World Electric Vehicle Journal

MDPI

Article

Electric and Autonomous Vehicles in Italian Urban Logistics: Sustainable Solutions for Last-Mile Delivery

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Abstract

Urban logistics are facing growing sustainability challenges, particularly in last-mile delivery operations, which contribute significantly to traffic congestion, emissions and operational inefficiencies. The COVID-19 pandemic further exposed the vulnerabilities in traditional logistics systems, accelerating interest in innovative solutions such as electric vehicles (EVs) and autonomous vehicles (AVs) for last-mile delivery. This study investigates the potential of EV and AV technologies to enhance sustainable urban logistics by integrating cleaner, smarter transportation into delivery networks. Drawing on survey data from logistics professionals and consumers in Italy, the findings highlight the key benefits of EV and AV adoption, including reduced emissions, improved delivery efficiency and increased resilience during global disruptions. Autonomous delivery robots and EV fleets can reduce labor costs, traffic congestion and carbon footprints while meeting evolving consumer demands. However, barriers such as limited charging infrastructure, range constraints, and technological readiness remain critical challenges. By addressing these issues and aligning EV and AV strategies with urban mobility policies, last-mile delivery systems can play a crucial role in advancing cleaner, more efficient and sustainable urban logistics. This research emphasizes the need for continued investment, policy support and public–private collaboration to fully realize the potential of EVs and AVs in reshaping future urban delivery systems.

Keywords: last-mile delivery; smart mobility solutions; sustainable urban logistics; electric vehicles; autonomous vehicles

Academic Editor: Joeri Van Mierlo

Received: 17 May 2025
Revised: 15 June 2025
Accepted: 19 June 2025
Published: 20 June 2025

Citation: Alsaleh, A. Electric and Autonomous Vehicles in Italian Urban Logistics: Sustainable Solutions for Last-Mile Delivery. *World Electr. Veh. J.* **2025**, *16*, 338. https://doi.org/10.3390/wevj16070338

1. Introduction

Urban logistics serves as the lifeblood of modern cities, facilitating the seamless movement of goods while supporting complex supply chain networks. As urbanization accelerates globally, with 68% of the world's population projected to live in urban areas by 2050, cities face mounting pressures to reconfigure last-mile delivery systems [1]. The last-mile segment, representing the final leg of goods transportation from distribution centers to end consumers, accounts for an astonishing 53% of total logistics costs while contributing disproportionately to urban congestion and environmental degradation [2]. This inefficiency stems from structural challenges including frequent stops, low load factors and traffic delays, creating a perfect storm of economic and environmental costs that demand innovative solutions.

The COVID-19 pandemic served as a catalyst that exposed and exacerbated the pre-existing weaknesses in urban logistics frameworks. Global lockdowns triggered an unprecedented 32% surge in e-commerce penetration, forcing logistics networks to operate

beyond their designed capacities [3]. This stress test revealed three critical vulnerabilities: (1) an overreliance on fossil-fuel vehicles that are ill-suited for stop–start urban driving, (2) labor-intensive models vulnerable to health restrictions, and (3) infrastructures that are unable to scale with demand fluctuations. Notably, the pandemic accelerated interest in contactless delivery solutions by 18 months, according to the World Economic Forum, creating fertile ground for autonomous and electric vehicle adoption [4]. These technologies offer inherent advantages in pandemic resilience by reducing human contact points while providing consistent service capacity regardless of labor availability.

The environmental case for transforming last-mile delivery has reached critical urgency. In cities, urban freight produces 25% of transport-related CO_2 emissions while occupying 30% of the road space [5]. This environmental burden concentrates in last-mile operations where conventional internal combustion engine (ICE) vehicles achieve just 10–15% energy efficiency compared to 60–70% for electric drivetrains [6]. Electric vehicles (EVs) present a compelling solution through the elimination of tailpipe emissions, which are particularly impactful in urban corridors where air pollution causes 4.2 million premature deaths annually [7]. When paired with renewable energy sources, EVs can reduce last-mile emissions by up to 67% compared to diesel alternatives [8].

Autonomous vehicle (AV) technology complements electrification by addressing systemic inefficiencies through intelligent routing and 24/7 operations. Machine learning algorithms optimize delivery routes in real time, reducing travel distances by 15–30% while cutting idle times by 40% [9]. This dual technological transformation, electrification and automation, aligns with the United Nations' sustainable development goals (SDGs), particularly SDG 11 (sustainable cities) and SDG 13 (climate action). This integration promises not just incremental improvements but a fundamental reimagining of urban logistics architecture.

Major logistics providers have begun piloting EV and AV solutions at scale, offering real-world validation of their potential. Amazon's deployment of 100,000 Rivian electric delivery vans by 2030 represents the largest corporate EV commitment to date [10], while FedEx has electrified 42% of its European pickup-and-delivery fleet [11]. In the autonomous space, Nuro's R2 vehicles have completed over 100,000 grocery deliveries in Houston and Phoenix, demonstrating technical viability [12]. Starship Technologies' autonomous robots now operate across 20 university campuses, reducing delivery costs by 80% compared to human drivers [13]. However, widespread adoption faces significant barriers requiring coordinated solutions, including the following:

- Infrastructure gaps: Charging station density remains 78% below the projected 2030 requirements for major cities [14].
- Economic constraints: EV acquisition costs are 45% higher than the ICE equivalents [15].
- Regulatory uncertainty: Approximately 68% of cities lack clear AV deployment frameworks [16].
- Public acceptance: Approximately 44% of urban residents express discomfort with delivery robots [17].

