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Review

Efficient Operation of Metropolitan Corridors: Pivotal Role of Lane Management Strategies

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Abstract: Lane management strategies are vital for solving traffic congestion and improving transportation efficiency in metropolitan corridors. These corridors, which facilitate economic and social interactions by connecting major urban areas, face significant challenges such as congestion, environmental concerns, and the need for sustainable growth. Effective lane management involves techniques such as HOV lanes, HOT lanes, reversible lanes, and dynamic toll pricing, which have been implemented worldwide. This study addresses the questions 'What are the benefits and limitations of lane management strategies in metropolitan corridors?' and 'When should decision-makers consider implementing lane management strategies in a metropolitan corridor?' This paper aims to evaluate lane management strategies to increase the multimodal efficiency of metropolitan corridors. A systematic literature review of case studies reveals that while these strategies significantly reduce congestion and emissions, they also face road safety, compliance, and public resistance issues. In addition, gaps in existing research on metropolitan corridors and lane management will be identified, and areas for future research are proposed. The impacts of new societal trends and evolving urban planning concepts are examined. The study highlights the need for adaptive planning and innovative solutions.

Keywords: lane management strategies; metropolitan corridors; traffic congestion; transportation efficiency

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1. Introduction

Metropolitan corridors refers to linear urban systems of interconnected urban areas and the transportation networks linking them. These corridors represent an urban organisation that spans different municipalities, facilitating economic, social, and spatial interactions [1]. They often include significant transportation infrastructure such as railways, highways, and transit systems supporting high-density development and connecting major metropolitan areas. As critical arteries for economic activities, metropolitan corridors enable the efficient flow of goods, services, and people across regions. They help to manage urban sprawl by concentrating development along specific pathways and promoting sustainable growth.

Activities in large metropolises tend to concentrate in nodes with a high density of land use (e.g., business, administrative, educational, health services, leisure, or residential). Also, most people perform their daily routines according to business hours. These two facts induce a pendular pattern of mobility demand along the corridors, with peaks corresponding to many travellers going to their regular occupations in the morning and returning home in the afternoon. These asymmetric demand peaks occur in opposite directions and originate congestion, incidents, and pollution problems in corridors. It is unfeasible to solve these problems with just more vehicles and infrastructure due to geographical, environmental, and monetary constraints.

Social inclusion is essential to ensure that all residents, including those in underserved communities, benefit from the development of metropolitan corridors. This involves providing affordable housing, access to public services, and economic opportunities [2]. Economic and social integration within metropolitan corridors is crucial for regional development. These corridors must address disparities in access to services and employment opportunities to ensure that benefits are equitably distributed across the region [2]. This involves targeted investments and policies to support inclusive growth and reduce economic disparities.

One of the main challenges in developing metropolitan corridors is integrating transport services and modes with land uses. Effective integration is crucial for creating sustainable urban environments [3]. This requires long-term, consistent planning across the entire metropolitan region to ensure that transportation infrastructure supports high-density development and vice versa. In addition to the integration, spatial planning and governance present significant challenges. Metropolitan corridors often span multiple municipalities with different administrative boundaries, leading to spatial planning and governance complexities. Effective urban planning must navigate these boundaries and integrate various spatial layers to address the pressures of urbanisation and globalisation [4]. Effective coordination is essential to align planning and development efforts across these jurisdictions despite differing priorities and regulatory frameworks [5].

Moreover, sustainability and mobility within metropolitan corridors are critical concerns. Achieving sustainable development requires balancing transportation efficiency, land use, and environmental considerations. Promoting public transport and reducing car dependency are essential strategies [6]. Managing growth and urban expansion is another critical challenge. Rapid urban growth and the expansion of metropolitan areas require comprehensive planning to manage land use and transportation infrastructure effectively. Adaptation to changing demands is crucial for the sustainability of metropolitan corridors. These areas must accommodate shifts in population, changes in economic activities, and evolving transportation technologies to remain relevant and effective [7].

The necessity of making the most of the available right-of-way in a metropolitan road corridor raises the possibility of using different custom lane operation strategies to attain capacity, speed, reliability, and sustainability benefits. Therefore, customised lane management has the potential to be pivotal in the efficient management of all lanes in a corridor. Lane management involves techniques where specific lanes on a metropolitan corridor are designated for particular purposes or types of vehicles, and their access can be controlled dynamically. On the one hand, a highway lane is 'managed' if its operator proactively implements and oversees strategies according to changing conditions to improve performance [8]. Proactively managing these lanes is critical as it allows operators to adjust strategies quickly in response to changing traffic conditions, optimising roadway performance and safety. This includes deploying variable speed limits, opening or closing lanes to traffic, and using real-time traffic information systems to inform drivers about the best routes and lane usage during their commute. Moreover, reasonable speed control is essential to prevent excessive speed differences between lanes, ensuring traffic stability and driving safety. In essence, proactive and customised lane management, combined with thoughtful highway construction practices, can significantly enhance the efficiency and sustainability of road corridors [9].

Additionally, technology integration plays a vital role in managed lanes, enhancing their effectiveness. Technologies such as automated traffic sensors, real-time data analytics, and intelligent transportation systems (ITSs) monitor traffic conditions, manage lane usage, and communicate with drivers. This technology-driven approach ensures lanes are reactive to current traffic conditions and predictive, helping manage congestion before it becomes problematic.

By tackling these challenges, metropolitan corridors can effectively contribute to regional development and sustainability, ensuring they play a pivotal role in shaping the future of urban areas. This paper aims to evaluate lane management strategies to increase the multimodal efficiency of metropolitan corridors. The motivation for this study stems from the need to enhance the multimodal efficiency of metropolitan corridors, which are crucial for economic and social interactions in urban areas. Given the evolving technological and socioeconomic landscape, revisiting and refining lane management strategies is imperative to optimise their effectiveness. This study aims to fill these gaps by providing a holistic evaluation of lane management strategies and their integration with emerging technologies. The following research questions are addressed in this paper: What are the benefits of lane management strategies in addressing the challenges of metropolitan corridors? What are the limitations and challenges of implementing lane management strategies in metropolitan corridors? When should decision-makers consider implementing lane management strategies in a metropolitan corridor? To answer these questions, this paper conducts a systematic literature review on methodologies and noteworthy use cases of metropolitan corridors focusing on lane management strategies.

The remainder of this paper is divided as follows. Right after this introduction, Section 2 defines the methodology followed for the review, identifying the main topics to be developed. Section 3 describes the concept and types of lane management strategies. After that, Section 4 describes the strategies implemented and their outcomes in Metropolitan corridors. Challenges and limitations of lane management strategies in metropolitan corridors are discussed later in Section 5. Section 6 evaluates the suitability of managed lane strategies for a particular corridor. Finally, the key findings point out policy recommendations that may help to optimise lane management strategies on metropolitan corridors and identify future research gaps.

