobility. CAVs need seamless interaction among various technologies, such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), or vehicle-to-everything (V2X) communication. These systems need to work with existing road infrastructure, such as traffic lights, sensors, and public transportation systems. In addition, the use of dedicated lanes for AVs and EVs in key zones can enable more effective testing. ICT, IoT, and ITS are the most useful technologies, especially in view of developing multimodal mobility services, which, with the integration of CAVs, will enable levels of service for citizens that are unthinkable today. However, these technologies need further development to ensure higher levels of performance. Most of these technologies are developed autonomously, so it will be necessary to use a systemic and organic approach that can integrate and manage them. This is why it is important to introduce an unambiguous taxonomy and international standards for technologies and services to be adopted. Thus, the development of infrastructures able to support CAVs in a ULL environment will have to consider not only the technical aspect but also the need for the standardization and cost sustainability of these technologies and services. In particular, open standards for data exchange and communication protocols to ensure the compatibility of various technologies are required.

The scalability of initiatives using AVs in real-world conditions is a complex process. Investigations are required to evaluate the impact of self-driving technologies functioning in connected environments. It is common to find studies proposing agent-based simulations to evaluate the effect of AVs' introduction in urban environments [83]. These investigations enable the use of real case scenarios, and the results can vary depending on the variables selected for the agents, such as the mode of transportation, the length of trips, traffic conditions, and demand, among other characteristics of mobility [84]. The ability to control the dynamics of the simulation and apply a variety of scenarios with the desired characteristics for each city of interest allows for gaining insights into a wide range of implications, such as the operational efficiency of fleets, economic advantages, the impact on traffic congestion, and energy consumption [85,86]. This approach could also lead to real-world deployments that have already validated their proposals and impacts with existing urban data, facilitating the cooperation of public-sector transportation planners and policymakers. Nonetheless, it is more common to find these studies limited to simulation models.

The number of studies contributing to investigations regarding smart mobility is extensive, but focusing on autonomous, connected, and digital technologies reduces the number of initiatives to be included. It is important to highlight that developed countries in Europe are constantly supporting the adoption of future and clean mobility. Some studies may even focus on new street types to improve public transport efficiency, leading to low-carbon and low-speed multimodal solutions [87]. It is also evident that converting a study into a contribution with real-world testing is viable since the artificial intelligence (AI) algorithms and systems developed could be part of the chain to make a living laboratory platform with smart energy and mobility solutions function [88]. Nevertheless, even when investigations contribute to sustainable and intelligent mobility, some limitations prevent the scope from ever reaching an actual AV deployment on public roads. The main difference between precincts, urban corridors, and ULLs, all considered large-scale deployments of self-driving vehicle implementations, is that government departments are involved from the beginning of the project activation [89], or the initiatives are aligned with long-term funding programs that ensure their continuity [5]. In either case, it is evident that the government plays a crucial role in the policies and strategies that shape the direction of research and innovation in smart mobility interventions.

Even though the scope of some studies found in Scopus is limited to simulations and structural equation modeling for AV operation or impact research purposes [90,91], they are still included in the bibliography because their findings are related to the Horizon Europe program or previous editions, providing an assessment framework for future research and deployments. In other cases, it is interesting to see how specific initiatives supported by EU funding, such as the Ride-to-Autonomy project, are reported as scalable models for integrating autonomous shuttle solutions into public transport systems during designated periods, with pilot programs conducted across various European cities [92]. This enables an initial approach to future smart mobility strategies, serving as a basis for developing subsequent large-scale deployments such as ULLs [6,44,93] found in the literature.