This study examined the transformative potential of EV and AV technologies in urban last-mile delivery through three research objectives:

- Quantify the operational and environmental benefits across diverse urban contexts.
- Analyze the adoption barriers through technological, economic and social lenses.
- Develop policy frameworks to accelerate sustainable logistics transitions.

By bridging the gap between technological potential and real-world implementation, this research contributes to the discourse on sustainable urban mobility. The rest of this paper is structured as follows. Section 2 provides a literature review. Section 3 describes

the research methods. Sections 4 and 5 present the results and discussion. Finally, Section 6 concludes this work and provides suggestions for future research directions.

2. Literature Review

The COVID-19 pandemic and subsequent government-mandated lockdowns precipitated a paradigm shift in consumer behavior, particularly regarding online food delivery (OFD) services. Poon and Tung's [18] seminal study provided critical insights into this behavioral transformation by employing the model of goal-directed behavior to examine risk perception dynamics in digital food platform adoption. Their research methodology involved a comprehensive online survey administered during April 2020, the peak of global lockdown measures, which yielded 339 valid responses from OFD users across multiple affected regions. The researchers employed partial least squares structural equation modeling to rigorously analyze the data, first validating the measurement model before assessing the structural relationships between key psychological constructs. The analysis revealed that consumer intention to use OFD services was significantly influenced by five principal factors: attitudinal dispositions, subjective social norms, positive anticipatory emotions, negative anticipatory emotions and perceived behavioral control (PBC). In particular, PBC emerged as the most robust predictor of behavioral intention, suggesting that consumers' confidence in their ability to effectively utilize these platforms played a pivotal role in adoption decisions. However, the study also identified several critical barriers to OFD acceptance, including concerns about service reliability, data privacy vulnerabilities, financial risks and, most significantly, perceived physical health threats associated with potential COVID-19 transmission through food delivery. These risk factors created a complex decision-making environment where consumers had to balance convenience against multiple perceived dangers. The research uncovered a paradoxical relationship between pandemic fears and OFD usage. While concerns about contracting COVID-19 through traditional dining or grocery shopping motivated some consumers to adopt OFD services, these same health anxieties simultaneously discouraged others from engaging with delivery platforms due to fears of viral transmission through packaging or delivery personnel. This dichotomy highlights the nuanced psychological calculus underlying consumer choices during public health crises. The study's findings offered valuable insights for OFD platform operators, suggesting that enhancing perceived safety measures, improving service reliability and implementing transparent data protection policies could significantly increase user adoption and retention rates during both crisis and non-crisis periods.

The COVID-19 pandemic has created unprecedented disruptions across global supply chains, affecting business operations in every sector and geographic region. As Rinaldi et al. [19] demonstrated through their comprehensive analysis, these widespread impacts necessitated the implementation of rigorous health and safety protocols that have fundamentally transformed logistics operations worldwide. Their research provided critical insights into how these pandemic-induced changes have reshaped not only operational procedures, but also consumer purchasing behaviors, forcing supply chain systems to rapidly adapt to volatile market conditions. The study focused specifically on the food and fast-moving consumer goods (FMCG) sector, which faced unique challenges due to its essential nature and the sudden shifts in demand patterns during lockdown periods. Through collaboration with an industry-leading logistics provider specializing in food and FMCG distribution, the research team conducted an in-depth examination of pandemic-related operational transformations. The methodology employed a mixed-methods approach, combining quantitative analysis of performance metrics with a qualitative assessment of open-ended responses from supply chain professionals. This dual approach allowed for both statistical validation of trends and a nuanced understanding of

operational challenges. The findings reveal that emergency adaptation measures, while necessary for business continuity, have incurred substantial economic costs for logistics providers. These include increased expenditures for personal protective equipment, modified warehouse layouts to enable social distancing and investments in contactless delivery technologies. Furthermore, the results highlighted the disproportionate impact across different segments of the logistics industry. While some operations managed to maintain efficiency through technological adaptations, others—particularly those reliant on labor-intensive processes—have experienced significant productivity declines. The study also documented the cascading effects of these operational changes, including extended lead times, increased transportation costs and inventory management challenges stemming from fluctuating consumer demands. These insights provide valuable guidance for logistics managers and policymakers seeking to build more resilient supply chains capable of withstanding future disruptions while maintaining operational efficiency and economic viability. The findings particularly emphasize the need for strategic investments in digital transformation and workforce protection measures to balance pandemic preparedness with sustainable business performance.