2. Methodology

This work follows the methodology used in many other systematic literature review papers, such as the paper by Casquero et al. [10], which studies how the design of mobility apps can improve urban travel patterns, or the article about mobility as a service (MaaS) by Kriswardhana & Esztergár-Kiss [11]. As shown in Figure 1, the process begins by establishing the scientific databases and defining the keywords that will serve as guidelines. Next, thorough research is conducted in academic reference and citation databases to obtain a list of papers relevant to our research questions, resulting in 412 articles related to the established keywords. The third and fourth steps involve selecting the relevant articles according to their abstracts and then carefully reading them, noting their unique contributions without reaching premature conclusions. Finally, 73 articles were chosen for their significant contributions to the study.

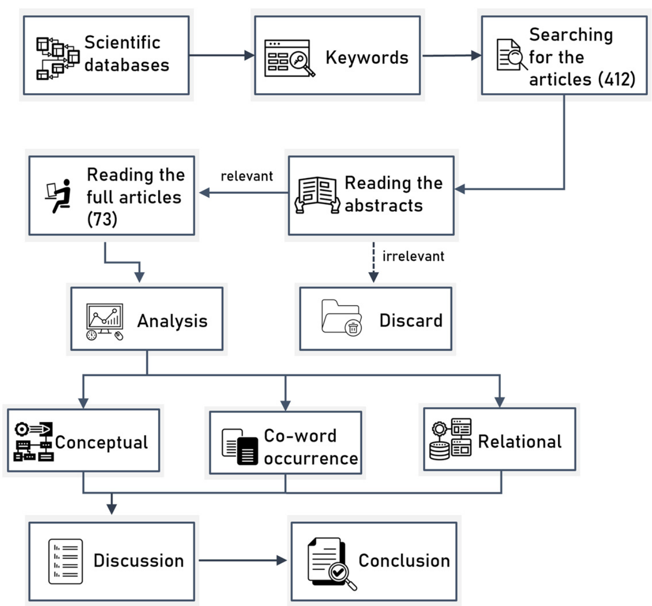

Figure 1. The methodological framework of the review process.

Afterwards, the relevant articles were classified and sorted to identify research patterns and gaps. This task includes analysing the distribution of publications over the years and identifying similarities or common themes using word co-occurrence analysis. This analysis involves processing the texts to find pairs of keywords that appear within a certain distance from each other. Each word in such a pair has one co-occurrence. A high co-occurrence rate for a keyword indicates that it frequently occurs with other keywords in the graph [10]. The fifth and sixth steps discuss the information after it has been classified and the conclusions reached.

2.1. Databases and Keywords

The primary sources for this paper were the scientific databases Web of Science, Scopus, and the Google Scholar search engine. The authors entered relevant combinations of the keywords: 'managed lanes', 'corridors', 'lane management', 'multimodal roads', 'reversible platforms', 'tidal flow systems', 'high occupancy toll lanes', and 'high occupancy vehicle lanes'. When these sources cite promising works not found by the initial search, the authors also include them.

2.2. Bibliographic Analysis

This work uses the Bibliometrix R package, an advanced bibliometric analysis tool developed to aid researchers in evaluating scientific literature [12]. This tool provides the metrics shown in Table 1 from the abstracts of the publications that have been analysed. It is also used to create and visualise the co-occurrence network displayed in Figure 2, where the number of co-occurrences affects each keyword's size. The thickness of a link increases with the number of co-occurrences between two terms.

Following an initial search, the co-occurrence network graph was generated. It included clusters to ensure the search was targeted at the research object and to display the network of all the important concepts in the list of searched scientific publications and their relationships. Figure 2 highlights three relevant clusters of this study and its networks of relationships to other keywords.

Three measures are computed to analyse these words' importance and roles within the network: betweenness centrality, closeness centrality, and PageRank. 'Betweenness centrality' assesses how often a node is in the shortest path connecting two others. It identifies key terms, entities, or concepts that frequently occur together and serve as bridges connecting different topics or themes within the network. These nodes can be seen as important in the overall structure of the network and can help in understanding the relationships between various elements. 'Closeness centrality' quantifies how near a node is to all other nodes in the network, focusing on the average distance from it to all others. 'PageRank' estimates the importance or influence of a node by evaluating the probability that a connection between any two nodes will pass through a particular vertex, thus quantifying its significance or impact. This measure identifies highly influential words frequently referenced by other significant words central to the main topics and themes discussed. Nodes are classified in clusters with the Walktrap algorithm [13], which helps identify tightly knit groups within the network that share strong thematic or conceptual similarities. This classification provides insights into the underlying structure of the network and the relationships between different themes.

The co-occurrence network visually represents the relationships between various keywords related to metropolitan corridors, managed lanes, and associated traffic concepts. It highlights three distinct clusters: road infrastructure, multimodal mobility, and lane management strategies.

The Cluster 1 *Road Infrastructure* includes keywords about infrastructure development and strategic planning, which are essential for well-maintained and technologically advanced road networks. It emphasises the need for a robust infrastructure that supports the overall metropolitan corridor, addressing themes such as "infrastructure development", "road maintenance", "technological advancements", and "strategic planning". The cluster highlights the importance of comprehensive road networks in supporting economic growth and urban development.

Table 1. Clustering and centrality measures.

Cluster	Node	Betweenness Centrality	Closeness Centrality	PageRank
Cluster 1 Road Infrastructure	Road	37.279	0.015	0.038
	Transportation	12.040	0.013	0.022
	Dynamic	34.173	0.013	0.025
	Pricing	9.562	0.013	0.022
	Analysis	21.367	0.014	0.013
	Strategies	0.259	0.013	0.018
	Multimodal	14.871	0.013	0.021
	Network	0.894	0.011	0.014
	Toll	0.000	0.009	0.007
Cluster 2 Multimodal Mobility	Corridor	48.069	0.011	0.047
	Urban	104.707	0.014	0.046
	Transit	2.442	0.010	0.025
	Development	0.000	0.008	0.012
	Bus	16.535	0.014	0.010
	Mobility	0.000	0.009	0.008
	Modelling	0.000	0.009	0.008
Cluster 3 Lane Management Strategies	Lane	265.643	0.020	0.129
	Vehicle	29.280	0.016	0.081
	Traffic	129.547	0.018	0.065
	Management	18.688	0.015	0.058
	Connected	9.579	0.015	0.056
	Managed	3.765	0.014	0.032
	Safety	13.903	0.015	0.026
	Autonomous	0.000	0.013	0.021
	Impact	1.361	0.013	0.025
	Model	3.470	0.014	0.017
	Automated	0.245	0.014	0.027
	Control	0.000	0.013	0.012
	Freeway	1.137	0.013	0.022
	Approach	0.000	0.014	0.011
	High-Occupancy	0.000	0.014	0.019
	Mixed	0.000	0.014	0.014
	Occupancy	0.000	0.012	0.009
	Operational	0.000	0.012	0.013