For cases in USA cities, a situation similar to the European state of development can be observed; while industries and agencies sum up the AV tendency, urban areas present some type of on-road deployment with self-driving technologies. In this way, travel demand models and simulation scenarios with different levels of AV adoption serve as tools to evaluate the benefits of its use and predict how mobility could be reconstructed with more equity in metropolitan areas [94]. Data fusion models also contribute to investigations since they allow traffic signal control evaluation from a safety perspective, reducing collision risk for CAVs when implemented [95]. Even when research is limited to simulations, contributions based on modeling frameworks are oriented to corridors and street network implementations. Contributions in the design of a system architecture for V2X communication for connected corridors as a testbed allow the system's reliability and scalability so that it can also be applicable to similar urban deployment in other cities [96]. In addition, 5G networks are a crucial factor supporting the deployment of AVs, as they mediate the applications involved in service migration, as well as the security and privacy of data [97].

The urban deployment of self-driving technologies is often related to a CAV network, which refers to the operation of CAVs over a road network, corridor, or segment. The development of control algorithms in this context is what ensures safe operations in their movements [98]. The approach taken by institutions and centers conducting active research and development on AI algorithms typically involves simulations that consider real-world data and the characteristics of the network where they are hypothetically implemented.

Testbeds offer a viable option to validate the functionality of control systems, depending on the resources available for each investigation. Algorithms, communication systems, and any other technology related to the operation of CAVs can be tested in a reduced-scale environment [53,64] or within a specific spatial scope that replicates the urban conditions of a city [73,74]. It is important to recognize that successful urban deployment is only achieved when the CAV network operates within a multi-agent context, interacting seamlessly with other vehicles, users, and objects on the road [30,35]. Precincts and corridors that offer mobility services or provide other transportation solutions in urban areas are also included in this scope. A ULL does not necessarily refer to the next step after successfully implementing a CAV network but rather to an environment capable of encompassing all the previously discussed points to facilitate innovation and sustainable mobility [3–5].

Beyond the steps needed to achieve the urban deployment of AVs in public spaces, the core of ULL initiatives lies in addressing sustainability challenges to co-design the future of mobility [99]. Success will depend on the effective organization and prioritization of stakeholders' needs. Collaboration between cities and technology companies is another success factor in ensuring the implementation of these testing environments for future smart mobility solutions. A strong commitment by cities to the development of innovative mobility with the use of AVs is the main aspect that fosters collaboration with technology companies. Based on this aspect, data sharing (preserving data privacy and security), assisting companies in authorization and permit procedures, and the propensity for public investments in infrastructures and technologies useful for urban mobility, as well as forms of co-participation in public services, such as public–private procurement, are significant factors.

In this context, scalability can only occur when an ideal state is reached, offering tangible benefits for the involved parties and an appropriate design of strategies beyond testing purposes. Stakeholders will end up taking multiple roles in the management of the CAV supply chain as the adoption of these technologies increases in public transport. However, special attention should be given to preserving data privacy, along with all the adaptations in regulations and policies that this aspect involves [100]. The deployment of automated mobility strategies represents a challenge in a wide range of issues, but connectivity and data transmission still represent the principal obstacles to achieving the full development of smart infrastructure, where all the information coming from the mobility ecosystem is processed and interpreted successfully [101]. It has been demonstrated how the ULL plays a role in the introduction of innovations in mobility with AVs for the community, providing insights into transportation habits, public readiness, and acceptance to help policymakers create a safe and secure environment [102]. Considering that agenda-setting and policymakers need regulation-oriented measurements to ensure a safe and shared transition in automated mobility [103], ULLs offer a controlled urban space where this information can be obtained, adapted, and gradually expanded.

Indeed, regulatory bodies play a key role in ensuring the safe and effective use of AVs in test environments for future smart mobility solutions, as they clearly indicate which features and aspects need to be considered. They can influence different fields with specific indicator values that are necessary to achieve for future smart mobility solutions with AVs, such as defining the characteristics of AVs and the approval homologation process to be authorized for use on public roads; defining the infrastructural and environmental conditions for test implementations on public roads; defining harmonized authorization procedures for testing implementation; defining procedures in case of emergency events (passage of ambulances, police, etc.); defining administrative activities (insurance, etc.) required for test implementation; and defining priority rules with respect to other road users. In this vision, the European Commission adopted the first worldwide legislation (EU Regulation 2022/1426) concerning the conditions for the type-approval of Automated Driving Systems of fully automated vehicles to become the first market with a complete and unambiguous legislative framework.