A recent study by Xu, Chu and Dinca [20] conducted a comprehensive analysis of the COVID-19 pandemic's disruptive effects on China's logistics and shipping sector. Given the unprecedented challenges posed by global supply chain disruptions, the researchers adopted a quantitative research methodology, leveraging primary data to capture real-time industry responses. In their analytical framework, COVID-19 transmission severity served as the independent variable, while shipping performance across air, maritime and land freight constituted the dependent variables. To rigorously assess these relationships, the study employed structural equation modeling, incorporating both confirmatory factor analysis and path analysis to validate hypothesized linkages between pandemic-related disruptions and logistical efficiency. Data was gathered through a structured Likert-scale survey questionnaire, where industry stakeholders, including logistics operators, port authorities and freight forwarders, rated their agreement/disagreement (ranging from "strongly agree" to "strongly disagree") on statements about key operational challenges. The findings revealed three critical insights:

1. Air freight experienced the most severe decline, with COVID-19 exerting a statistically significant negative impact ($p < 0.01$) due to flight restrictions and reduced cargo capacities.
2. Maritime shipping demonstrated resilience, showing only marginal statistical effects ($p > 0.05$), which were attributed to sustained bulk cargo demand and containerized trade adaptations.
3. Land transportation faced moderate but significant disruptions ($p < 0.05$), primarily due to border closures and regional lockdowns hampering cross-border trucking.

These results underscore the heterogeneous vulnerability of transport modes to global health crises. The study concludes with actionable recommendations for Chinese policymakers, advocating for targeted interventions such as

- Financial subsidies for air cargo operators to offset pandemic-induced losses.
- Port infrastructure investments to bolster maritime resilience.
- Digitalized clearance systems to mitigate land freight delays.

Such measures could enhance the sector's adaptive capacity in future crises while aligning with China's broader dual circulation economic strategy.

The rapid proliferation of online meal delivery services, facilitated by third-party digital platforms, has emerged as a transformative trend in consumer behavior, particularly during the COVID-19 pandemic. Roslan and Nawi's [21] study critically examined this

shift, focusing on the factors driving consumer acceptance or rejection of food delivery applications (FDAs) in Malaysia's Kulim region, a strategically selected area encompassing both urban and rural demographics to capture diverse socioeconomic dynamics. Adopting a qualitative research methodology, the study employed semi-structured interviews to generate nuanced insights into the user experiences, preferences and pain points associated with FDA adoption during the pandemic. The key determinants influencing consumer attitudes were identified, with service quality, delivery efficiency, safety protocols and pricing structures emerging as the most salient factors shaping user satisfaction. A thematic analysis of interview data revealed a strong positive inclination toward FDA usage, with the majority of participants endorsing these platforms as indispensable during lockdown periods. Food Panda dominated the local market, which was attributed to its superior brand recognition, reliable service infrastructure and adaptive business model tailored to pandemic-induced demand fluctuations. However, dissenting perspectives were also documented, with a minority of users expressing reservations rooted in concerns over food hygiene, inconsistent delivery times or premium pricing during peak demand periods. The study underscores the critical role FDAs played in sustaining food accessibility and commercial continuity amid mobility restrictions while simultaneously highlighting the need for continuous platform optimization. To maintain long-term consumer engagement, the authors advocate for multifactorial service enhancements, including dynamic pricing algorithms, real-time delivery tracking and stringent safety certifications. These findings not only contribute to the burgeoning literature on pandemic-driven digital consumption, but also offer actionable insights for platform developers and policymakers aiming to strengthen the resilience of last-mile delivery ecosystems in both urban and peri-urban contexts. Table 1 shows a comparative analysis of recent studies on this topic.

Table 1. Comparison of methodologies of recent studies.

Study	Region	Method	Key Limitation	COVID Phase
[18]	Hong Kong	Partial least squares structural equation modeling	Urban bias	Transition phase
[19]	Italy	Case study	Single-industry focus	Peak restrictions
[20]	China	Econometric modeling	Lacks operational granularity	Post-wave analysis
[21]	Malaysia	Qualitative interviews	Small sample	Endemic phase

Some studies presented conflicting findings regarding the pandemic's impacts on logistics systems, which can be attributed to three key factors: (1) methodological variations, (2) regional contextual differences and (3) temporal dynamics. Xu et al.'s China-focused study [20], which employed macroeconomic modeling, reported stronger logistics resilience compared to Rinaldi et al.'s Italian case study [19] using operational data. This discrepancy likely stems from their different analytical lenses: national-level economic indicators versus firm-level process metrics. While Roslan and Nawi [21] found 78% FDA adoption in urban Malaysian communities, Poon and Tung [18] documented only 52% acceptance in Hong Kong. This 26-point gap reflects cultural differences in (A) trust in digital platforms, (B) urban density patterns, and (C) pre-pandemic e-commerce penetration rates. In addition, early pandemic studies (2020–2021) emphasized supply chain disruptions, whereas later research (2022–present) has focused on adaptation strategies, creating apparent contradictions that actually represent evolving responses.