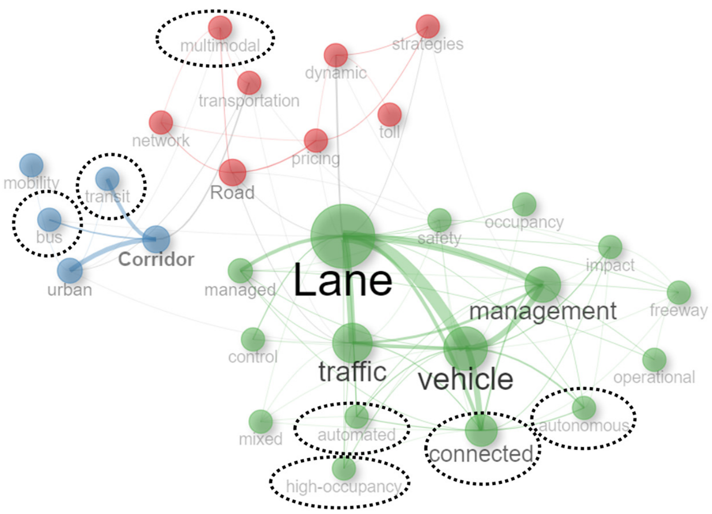

Figure 2. Co-occurrences network based on the abstracts of the literature reviewed for this work.

The Cluster 2 *Multimodal Mobility* focuses on broader urban mobility themes and includes keywords related to comprehensive transit systems, metropolitan corridors, and integrated transportation networks. It addresses the strategies and policies that enhance urban mobility by ensuring efficient transit systems that cater to the needs of a growing urban population. Keywords such as "urban mobility," transit systems", and "public transportation" are central to this cluster.

The Cluster 3 *Lane Management Strategies* focuses on specific strategies of lane management and their various types. This cluster is essential for understanding how targeted interventions at the lane level can contribute to broader traffic management goals within metropolitan corridors. Keywords like "managed lanes", "traffic management", "lane-level interventions", and "high-occupancy vehicle lanes" are integral to this cluster. The cluster explores how specific lane strategies, such as tolling for mixed traffic flows, including connected and automated vehicles (CAVs), high-occupancy vehicles (HOVs), and human-driven vehicles (HDVs), can optimise traffic flow and minimise social costs.

3. Lane Management Strategies: Concept and Types

A lane is 'managed' if its operator proactively implements and oversees strategies according to changing conditions to improve performance. Lane management strategies are typically undertaken to enhance traffic capacity, speed, or reliability in corridors that operate near or at capacity. These strategies typically focus on regulating demand, separating traffic streams to reduce turbulence, and utilising available and unused capacity [14]. In corridors, the construction costs of MLs are likely to be high, mainly if the right of way is insufficient to accommodate new lane(s), necessitating costly land acquisition or elevated or below-grade facilities [15]. Concerning the roadway, they can be run along separate rights-of-way, within a road's right-of-way but physically separated from general purpose lanes (GPLs), concurrent with the direction of travel of the rest of their carriageway, or contraflow. In the last case, the movement is opposite to the other lanes in the off-peak direction carriageway. Lane management strategies can be classified into three main types: pricing lanes, eligibility lanes, and permission lanes (see Figure 3) [8,16].

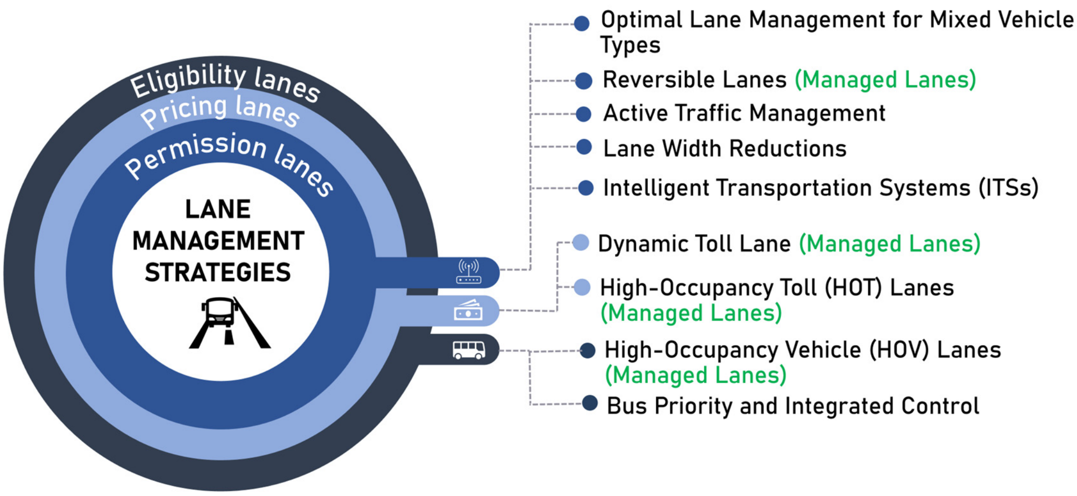

Figure 3. Lane Management Strategies.

Eligibility lanes are specialised traffic lanes designed to optimise traffic flow and increase efficiency by restricting access based on specific criteria. These lanes are typically reserved for vehicles that meet specific eligibility requirements, such as high-occupancy vehicles (HOVs) or buses. HOVs are also known as carpool lanes in the USA or 2+ lanes in the UK. These lanes require a minimum number of occupants per vehicle, though many authorities consider exemptions for certain types, such as low-emission vehicles or motorcycles. HOV lanes maximise the number of people moved through congested corridors.

They can also be used for ramp meter bypasses or exclusive entrance ramps. These meters control traffic flow onto a facility, reducing traffic turbulence (Chang et al. [17]). It has been noticed that HOV lanes do not always provide the expected advantages, frequently encountering issues impacting efficiency. One prevalent problem is the "empty-lane syndrome" phenomenon, where HOV lanes are underutilised, leading to suboptimal operation, especially during high-demand periods. Balancing the proper utilisation of these lanes poses a considerable challenge for HOV operators, particularly when confronted with peak-hour congestion. The issues stemming from peak directional flows further complicate the efficient operation of HOV facilities.

Alternatively, effective lane management strategies for bus priority involve using dedicated bus lanes, intermittent bus lanes (IBLs), dynamic lane allocations, and integrated signal controls to improve efficiency and reliability. Bus lanes with intermittent priority (BLIP) allow general traffic to use bus lanes when buses are absent. This approach can reduce overall traffic congestion while prioritising bus transit when necessary [18]. On the other hand, intermittent bus lanes are activated based on real-time traffic conditions and bus schedules. They are effective in maintaining bus service efficiency while minimally impacting general traffic. Studies show that IBLs can significantly reduce bus delays and improve schedule adherence in moderate traffic conditions [19]. Perimeter control involves managing vehicle accumulations at the periphery of a controlled zone to maintain free-flow conditions within the zone, potentially replacing the need for dedicated bus lanes and improving overall traffic efficiency [18].

Truck lanes operate similarly to bus-only lanes. However, they aim to separate truck and passenger traffic to improve flows and increase safety. They may be feasible if truck volumes exceed 30% of vehicular traffic and total volumes exceed 1800 vehicles/lane-hour and 1200 vehicles/lane-hour during peak and off-peak hours, respectively [14].