5. Conclusions

The creation of a ULL is a complex process that can only be achieved through alliances and cooperation among stakeholders. Focusing on the development of ITSs and ADSs requires gradual steps to ensure scalability without issues. The strong presence of such projects and initiatives in the EU and USA highlights the need for grants and well-established programs to support sustainable solutions for the development of smart mobility in other parts of the world. In developing countries, the lack of regulations and adequate infrastructures must be overcome to achieve the necessary technological advancements for smart urban mobility.

In ULLs using AVs and EVs in public spaces, the necessary sensors, infrastructure, and ICT for safe deployments are revealed. Depending on the focus of each initiative, the simulations and studies presented may concentrate on assessing the impact of AV technology on mobility. However, it has been demonstrated that the use of software for microscopic simulations can lead to real-world deployments of electric, connected, and autonomous vehicles, supported by insights gained from these investigations into traffic operations, energy consumption, and travel demand preferences.

Universities lead research and develop strategies for AVs, while industrial partners enable the involvement of various private sectors to bring that technology to life. The government acts as the principal regulator, facilitating the legal use of this technology in urban areas. This collaboration is what distinguishes developing a model from actually having it functioning on the streets.

In summary, to implement a ULL for the innovation, testing, and scalability of AVs in mobility, it is necessary to have a diversified network of stakeholders covering the needs for regulatory frameworks, applied research, community engagement, and technological development under a sustainable vision. Once the models and control algorithms for ADSs have reached sufficient maturity through closed testing and simulations, the adaptation of urban infrastructure to create a connected environment where data transmission is successfully achieved could be considered. However, this is only possible when legal authorization for such operations is granted. Once again, the level of development achieved is restricted by the stakeholder network and how effectively they cooperate to enable experimentation.

Author Contributions: Conceptualization, A.A.M.-A., L.C.F.-H., B.S., A.C.V.-S., M.R. and J.d.J.L.-S.; formal analysis, A.A.M.-A., L.C.F.-H., B.S. and M.R.; investigation, A.A.M.-A.; methodology, A.A.M.-A., J.C.T.-M. and J.d.J.L.-S.; project administration, M.R., A.C.V.-S. and J.d.J.L.-S.; resources, J.d.J.L.-S.; software, A.A.M.-A.; supervision, L.C.F.-H., B.S. and M.R.; validation, L.C.F.-H. and M.R.; visualization, A.C.V.-S., B.S. and J.d.J.L.-S.; data curation, A.A.M.-A.; writing—original draft, A.A.M.-A.; writing—review and editing, A.A.M.-A., L.C.F.-H., B.S., J.C.T.-M., M.R. and J.d.J.L.-S. All authors have read and agreed to the published version of the manuscript.

Funding: The research was funded by the CampusCity initiative from Tecnológico de Monterrey.

Acknowledgments: The authors would like to acknowledge the Conscious Technologies research group, the CampusCity initiative at Tecnológico de Monterrey, and the collaboration with Politecnico di Bari for their support in the development of this work.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ULL	Urban living lab
AV	Autonomous vehicle
CAV	Connected and autonomous vehicle
AMD	Automated Mobility District
NREL	National Renewable Laboratory
AMoD	Autonomous mobility on demand
EU	European Union
CCAM	Cooperative, Connected, and Automated Mobility

ADS	Automated driving system
ITS	Intelligent transportation system
IMU	Inertial motor unit
GPS	Global positioning system
CEAV	Connected Electric Autonomous Vehicle
MaaS	Mobility-as-a-Service
AEV	Autonomous electric vehicles
SAV	Shared autonomous vehicles
V2X	Vehicle-to-everything
HMI	Human–machine interface
ZEV	Zero-emission vehicle
IoT	Internet of Things
ODD	Operational design domain
ICT	Information and communications technology
SAEV	Shared autonomous electric vehicles
AI	Artificial intelligence

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