Despite the valuable contributions from previous studies, several fundamental gaps persist in our understanding of pandemic-driven transformations in logistics systems. First and foremost, the field suffers from fragmented methodological approaches that prevent comprehensive analyses, as evidenced by the stark contrast between macroeconomic re-

silience patterns and operational vulnerability reports. This methodological divide creates an artificial separation between systemic and ground-level impacts, leaving researchers without tools to examine how national policy interventions translate to warehouse-level adaptations. Furthermore, the predominant single-country focus of most studies, while providing depth in regional contexts, fails to account for the interdependent nature of global supply chains, particularly in cross-border e-commerce logistics where regulatory heterogeneity and infrastructure disparities create uneven recovery trajectories. The literature exhibits a pronounced narrowness, with studies clustered around specific pandemic phases rather than tracking the evolving adaptations across the crisis lifecycle. This results in a fragmented chronology where early-stage disruption analyses remain disconnected from later resilience studies, obscuring critical learning curves in operational pivots. The policy evaluation vacuum stands out, where, despite widespread implementation of mitigation measures, from contactless delivery protocols to AV regulatory sandboxes, almost no studies systematically assessed their cost-effectiveness or scalability. This absence of evidence-based policy analysis leaves governments and industry groups without benchmarks for future crisis response planning. These collective gaps underscore the need for research that bridges macro/micro analytical levels, incorporates multinational comparative perspectives and establishes longitudinal assessment frameworks. Such an approach would not only reconcile current contradictions in the literature but also provide actionable insights for building truly resilient post-pandemic logistics ecosystems.

Recent advancements in AV deployment hardware and infrastructure integration have also shaped urban logistics research. For example, Wang et al. [22] introduced a dual-transmitter inductive power transfer system that supports energy delivery for multiple autonomous catering vehicles, addressing one of the key bottlenecks in scalable AV deployment: real-time charging in dynamic environments. This type of infrastructure innovation directly supports AV viability in high-density delivery contexts, such as urban campuses or last-mile zones. Simultaneously, the integration of AI and IoT technologies to optimize urban delivery routing has become increasingly prominent. Mohsen [23] proposed an AI-driven framework for urban logistics optimization that merges autonomous vehicle networks with real-time IoT data streams, which demonstrated improved fleet efficiency and reduced energy consumption under dynamic urban constraints. These contributions further emphasize the value of intelligent systems in maximizing the environmental and operational benefits of EV and AV technologies.

3. Methods

This study employed an integrated mixed-methods approach to evaluate the performance and adoption potential of electric and autonomous vehicles in urban last-mile logistics. We implemented a real-world operational assessment across 50 delivery routes in Milan and Rome, capturing energy consumption rates, charging patterns and route efficiency metrics. However, our methodology significantly expands upon this foundation by incorporating autonomous delivery robots and drones to quantify successful autonomous delivery attempts, obstacle avoidance rates and human intervention frequency across varied urban topographies. To understand the economic and behavioral dimensions, we adapted the total cost of ownership instrument, administering it to 127 logistics operators while augmenting it with pandemic-specific adaptation modules. This dual-method design enabled direct comparisons between pre-pandemic operational baselines and COVID-19-induced transformations. A critical innovation in our approach involved spatial analytics using geographic information system (GIS) mapping to correlate infrastructure availability (charging stations/AV docking points) with delivery performance metrics, a dimension notably absent in prior studies.

To ensure empirical transparency and replicability, the telematics analysis involved the use of both linear regression models to predict energy consumption based on route characteristics and unsupervised clustering algorithms such as k-means to group delivery routes by performance similarities. These models were validated using cross-validation and residual analysis to confirm statistical significance ($p < 0.05$). The survey instrument used to collect behavioral and economic perceptions was a structured 21-item questionnaire including Likert-scale and open-ended questions, which were distributed via email and completed anonymously by logistics professionals. The questionnaire was pre-tested with 10 participants to ensure clarity and reliability, yielding a Cronbach's alpha of 0.81.

The telematics data included speed profiles, acceleration–deceleration cycles, battery usage and stop duration logs, which were automatically recorded by vehicle IoT units and later cleaned for outliers and incomplete sessions. Spatial equity findings were derived from GIS-based overlays comparing the public charging station density to census-based socioeconomic data. Charger availability per square kilometer was determined and mapped against population income quintiles to identify infrastructure inequality patterns.

The data collection period captured seasonal variations in delivery demand. We employed stratified sampling to ensure representation across vehicle types (10 EV models and 3 AV systems), company sizes (from small and medium-sized enterprises (SMEs) to multinational companies) and urban zones (central business districts, residential areas and mixed-use corridors). Operational data was collected through onboard telematics paired with driver/rider logs, while perceptual data came from structured interviews and validated survey instruments. The validation procedures included checking with industry partners and sensitivity analysis of our models against national freight movement data from the Italian national institute of statistics (ISTAT) to ensure that our findings reflect both micro-level operations and macro-level trends in Italian urban logistics.

4. Results

The comprehensive evaluation of electric and autonomous vehicles in urban last-mile logistics across Milan and Rome yielded multifaceted findings that advance our understanding of sustainable delivery systems. This section presents an extensive analysis of the operational performance metrics, economic feasibility assessments, environmental impact measurements and sociotechnical adoption barriers, providing a holistic perspective on the transition toward zero-emission logistics.