Pricing lanes comprise high-occupancy toll (HOT) lanes, utilising dynamic toll pricing to manage traffic flow and congestion. Fielding and Klein [20] introduce the term "HOT lane", and Dahlgren [21] states that a HOT lane is designed for HOVs but is also accessible to non-HOVs willing to pay. Toll rates are set to maintain usage below full capacity, and the toll collection process is electronic, ensuring minimal or no delays when entering the lane. Typically, HOT lanes are physically separated from the main lanes by pylons, striped zones, or fixed barriers, reducing the need for enforcement at specific entry points. Their price may be set in a regular toll schedule, it may change by time of day or day of the week, or it may change dynamically in response to the current level of congestion [14].

Gomez-Ibanez et al. [15] analysed and compared seven toll-managed lane projects in the USA, identifying three types. Firstly, conversions from HOV to HOT lanes, where toll-paying single-occupant vehicles may use the former HOV lanes to increase their utilisation. These allow more vehicles to access them while still encouraging carpooling by maintaining free or reduced tolls for multi-occupant vehicles. To implement this idea, Yuan et al. [22] propose an additional toll on HOV lanes, where ride-sourcing vehicles must pay the entire toll while carpool users can split it. This tolling scheme effectively reduces the occupancy of ride-sourcing vehicles in HOV lanes, promotes carpooling, and helps ensure that HOV lanes fulfil their intended purpose of reducing congestion and improving traffic flow. Secondly, the construction of new HOT lanes alongside the original general-purpose ones. This approach adds capacity to the roadway and offers a faster and more reliable travel option for those willing to pay the toll without reducing the number of general-purpose lanes available. And lastly, the construction of new lanes and rebuilding of existing general-purpose ones to fit more lanes in the available transversal space, modernise older infrastructure, or better integrate general-purpose and managed lanes. They point out that HOT lanes almost always compete with free GPLs, which results in more traffic in the latter than is socially optimal and makes it harder to cover costs. This strategy is usually built where traffic volumes are close to the highway's capacity. In these circumstances, speeds are very sensitive to volume fluctuations, which makes it difficult to estimate the optimal toll scheme for HOT lanes, fostering the implementation of dynamic pricing.

Yin and Lou [23] compare two dynamic pricing strategies. The first is based on feedback control, where the toll rate at a time depends on the previous one and current lane occupancy. The other strategy is reactive self-learning, based on modelling users' willingness to pay. In this approach, the flow rates from the previous time interval reveal users' preferences and can be used to calibrate the model and determine an optimal toll rate continuously. The self-learning controller shows better performance.

In metropolitan corridors, dynamic pricing is particularly crucial due to the high variability in traffic flow. Anticipatory dynamic pricing, for instance, adjusts tolls based on predicted traffic conditions rather than just real-time data, helping to maintain target levels of service and avoid traffic breakdowns [24]. Additionally, model-based dynamic toll pricing non-linear model predictive control (MCP) can further optimise traffic flow by dynamically adjusting tools to respond to traffic conditions and reduce congestion effectively [25].

Permission lanes are designated lanes whose criteria for allowing or restricting the flow of vehicles at a given time are independent of their characteristics. They allow or restrict access based on certain conditions or times to optimise traffic flow and manage congestion. The most common type of permission lane is the reversible lane, also known as a tidal flow, bidirectional, or buffer lane, which are lanes that change direction during different times of the day to accommodate peak traffic flows. This strategy has effectively alleviated congestion and improved traffic conditions [26]. Frejo et al. [27] explain that reversible lanes (RLs) are the most cost-effective method for increasing the capacity of an existing freeway, aligning available transportation with mobility demand. The direction of traffic in these lanes is altered to enhance the roadway's throughput. According to Pande et al. [28], RLs are the most efficient way to increase road capacity during rush hours and decrease traffic congestion. Avelar et al. [29] state that RLs are essential for accommodating directional demand in metropolitan areas and study how the adjacency of GPLs affects both performances. They suggest that transportation planners and engineers consider designing and placing pylons or other physical barriers to minimise the impact of GP lane traffic on managed lane speeds.

In addition, lane width reduction is the practice of narrowing the lanes designated for motor vehicles in urban settings to create additional space for other uses, such as bicycle lanes or broader sidewalks, without significantly impacting vehicle flow. This strategy can enhance multimodal mobility by improving the safety and accessibility of roads for various users.

While narrower lanes might slightly affect vehicle flow, the impact is minimal if adequately managed. Considering traffic volume and design, proper lane reconfiguration can mitigate potential delays. For instance, accommodating bicycle lanes within existing roadway widths can lead to significant cost savings and environmental benefits without drastically affecting traffic flow [30].

Active traffic management (ATM) leverages various technologies, such as CCTV cameras and sensors, to inform drivers about incidents, congestion, or changes in lane patterns ahead. Proactively managing lane permissions is crucial for responding to real-time traffic scenarios and improving overall traffic flow. In the United States, Perez and Philips [31] noted that while drivers generally understand and correctly interpret lane control and speed limit signs used in ATMs, some errors still occur, particularly with specific advisory messages. This underscores the importance of establishing clear guidelines and standards for these signs to enhance driver comprehension [31]. Furthermore, advanced traffic monitoring systems, like those developed by the Indiana Department of Transportation, utilise real-time CCTV video feeds to detect traffic conditions and incidents automatically. This technology not only reduces the workload on human operators but also significantly enhances the efficiency of traffic management [32].

Intelligent transportation systems (ITSs) applies technology to develop user-friendly transportation solutions in urban areas. Specifically, for urban corridor management, ITSs can significantly enhance mobility, safety, and productivity in densely populated areas.

These systems integrate advanced monitoring, communication, and control technologies to optimise transportation networks [33]. Recently, this strategy used connected and autonomous vehicles (CAVs) to enhance traffic efficiency, safety, and overall performance of transportation systems. CAVs utilise various technologies, including sensors, communication systems, and artificial intelligence, to navigate and communicate with other vehicles and infrastructure [34]

Many use cases show characteristics from two or more categories. In the literature, the term "Managed Lanes" (MLs) commonly refers to designated lanes in metropolitan corridors where various operational strategies are implemented to optimise traffic flow, reduce congestion, and enhance overall transportation efficiency. These strategies include vehicle eligibility, pricing, and access control. Figure 3 illustrates that MLs incorporate different lane management strategies, including HOV, HOT, express, and special-use lanes for trucks or buses.

Each strategy has distinct advantages: pricing lanes manage demand and generate revenue, eligibility lanes promote carpooling and environmental benefits, and permission lanes optimise traffic flow and support public transit. However, they also present limitations such as equity issues, public acceptance challenges, and the need for effective enforcement. A comprehensive approach that combines elements of all three strategies may offer the most balanced solution for improving metropolitan corridor efficiency. Table 2 provides an overall comparison of the three lane management strategies, highlighting their advantages and disadvantages.

Table 2. Comparison of Lane Management Strategies.

Aspect	Pricing Lanes	Eligibility Lanes	Permission Lanes
Congestion Reduction	High, due to managed demand	Moderate, promotes carpooling	Moderate, prioritises essential services
Revenue Generation	Yes, through tolls	No	No
Environmental Impact	Positive, reduces congestion	Positive, reduces single-occupancy vehicles	Positive, promotes public transit use
Equity Concerns	High, affects lower-income drivers	Lower, though still some access limitations	Low, as it prioritises public and essential services
Public Acceptance	Often resisted	Mixed, depends on public perception	Generally accepted, especially for emergency lanes
Compliance/ Enforcement	Requires robust systems	Can be challenging	Requires enforcement to prevent misuse
Utilisation Efficiency	Variable, depends on demand	Can be underutilised if not enough eligible users	Risk of underutilisation during non-peak times

Table 3 overviews ML evolution over time. It highlights the types introduced in each period, examples where they were implemented, and the corresponding sources for reference. It starts with the early instance of the reversible lane of the Lions Gate Bridge in Vancouver, Canada. The next stage is the bus rapid transit (BRT) lanes [33]. HOV lanes followed, later evolving to HOT lanes. Afterwards is the modern concept of autonomous and connected vehicle (ACV) lanes. Finally, Table 3 includes an emerging new type of ML linked to the popularisation of electric vehicles: the wireless charging lane, which has been proposed as a new type of ML [35].

The evolution of ML from simple reversible lanes to complex, technology-integrated systems illustrates a dynamic approach to addressing traffic management and transportation efficiency in metropolitan corridors. This ongoing evolution underscores the importance of innovation and adaptability in developing resilient and efficient urban infrastructure.

Table 3. Key examples of managed lanes (MLs) over time.

Period	Characteristics	Case Examples	Source
1950s	Reversible lanes.	Lions Gate Bridge	The Vancouver Sun from Vancouver, British Columbia, Canada [36]
1960s	1st Bus Rapid Transit (BRT) lanes.	Shirley Highway (I-95 and I-395) Washington, DC.	Poole [37]
1970s–1980s	High-Occupancy Vehicle (HOV) lanes.	A-6 in Madrid (Spain).	Pfaffenbichler & Mateos [38]
1990s–2000s	HOT lanes. Truck or Freight lanes. Enhanced BRT lanes.	I-10 and US-290 Houston, Texas.	Gomez-Ibanez et al.; X. Liu et al. [15,39]
Future	Autonomous/Connected Vehicle (AV/CV) Lanes.	Theoretical, with data from a metropolitan corridor in Sacramento (USA) and cyber-physical simulation.	Abdel-Aty et al., 2020; Zhao et al., 2023 [40,41]
	Wireless charging lanes. 'Intermittent bike/non-motorised lane'	Tests in a safe driving track in Italy. Tunnel management in Gran Canaria (Spain)	Interviews with Cabildo de Gran Canaria personnel [42]

4. Evidence of the Impact of Lane Management Strategies on Metropolitan Corridors

The following section evaluates the impact of lane management strategies on metropolitan corridor challenges, comparing solutions for congestion management, emissions reduction, safety, and equity.

4.1. Congestion Management

HOV lanes have been effective for over 30 years in managing congestion, enhancing person-moving capability, and maintaining trip reliability; for instance, Wei et al. [43] use microsimulation to study the conversion of one lane per direction into a contraflow HOV lane in Riverside County, California (USA). This lane would utilise underused capacity to alleviate congestion. They predict a reduction of average delays during peak hours by 76% and increased speeds from 60.83 kph to 88.51 kph. They recommend the adoption of full contraflow HOV lanes in areas with significant tidal traffic patterns. This approach maximises the efficiency of existing road infrastructure without requiring extensive physical expansions.

Similarly, HOT lanes, which allow single-occupant vehicles to use HOV lanes for a fee that can be adjusted based on real-time traffic conditions, can significantly improve travel time reliability and reduce peak-hour congestion. Nohekhan et al. [44] perform a before–after study of a HOV to HOT conversion in Washington, DC, USA. A dynamic tolling scheme was implemented, varying prices dynamically every six minutes, with higher tolls during morning peak hours (up to $50 eastbound) compared to afternoon peak hours (up to $25 westbound). The calculated value of time for toll payers ranged from $10 to $300 per hour, with a median of $70 per hour, indicating users' willingness to pay for reduced travel time. The HOV to HOT conversion reduced congestion and improved travel time reliability.

In the case of the Los Angeles Congestion Reduction Demonstration (CDR) project, HOV lanes were converted to HOT lanes ('ExpressLanes') in two freeways. Vanpools, buses, motorcycles, and emergency services are non-revenue vehicles, while each ExpressLane has its policy regarding other toll exceptions or discounts for clean air vehicles and HOV2+s or HOV3+s. If an ExpressLane has not reached capacity, others may pay a congestion level-dependant toll (e.g., $0.25 per mile to $1.40 per mile) to access it. Low-income commuters can apply for a $25 subsidy to use the ExpressLane. The final report [45] could not isolate the influence of exogenous factors like economic growth but finds a positive impact on congestion. The authors suggest that the ExpressLanes help improve travel time, travel time reliability, and throughput in their corridors. However, congestion in the GPLs did not change in their case studies due to latent demand. The introduction of tolled traffic does not negatively impact the ExpressLane performance. The number of trips on the ExpressLanes increased in all categories: HOV3+, HOV2+, single-occupant vehicles, vanpools, etc.

In their before–after study of seven toll-managed projects, Gomez-Ibanez et al. [15], highlight the difficulty of assessing if they are socially worthwhile due to the number of assumptions they need to make. They study the benefits/costs ratio of the projects, with the former composed of investment and operating costs and the former of the monetary value of the time saved by users. Particularly, the cost-effectiveness of the projects depends on the value of time and reliability. They calculate six scenarios for each project with three values of time and two federal discount rates. In the most unfavourable situation (value of time of $17/hour and discount rate of 7%), only two out of the seven projects attain a cost-effectiveness above 1. Conversely, with a time value of $70 and a discount rate of 3%, six projects would be cost-efficient. However, the authors argue that the fast adoption rate by users of those projects indicates their success.

Reversible lanes, which adjust direction based on real-time traffic conditions, also improve traffic flow. Waleczek et al. [46] studied a segment of the Autobahn A 3 in Frankfurt, Germany. Its typical section is three lanes plus a temporary hard shoulder during peak traffic per direction. However, during road work, four lanes in the peak direction and three lanes in the off-peak direction could be maintained using a reversible lane system. The reversible lane carried around 1500 veh/h with an overall decrease of around 15% of the capacity compared to before the road work. However, this strategy still managed to save around 400,000 veh·h of congestion-related travel time losses during road work compared to not implementing it. Even though crashes increased during the road work, only 10% of them and none of the severe ones could be linked to the RL.

Conceição et al. [47] propose a linear integer programming model to design where a city with only automated vehicles should implement reversible lanes. They apply it to Delft, Netherlands, concluding that the busier streets in the city centre should hold most of the RLs, reducing congestion, total travel times, and delays by up to 36%, 9%, and 22%, respectively.