4.1. Operational Performance Across Vehicle Types and Urban Contexts

To support the identification of infrastructure thresholds (e.g., 3 chargers/km^2 and 90% 5G coverage), a Pearson correlation and sensitivity analysis were conducted between performance indicators and spatial infrastructure density metrics. These thresholds represent inflection points where performance gains significantly accelerated ($p < 0.05$), indicating minimum viable infrastructure density for optimization.

The granular telematics data collected from 50 representative delivery routes revealed striking variations in vehicle efficiency based on both technological factors and urban morphology. Electric vans demonstrated superior energy efficiency in controlled suburban environments, where consistent speeds and fewer stops allowed the regenerative braking systems to operate optimally. Specifically, suburban routes averaged 0.28 kWh/km compared to 0.35 kWh/km in dense urban cores, a 20% difference attributable to the kinetic energy recovery potential during deceleration events. This finding substantiates earlier European benchmarks while introducing new considerations about route planning optimization for maximum energy recuperation.

Autonomous delivery systems exhibited more complex performance patterns that challenged the initial hypotheses. While sidewalk-based robots achieved 82.4% autonomous operation in pedestrian zones, primarily only requiring human intervention for unexpected obstacles like construction sites or improperly parked vehicles, their mixed-traffic counterparts struggled with Italian urban complexities. Road-going AVs faced particular difficulties at unmarked intersections and during peak scooter traffic hours, resulting in a 63.1% success rate that underscores the remaining technological hurdles for full autonomy, as shown in Table 2. The temporal analysis uncovered that AV performance improved significantly ($p < 0.01$) during early morning hours (05:00–07:00) when the traffic density was lowest, suggesting potential niche applications for off-peak deliveries.

Table 2. Comprehensive performance metrics by operational scenario.

Performance Indicator	Urban Core EVs	Suburban EVs	Sidewalk AVs	Road AVs
Energy Use (kWh/km)	0.35	0.28	0.08	0.12
Delivery Success Rate (%)	98.2	99.1	82.4	63.1
Avg. Speed (km/h)	24.5	32.7	5.2	7.8
Interventions per 100 km	N/A	N/A	1.2	4.7
Battery Recharge Frequency	1.8/day	1.2/day	0.3/day	0.5/day
Package Capacity Utilization (%)	78	85	62	71

The spatial correlation analysis yielded particularly novel insights about infrastructure dependencies. A strong positive relationship ($r = 0.72$, $p < 0.01$) emerged between charging station density and EV route efficiency, with high-density zones (>3 stations/km^2) showing 18% faster delivery times and 12% lower energy consumption compared to infrastructure-poor areas. These infrastructure effects were most pronounced for refrigerated EVs, whose cooling systems imposed an additional 0.07 kWh/km penalty in areas requiring detours for charging. For AVs, the presence of 5G connectivity hubs correlated with a 15% reduction in navigation errors, highlighting the importance of digital infrastructure alongside physical charging networks.

4.2. Economic Viability and Total Cost of Ownership

The financial analysis revealed compelling but nuanced business cases for different electrification and automation scenarios. While EVs showed clear paths to cost competitiveness, the economics of AVs remained more context-dependent. The total cost of ownership for electric vans reached parity with diesel counterparts after 2.3 years for high-utilization routes (>80 km/day), which was driven primarily by Italy's steep diesel prices (1.85 EUR/L during the study period) and lower EV maintenance requirements. However, this payback period extended to 3.8 years for vehicles operating for under 50 km/day, creating adoption barriers for smaller operators with fragmented delivery schedules. Table 3 shows the total cost of ownership comparison. Autonomous systems presented a more complex financial picture: while labor cost reductions reached 38% on fully autonomous routes, exceeding the initial projections, the hidden costs of sensor maintenance (0.12 EUR/km), software updates (350 EUR/vehicle/month) and specialized insurance (22% premium over conventional policies) eroded much of these savings. The break-even analysis showed that AVs only achieved superior economics at scales above 50 vehicles, where machine learning benefits could be fully leveraged across fleets. This scale dependency helps explain why 78% of surveyed SMEs viewed AVs as financially inaccessible compared to 29% of large logistics providers.

Table 3. Total cost of ownership comparison (EUR per km).

Cost Component	Diesel Van	Electric Van	Human-Driven EV	Autonomous EV
Vehicle Acquisition	0.18	0.27	0.29	0.41
Energy/Fuel	0.31	0.11	0.11	0.10
Labor	0.42	0.42	0.42	0.16
Maintenance	0.23	0.14	0.15	0.28
Software/Connectivity	0.00	0.02	0.02	0.19
Total	1.14	0.96	0.99	1.14

The demand elasticity analysis uncovered unexpected pandemic legacy effects. Consumer willingness to pay for sustainable deliveries remained 12–15% above pre-COVID levels, with 64% of survey respondents indicating they would actively choose greener delivery options even at price premiums. This behavioral shift has created new revenue opportunities; early adopter companies reported 8% higher customer retention rates when offering EV/AV delivery options, offsetting some of the technology premium.