Cheng et al. [48] use microsimulation to study the I-95 express lanes in Miami, USA. They propose a tolling strategy with dynamic feedback control, which varies toll rates based on congestion levels, ensuring smooth traffic flow and maintaining a minimum level of service. This strategy maximises toll revenue while ensuring managed lanes operate at a minimum speed of 72.4 kph. Compared to the existing static tolling scheme, the new approach would lead to higher toll revenue without significantly affecting the level of service.

Jang et al. [49] formulate a dynamic toll pricing strategy that considers the differences in travellers' value of time and expected travel delays in GP lanes. Using traffic data from an 8.69 km freeway segment in the San Francisco Bay Area, USA, and a travel survey of the Bay Area, they state that their strategy would reduce travel times by 20% and emissions.

4.2. Emissions Management

Lane management strategies also play a crucial role in reducing emissions. HOV lanes encourage carpooling, reducing the number of single-occupant vehicles and thus lowering vehicle emissions and improving air quality; for example, Fontes et al. [50] simulate the impact of HOV or/and eco-lanes on medium-sized cities' freeways and arterial and urban roads. They find that HOV lanes would increase average occupancy and positively impact emissions, with a minor travel time reduction. In contrast, eco-lanes would not directly impact emissions, though increasing the market share of EVs does. Similarly, narrowing lane widths can reduce vehicle speeds and emissions. This strategy also contributes to sustainable urban design by integrating bicycle lanes and pedestrian pathways, reducing vehicular emissions. Incorporating these elements can improve air quality and reduce greenhouse gas emissions by lowering dependency on single-occupant vehicles and encouraging active transportation [51].

Active lane management (ALM) strategies, including dynamic lane management and variable speed limits, improve traffic flow and reduce stop-and-go conditions, lowering vehicle emissions. For instance, Kolosz et al. [52] compare different ITS schemes if they were to be applied in the M42 motorway (UK). They find that active management policies would have the highest cost–benefit ratio (almost 6).

Ekedebe et al. [53] analyse six weeks of traffic data from two locations in Washington and Virginia (USA). Using a V2X communications model and a traffic microsimulation model, they conclude that ITSs and vehicle-to-infrastructure (V2I) communications can significantly improve travel time and reduce fuel consumption by 11.8%, resulting in a safer and more efficient traffic system.

Shewmake et al. [54] study the environmental repercussions of allowing hybrid cars to enter HOV lanes with data from the California Clean Air Access Sticker Program. They find that the value of the lane occupied by the hybrid vehicles is considerably higher than the air pollution benefits attained. They suggest that converting the HOV to a HOT lane would be more beneficial, using the revenue to incentivise hybrid demand with subsidies.

4.3. Safety

Several authors study the safety impact of implementing lane management strategies. Cooner et al. [55] consider a case in Dallas (Texas), where HOV lanes have been retrofitted into an existing freeway by reducing lane widths and separating them from GPLs in the same direction with a 91 cm painted buffer. The data show increased crash rates in the HOV lane and the first adjacent GPL, particularly near ingress and egress points and enforcement areas. The authors attribute this trend to speed differentials between HOV and general-purpose lanes; they also recommend increasing the total width of the HOV cross-section elements (inside shoulder, lane, and buffer). A paper by Manuel et al. [56] points in the same direction. They perform a meta-analysis of ten RL studies in the USA, using before–after and cross-sectional comparisons. They find a 30.9% higher collision rate for roads with RLs and higher rates of property-only damage and injury collisions. Operating during peak hours shows a significant and positive correlation with accidents, while restrictions of left turns and longitudinal barriers show a negative one.

Regarding lane width reduction, Wood et al. [57] state that many cross-sectional studies that link it with more car crashes have multiple issues. They analysed data from ten years of mid-block crash data on Nebraska's urban arterial and collector roads (USA). Their findings suggest that narrower lanes can be safer depending on traffic volumes and other factors. Sharma [51] presents a bi-level methodology to optimally select the corridors where it is optimal to narrow multiple lanes and by what amount. This methodology aims to improve system-level travel time without harming travellers' security.

Chen et al. [58] consider another aspect of urban road space allocation: the balance between the widths of lanes and footpaths. They analyse occupant and pedestrian injuries depending on road geometry variables and annual daily traffic. Their methodology allows weighting safety and construction costs associated with each right-of-way allocation. Finally, considering CAVs, setting lanes just for them can optimise flow and reduce congestion, especially since they require less spacing and headway than human-driven vehicles (HDVs). An optimal lane management strategy can reduce delays in urban corridors by up to 78%, with an increasing penetration rate of AVs and CAVs [59].

In the FHA report, Tantillo et al. [60] analyse how incidents on MLs are handled from transportation management centres in eight existing ML facilities, compiling a comprehensive classification of best practices. They emphasise that incidents that occur in managed lanes will affect greater numbers of people, as vehicle occupancy rates are typically higher in managed lanes than in other lanes. Also, optimal incident management is vital for MLs, as their success depends on their travel time reliability. MLs can support incident response by using VSM to deny access to the lane, or by reducing flow by changing vehicle eligibility or increasing toll rates where possible.

Miller et al. [61] use sketch planning techniques to formulate a 10-practices framework to foster active traffic management policies like variable speed limits, hard shoulder running, or dynamic ramp metering in the regional planning process. They estimate these practices should contribute to a safer, more efficient, and less polluting traffic system.

Regarding bus lanes, bus rapid transit routes in Melbourne (Australia) showed a 14% reduction in accidents after bus priority treatments, with severe and fatal incidents dropping from 42 to 29 per year [62]. Also, Wu et al. [63] study how V2V communications can improve the performance of BLIPs. Using a two-scale cellular automaton model, they conclude that BLIPs could mitigate collision risk by dynamically regulating lane usage. Additionally, they assert that implementing bus lanes can significantly reduce crash rates.

4.4. Equity

In a CDR project in Atlanta, a HOV2+ lane was converted to a dynamically priced HOT3+ lane. The Federal Highway Administration (FHA) studied its equity impacts through three perspectives: income, geographic, and modal [64]. Firstly, regarding income and geography, the existence of a free alternative softens the impact of the tolls, especially when compared to full-facility pricing (e.g., a tolled bridge). Conversely, when there are limited or highly congested alternative routes to the HOT lane, the equity impact is higher. Considering modal equity, increasing occupancy requirements at the same time as introducing tolling created great dissatisfaction and reduced use by carpoolers due to the difficulty of coordinating the schedules of three commuters.

This equity analysis is further illustrated by another case study in the I-85 corridor in Atlanta, where a similar conversion from a HOV2+ lane to a HOT3+ lane was implemented. This conversion allowed single-occupant vehicles to access the lane by paying a toll, while vehicles with three or more occupants could use it for free. The introduction of HOT lanes in this corridor resulted in notable changes in traveller behaviour, with increased use of the express lanes by solo drivers and shifts in vehicle occupancy patterns across both express and general-purpose lanes [65]. Additionally, the FHA report highlights contextual factors such as regional familiarity with tolling, public participation in the project, and effective communication with the public that can significantly improve attitudes toward tolling.