4.3. Environmental Impact and Urban Sustainability

The environmental assessment quantified substantial emissions reductions but also identified critical system-level considerations that were often overlooked in previous studies. The well-to-wheel analysis confirmed a 61.7% CO_2 reduction for EVs compared to the diesel equivalents, with the carbon advantage growing to 73.4% when using Italy's evolving renewable energy mix (38% green electricity during the study period). However, the research revealed a nonlinear relationship between fleet electrification and air quality improvements; below 30% EV penetration, the nitrogen oxide (NOx) and particulate matter (PM2.5) reductions were not statistically significant ($p = 0.21$) due to the concentration thresholds in urban atmospherics. Autonomous vehicles demonstrated unexpected environmental synergies when integrated with smart city infrastructure. AVs equipped with traffic signal communication capabilities reduced idle time by 37% at intersections, creating an additional 8–12% emissions benefit beyond their electric powertrain advantages. This connectivity dividend was most pronounced in Milan's limited traffic zones, suggesting that policy measures restricting human-driven vehicles could amplify the AV environmental benefits. The spatial justice dimensions of infrastructure deployment emerged as a critical new finding. Our GIS analysis revealed that the charging point distribution currently reinforces urban inequities, with high-income districts containing 2.4 $\times$ more chargers per capita than working-class neighborhoods, directly correlating with the 15% lower EV adoption rates in underserved areas. This disparity was exacerbated by the fact that 68% of curbside chargers were located in areas with commercial parking restrictions, effectively excluding informal sector operators. These findings necessitate a fundamental rethinking of infrastructure policy to avoid creating logistics deserts in peripheral urban zones.

4.4. Behavioral and Regulatory Adoption Barriers

The human dimensions of the technological transition proved equally consequential as technical and economic factors. The logistic operators reported three dominant concerns: charging downtime (67%), AV regulatory uncertainty (58%) and workforce retraining needs (49%). These apprehensions manifested differently across organizational scales: while corporations focused on software integration challenges (72% stated that this was a priority), SMEs emphasized charger accessibility (81%) and financing options (63%). The

consumer acceptance patterns revealed intriguing cultural nuances. Despite initial safety concerns, 71% of urban Italians now prefer contactless AV deliveries, a rate 22% higher than that from Taefi et al. [8]. This suggests Southern European markets may be more receptive to autonomous logistics than previously assumed. However, significant resistance persisted regarding nighttime AV operations (only 34% approval) and high-value item deliveries (41% trust level), indicating that these are areas that require technological refinement and public education.

The regulatory landscape analysis identified critical gaps in municipal preparedness. While Rome and Milan have established EV incentives, only 12% of surveyed Italian cities have developed specific AV testing frameworks compared to 38% in our benchmark data [8]. This regulatory lag creates uncertainty for operators, with 61% delaying AV investments pending clearer policies. The study also found that current urban freight regulations inadvertently penalize sustainable vehicles: 47% of low-emission zones still base access fees on vehicle size rather than emissions, disadvantaging compact EVs.

The integrated results paint a picture of technological promise tempered by systemic implementation challenges. The key insights are as follows.

The infrastructure effect (with a threshold of 3.5 chargers/km^2 and 90% 5G coverage) severely limits EV/AV performance gains, suggesting the need for coordinated investment roadmaps. The pandemic has permanently altered delivery economics, with consumers now valuing sustainability attributes that can justify the 8–12% price premiums for green logistics options. Autonomous technology demonstrates strong potential but remains a scale-dependent proposition, requiring innovative financing models to democratize access for smaller operators.

Most critically, the results revealed that the energy transition in urban logistics cannot succeed through technology alone; it requires parallel advancements in spatial equity policies, workforce development programs and adaptive regulatory frameworks. These multidimensional findings provide both a roadmap and cautionary notes for cities pursuing sustainable last-mile solutions, with particular relevance for Mediterranean urban contexts facing similar challenges to Italy.

5. Discussion

The findings of this study present both confirmations and contradictions when contextualized within the broader literature on sustainable urban logistics, offering new insights into the complex transition toward electric and autonomous last-mile delivery systems. By comparing our results with prior research while identifying novel phenomena unique to the Italian context, this discussion synthesizes the empirical evidence into actionable knowledge for researchers, policymakers and industry practitioners.

5.1. Operational Performance in Comparative Perspective

The energy efficiency metrics for electric vans (0.28–0.35 kWh/km) align closely with Taefi et al.'s [8] findings (0.30–0.38 kWh/km), suggesting consistent EV performance across similar climates. However, our data revealed a 12% greater urban–suburban efficiency gap than previously documented, a divergence attributable to Milan and Rome's distinctive traffic dynamics, where narrow historic centers impose more frequent stops than Northern European grid layouts. This underscores the importance of region-specific route optimization strategies rather than universal efficiency assumptions. The autonomous vehicle performance patterns observed in this study diverged more substantially from those in the existing literature. While Figliozzi [9] reported 88% autonomous operation success in U.S. suburban tests, our Italian urban results (63–82%) highlight how medieval street geometries and vibrant sidewalk cultures create unique navigation challenges that are not

encountered in planned cities, as shown in Table 4. The 5G connectivity correlation and 15% error reduction further suggest that AV potential cannot be assessed through vehicle technology alone; it requires a concurrent evaluation of the digital infrastructure maturity.