5. Challenges and Limitations of Lane Management Strategies in Metropolitan Corridors

Lane management strategies should adapt to the evolving technological and socioeconomic context to make the most out of the available infrastructure and current technological developments. The increasing presence of CAVs is a prevalent topic; equity, safety, and performance questions arise as the proportion of CAVs increases. For instance, at lower CAV penetration rates, it might be helpful to set CAV-only queue-jump lanes to foster the arrangement of CAV vehicle platoons. [66] Dedicated lanes for CAVs can significantly increase the possibility of CAVs forming platoons compared to regular lanes and avoid potential conflicts between CAVs and HDVs [67]. From the safety perspective, CAV-only lanes will likely be necessary, especially in the earlier stages of CAV adoption [68]. Also, platooning behaviour on CAV-only lanes should be carefully designed to avoid impeding HDVs from changing lanes before merging points [69].

Advanced technologies such as dynamic tolling systems, automated license plate recognition (ALPR), and real-time monitoring can be pivotal in enhancing the effectiveness of these strategies. Dynamic tolling systems adjust toll rates in real-time based on current traffic conditions, optimising lane usage and preventing congestion. For instance, the DyETC system has demonstrated an 8% increase in traffic volume and a 14.6% reduction in travel time during peak hours, showcasing the potential of such technology in metropolitan corridors [70]. ALPR systems automate the identification of vehicles using toll lanes, ensuring accurate toll collection and enforcement. Implementations in Portugal have significantly reduced the need for manual intervention by improving toll enforcement accuracy [71]. These systems, alongside real-time monitoring technologies, provide continuous oversight of traffic conditions, enabling quick responses to incidents and facilitating dynamic traffic management. Intelligent transportation systems (ITSs), integrated with real-time monitoring, have proven effective in reducing congestion and improving traffic flow across urban corridors [72].

While setting a dynamic lane reversal scheme may help make the most of the critically demanded infrastructure in a corridor, its design faces two main difficulties. First, the reversal criteria should be free of inconvenient driving direction changes, and second, the drivers should be properly apprised of lane reversal decisions [73]. Smoothing, over time, the variables that trigger a lane reversal and self-learning models can help with the first obstacle and ITS technologies with the second.

Enabling hard shoulder running may increase the capacity of the infrastructure. However, careful measures are required to ensure safety and efficiency, including expanding refuge areas, monitoring systems, speed management, and choosing the traffic conditions for the opening and closing of the shoulder [74]. Implementing such measures involves significant costs, but the economic benefits of reduced congestion and improved traffic flow can offset these. For instance, the costs of monitoring systems and additional infrastructure might be balanced by savings in reduced fuel consumption and time savings for commuters. HOV lane-based strategies may cause the 'empty lane syndrome', where these lanes are underutilised, leading to a suboptimal operation, especially during high-demand periods [17]. Balancing the proper utilisation of all lanes poses a considerable challenge for HOV operators, particularly when confronted with peak-hour congestion. On a related topic, Cohen et al. [75] took advantage of the introduction of three HOV lanes in Israel in 2019 to study the impact of HOV lanes on carpooling adoption. They found a clear impact on travel times, cutting commuting times by 20% to 50%, on average, for carpools. HOV lanes make more users interested in carpooling. Also, their impact is greater if they can be used for roundtrips and if two passengers are enough to fulfil the occupancy requirement. Finally, they find that HOV lanes can shift travel behaviours and increase carpooling on non-HOV routes.

The issues stemming from peak directional flows further complicate attaining an efficient operation in a corridor. A tactical solution can be to open HOV lanes to general traffic while their flow or access queue length is lower than threshold values [76]. ITS technologies like variable message signals, longitudinal flashing lights, or the connected vehicle can keep drivers informed.

Several authors have proposed different strategies to improve bus-only lanes like intermittent bus lanes (IBLs) [77], bus lanes with intermittent priority (BLIP) [19], or bus lanes with intermitted use by car (BLIC) [78]. These solutions work well to improve the infrastructure's overall throughput with moderate public bus service frequencies, maintaining free-flow conditions within the previously bus-only lane [18]. Strategies like intermittent bus lanes (IBLs) and bus lanes with intermittent car use (BLIC) can cost between $100,000 and $300,000 per km. In a demonstration in Lisbon, Portugal, IBLs increased average bus speed by 5% to 20% [77], with an insignificant impact on general traffic. On a related topic, Luo et al. [79] use bi-level programming to explore the possible benefits of a dedicated lane for CAVs and buses. Under favourable bus frequencies and CAV penetration rates, this lane management strategy increases transportation efficiency and reliability, leading to increased ridership and reduced operational costs. These long-term benefits justify the initial investment.

Both HOV and HOT occupancy policies may face difficulties in ensuring compliance, though enhanced and more visible monitoring systems and more restrictive lane access can help. Also, they may miss their intended target. Authorities may want to encourage carpooling but fail to do so, only benefiting those users who were already sharing a car because of no other option. An example of this is fampoolers: families already travelling together when leaving or returning home. Implementing new facilities will meet greater social reluctance if the public is unfamiliar with tolled infrastructures and may only be socially feasible if new lanes or facilities are built [17]. The costs of implementing HOT lanes can be high, ranging from $2 million to $10 million per km. However, the revenue generated from tolls and the economic benefits of reduced congestion can potentially outweigh these costs.

Integrated management corridor policies must face the challenge of sharing the mobility and environmental and economic effects of ITSs and CAVs between all citizens, contributing to their equity. For example, changing general purpose lanes to managed ones should be accompanied by complimentary policies so those users who are dependent on them can find feasible alternatives like competitive public transport options or carpooling. Also, dynamic tolls might disproportionately hit lower-income service workers due to rigid working hours and children's daycare schedules [80].

When establishing a dynamic lane pricing policy, deep learning models outperform control heuristics to maximise revenue or minimise total system travel time [81]. However, the system must include adequate reward-shaping methods to avoid considering unwanted actions as valid suggestions (e.g., 'jam and harvest').

Regarding safety, difficulties to enter the ML due to physical lane separation and restricted access can be challenges for responders during incidents. Thus, it may be worthwhile to have dedicated response vehicles prepositioned at key locations along the MLs [60].

The increasing share of electric vehicles will likely introduce a new challenge soon: introducing and managing wireless charging technologies in urban corridors. Our review has found only one study in this avenue of research, by Tan et al. (2022) [82]. Implementing wireless charging infrastructure for electric vehicles can cost between $500,000 and $1 million per km. However, the long-term economic benefits of supporting EV adoption and reducing greenhouse gas emissions can justify these initial costs, as demonstrated by Khattak et al. [83] Despite the significant initial investment, the substantial long-term advantages make wireless charging technologies a worthwhile consideration.