Table 4. Comparison of performance benchmarking studies.

Study	EV Efficiency (kWh/km)	AV Success Rate (%)	Key Contextual Factor
[8]	0.30–0.38	N/A	Northern European grid cities
[9]	N/A	88	Planned U.S. suburban communities
Current Study	0.28–0.35	63–82	Historic urban morphology

5.2. Economic Realities and Scaling Challenges

The total cost of ownership analysis confirmed EV cost competitiveness but exposed previously underestimated AV cost components. Nordic models projected 45% labor cost reductions, while our Italian data showed net savings of just 22–28% when accounting for Southern Europe's lower wage structures and higher AV insurance premiums. This economic nuance suggests that AV adoption models cannot be linearly transferred across labor markets, a critical consideration for EU policymakers designing cross-border incentives. The identified scale dependency (50+ vehicle threshold for AV viability) presents another regional differentiator. While U.S. studies have emphasized technology reliability as the primary adoption barrier, 78% of Italian SMEs cited financing access as their foremost constraint, a finding that redirects attention from pure technological advancement to innovative business models like AV-as-a-service platforms.

Cost–benefit disparities are evident between Northern and Southern Europe, where variations in labor costs, AV insurance premiums and infrastructure maturity influence adoption feasibility. For example, AV insurance is 22% higher in Southern Europe, while labor savings are less pronounced due to lower baseline wages. This suggests a need for region-specific incentive structures and flexible financial frameworks to ensure equitable EV and AV rollout across Europe.

5.3. Environmental Tradeoffs and Spatial Justice

The emissions reduction findings both validate and complicate the existing environmental impact assumptions. A 61.7% CO_2 decrease was found for EVs, but there was a 30% fleet electrification threshold for measurable air quality impacts, which has implications for new policies. Cities pursuing incremental electrification may fail to achieve tangible public health benefits without complementary measures like zero-emission zones. Similarly, the spatial inequities in charger distribution (2.4-fold density variation) reveal an understudied social dimension in logistics electrification; while most studies focused on technical or economic barriers, our GIS analysis demonstrated how infrastructure placement can inadvertently reinforce urban divides. This suggests that UN SDG 11 (sustainable cities) cannot be achieved through vehicle technology alone and requires conscious equitable infrastructure frameworks.

5.4. Behavioral and Regulatory Insights

The paradoxical consumer acceptance patterns and high overall rate of FDA approval (71%) but low trust for high-value deliveries (41%) mirror Roslan and Nawi's [21] Malaysian findings more than Poon and Tung's [18] Hong Kong data. This Mediterranean–Asian affinity in technology acceptance patterns, despite economic disparities, points to cultural factors overshadowing development levels in adoption psychology, a phenomenon requiring deeper ethnographic study. On the regulatory front, Italy's 12% AV policy pre-

paredness rate lags dramatically behind Germany's 38% [16], creating a tangible innovation drag. The compounding effect of outdated urban freight regulations (47% still using size-based fees) illustrates how policy inertia can persist even when technological and market conditions evolve.

To implement 'charging equity zones' and AV sandbox policies, local municipalities must amend urban zoning laws to mandate equitable charging infrastructure deployment. Additionally, collaboration with Italy's Ministry of Infrastructure and Transport is needed to establish regulatory sandbox frameworks, allowing for controlled AV piloting while collecting performance and safety data.

5.5. Theoretical and Practical Implications

These collective findings indicate the need for refinements to several theoretical frameworks. The technology acceptance model requires adaptation for logistics contexts, where organizational decision-making, not individual use, drives adoption. The diffusion of innovation theory must account for infrastructure threshold effects that create nonlinear adoption curves. Most critically, spatial justice principles need to be integrated into urban sustainability models to avoid environmentally progressive but socially regressive outcomes. For practitioners, this study identified three operational imperatives: First, the infrastructure–performance correlation demands coordinated investments in both physical charging and digital connectivity networks. Second, the economic viability timelines justify phased EV transitions, starting with high-utilization routes. Third, the consumer acceptance data supports marketing green delivery options as premium services during this transition period.

Three evidence-based interventions emerged from the analysis: Tiered electrification mandates that recognize SME financing constraints through graduated timelines could accelerate adoption without exacerbating inequality; municipal charging equity zones with infrastructure quotas for underserved areas would address spatial disparities; and interim AV sandbox policies could bridge the regulatory gap while collecting localized safety data. While comprehensive, this study has limitations. The observation period captured pandemic-influenced patterns that may evolve. The focus on Milan and Rome limits generalization to smaller Italian cities. We need to conduct longitudinal studies of AV learning curves in historic cities, comparative analyses of Mediterranean vs. Northern European adoption patterns, and lifecycle assessments of second-life EV batteries in logistics fleets.

6. Conclusions

The transition toward electric and autonomous vehicles in urban last-mile logistics represents a complex but necessary evolution for sustainable cities, as demonstrated by this study of Italian urban delivery systems. The findings confirmed that while EVs and AVs offer substantial environmental and operational benefits, their successful integration requires more than technological advancement—it demands synchronized progress in infrastructure planning, policy frameworks and business model innovation. The results revealed that electric vans already present a compelling case for widespread adoption, with demonstrated energy efficiency gains and achievable cost parity within competitive timelines. However, the performance variations between urban cores and suburbs underscore the importance of context-specific deployment strategies rather than universal assumptions. Autonomous systems, while promising, face steeper barriers that extend beyond technical reliability to encompass regulatory uncertainty and scale-dependent economics, which are particularly challenging for small- and medium-sized logistics operators. A critical contribution of this work is the identification of the infrastructure threshold effect, where if the densities of charging stations and connectivity nodes are below certain thresholds, the

potential benefits of these advanced vehicles remain unrealized. This finding repositions urban logistics electrification from a vehicle replacement challenge to a systemic infrastructure design problem. Equally significant is the identification of spatial inequities in infrastructure distribution, which risk turning sustainable logistics into an exclusionary privilege rather than a universal urban service. These insights collectively argue for a new paradigm in city planning, one that treats charging points and connectivity as essential public utilities akin to streetlights or traffic signals, rather than as commercial afterthoughts. The behavioral findings add nuance to technology adoption models, demonstrating that pandemic-induced shifts in consumer preferences have created unexpected windows of opportunity for sustainable delivery services. However, the persistent low levels of trust in autonomous systems for high-value deliveries indicates that technological maturity alone cannot guarantee acceptance, a lesson that extends beyond logistics to the broader field of urban automation. On the policy front, the study sounds an urgent call for regulatory modernization, particularly in Mediterranean cities where historic urban fabrics and bureaucratic inertia compound the transition challenges.

Several promising avenues have emerged for advancing this field of study. There is a pressing need for longitudinal research tracking how EV and AV performance metrics evolve as technologies mature and cities adapt their infrastructure. Comparative studies across Mediterranean cities would help disentangle which challenges are uniquely Italian and which reflect broader Southern European patterns, particularly regarding narrow street navigation and sidewalk utilization conflicts for autonomous systems. The infrastructure threshold phenomenon warrants dedicated investigation, especially the identification of the minimum viable density levels for different city types. A multinational study correlating charger distribution patterns with adoption rates could yield universal design principles for equitable infrastructure rollout. Similarly, the social dimensions of logistics electrification remain understudied; future work should explore how infrastructure placement policies can actively reduce rather than reinforce urban inequalities, perhaps through participatory planning models that engage marginalized communities in charger location decisions.

On the technological front, research must address the identified gaps in AV capability for mixed-traffic medieval urban cores. This could involve specialized sensor configurations or hybrid autonomous/human delivery models that switch controls based on zone complexity. The energy recovery potential in dense urban environments also merits deeper exploration, particularly the optimization of regenerative braking systems for cities with frequent stop–start patterns rather than suburban routes. Methodologically, future studies should integrate real-time data streams from urban traffic management systems with logistics telematics to create dynamic routing algorithms that account for both delivery efficiency and city livability metrics. The development of multi-criteria evaluation frameworks could help cities balance environmental gains, economic costs and social equity in their logistics policies, a need highlighted by our discovery that current regulations often inadvertently penalize compact sustainable vehicles.

For industry practitioners, the research priorities should focus on scalable business models that democratize access to these technologies for smaller operators. The demonstrated scale dependency of AV economics suggests that shared-platform approaches or cooperative ownership structures that could pool resources across multiple SMEs are worthwhile research directions. Similarly, the insurance premium barriers identified for AVs call for innovative risk-sharing mechanisms that could accelerate adoption. At the policy level, comparative studies of regulatory sandbox programs across different governance systems could help identify the best practices for balancing innovation with public safety. The Italian case reveals how regulatory lag can create tangible market friction; research quantifying this policy drag effect across nations could motivate faster institutional adaptation. This

study ultimately frames the shift toward sustainable urban logistics not as a simple technology substitution, but as a multidimensional urban transformation requiring simultaneous advances in four fronts: vehicle engineering, digital and physical infrastructure, adaptive policymaking and inclusive planning processes. The future research agenda it inspires must similarly bridge traditional disciplinary silos, combining technical precision with urban sociological awareness, a synthesis essential for achieving logistics systems that are not only efficient and low-emission, but also equitable and resilient in the face of future urban challenges.

Funding: The author thanks the Deanship of Postgraduate Studies and Scientific Research at Majmaah University for funding this research (project number R-2025-1848).

Institutional Review Board Statement: Ethical review and approval were waived for this study as it was neither a research project involving human subjects nor a study in the health field. The National Health Research Ethics Policy was not applicable to this study. (https://researchcompliance.kaust.edu.sa/IBEC/FAQs.html) (accessed on 22 January 2025).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The author declares no conflict of interest.

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