6. Evaluation of the Suitability of Managed Lane Strategies for a Particular Corridor

A series of features—summarised and classified into four categories—increase the capacity, speed, and reliability benefits of a prospective ML project in a corridor. Table 4 shows these features. Conversely, if a corridor's current state does not support the immediate development of MLs, interim mitigation actions may be applied to reach a future scenario where MLs can be effectively employed. For instance, urban planners may predict that population and business activities along a relatively problem-free corridor will rise significantly, or the authorities may not have the resources to use all the available right-of-way in a single effort.

The particularities of each corridor should be considered when considering the implementation of ML strategies. If there is a significant imbalance between directions during travel demand peak hours in an existing freeway, reversible lanes are the most cost-effective method for increasing the capacity [26,27,77]. If emergency refuge areas can be designated along the road beyond the hard shoulder, HSR is an inexpensive way to increase capacity and safety temporarily during times of high demand or to alleviate the consequences of an accident. Accommodating an extra lane in the platform will likely result in narrower lanes and lower speed limits.

On the other hand, pricing (toll) or eligibility (HOV or bus) lanes work by tempering demand with restrictions and tariffs. Caution must be taken to avoid disproportionately affecting travellers who cannot afford to pay the fares or vehicles compliant with the ML restrictions (e.g., low-emission cars). Multiple studies [40,52,59] point to the performance benefits of setting CAV-only lanes depending on CAV adoption. Thus, decision-makers should consider preparing the infrastructure of a corridor for V2I communications.

Table 4. Desirable features of a ML project in a metropolitan corridor [15,84,85].

Planning factors	– Meeting target level of service for the design year. – Final possible widening of trunk highway. – Potential for ML system connection. – Support major origin–destination flows. – Serve areas with high time/reliability value (e.g., 100,000 workers). – Alignment with local/regional plans. – Sufficient corridor population (e.g., 1,000,000). – Public acceptance.
Geometric layout	– Adequate space for ingress/egress. – Sufficient right-of-way for new lanes.
Operational opportunities	– Bypass congested segments. – Maintains operations in general-use lanes. – Reduces conflicts with general lane traffic. – Easy access/egress for emergency vehicles. – No political constraints (e.g., toll authorisation).
Multimodality synergies	– Travel time savings for express bus services. – Connect intermodal hubs and facilities.

Regarding the economic costs of implementing a ML strategy in a corridor, the initial construction is usually pricey due to the low availability of extra space for new lanes and facilities. Also, many measures that can enhance the performance of managed lanes result in additional expenses. For instance [85], marketing efforts, local and regional fostering of carpooling, visible and automated enforcement mechanisms, physical separation of managed and general-purpose lanes [17], or dynamic management of access restrictions, lane direction, and tariffs. Strategies like IBLs [86], BLIP [87], or BLIC [78] may help bus lanes avoid the 'empty lane syndrome', where GPLs are congested while the managed lanes are severely underutilised. However, the benefit for the general traffic and the detrimental effect on the bus service should be weighted. For higher bus frequencies, other vehicles have to match the buses' lower speeds, while buses suffer delays due to other vehicles' manoeuvres to enter or exit the ML.

7. Limitations Found in Existing Research on Managed Lane Strategies

This literature review shows several weaknesses that can be the focus of future research. Firstly, relatively few papers utilize real traffic data before and after the implementation of a ML strategy to measure its impact directly. Most authors use simulation to assess the performance of their proposed strategies. However, as traffic data becomes easier to obtain, the availability of studies using real traffic data is expected to increase, providing more accurate assessments of lane configurations.

Secondly, there is limited research on how managed lane strategies should adapt to a growing number of electric vehicles. Particularly, the practicality of implementing wireless charging lanes has hardly been scrutinized.

Finally, to the best of the authors' knowledge, there is a gap in the existing literature concerning how ITS technologies can be used to implement active mobility-friendly lane management strategies. For example, using artificial vision to detect bikers in a lane and, if traffic conditions allow, divert motor vehicles to the others. Addressing these research gaps is essential for advancing the effectiveness and adaptability of managed lane strategies.

8. Discussion and Conclusions

Lane management strategies offer significant benefits in addressing the challenges metropolitan corridors face. In summary, this comparative analysis highlights their multiple benefits and challenges.

Decision-makers in a metropolitan corridor should first look for the peculiarities that increase the benefits of implementing ML strategies, including existing planning instruments or factors, geometrical layout, operational opportunities, and multimodal synergies. Even if the conditions at a particular time are unfavourable, it may be worth planning for a future where this changes.

Which lane management strategies are optimal in each case depends on the available infrastructure and the traffic demand. HOV lanes effectively manage congestion and can reduce emissions through carpooling but may pose safety risks due to speed differentials between lanes. The transversal design of the freeway (lane widths and buffer zones) is crucial to face this problem. HOT lanes improve travel time reliability and reduce congestion, with the added benefits of dynamic toll pricing to manage traffic flow. Still, care must be exercised to avoid increasing social inequity. Reversible lanes significantly enhance traffic flow and reduce delays. Still, some authors point out that they can increase the risk of collisions, which can be mitigated with the proper measures, like restriction of left turns and enhanced longitudinal separation. Several authors agree that hard shoulder lanes can be a cost-effective way to increase the capacity of a road if safety is maintained through a series of tools like variable speed limits and emergency refuge areas. Lane width modifications may enhance capacity under specific conditions while contributing to reduced emissions and sustainable urban design, but decision-makers should be careful regarding their effect on security. BLIP reduce traffic delays, improve flow, and decrease emissions while mitigating collision risks through dynamic lane usage. Active lane management (ALM) lowers emissions and improves traffic flow, providing environmental and economic benefits. Dedicated lanes for CAVs optimise traffic flow and reduce congestion with increasing CAV penetration rates. Integrated solutions and comprehensive strategies, including urban road space optimisation and ITS implementation, significantly enhance safety, reduce emissions, and improve overall traffic efficiency. Each strategy offers unique advantages and addresses specific challenges, making it essential to consider metropolitan corridors' context and particular needs when implementing lane management solutions.

Despite their benefits, lane management strategies face several limitations and challenges. Safety concerns are notable, as HOV lanes sometimes pose risks due to speed differentials between lanes, and reversible lanes can increase the risk of collisions. HOV lanes often face the 'empty lane syndrome', where they are underutilised during high-demand periods. In order to foster carpooling, planners should offer the possibility to use HOV lanes for roundtrips, and in most cases require a minimum occupancy of two passengers. Ensuring compliance with HOV and HOT lane policies can be challenging, necessitating enhanced monitoring systems. Additionally, introducing tolls and managed lanes can face social resistance, particularly in regions unfamiliar with such infrastructures.

The spatial context plays a crucial role in the effectiveness of lane management strategies. In the USA, the focus has been on dynamic toll pricing and reversible lanes to manage high traffic volumes. In Europe, particularly in cities like Madrid and Frankfurt, strategies such as HOV and reversible lanes have been adapted to cater to specific urban mobility patterns. With its dense urban populations, Asia has seen innovative bus lanes and implementations of multimodal integration to enhance public transport efficiency. These regional adaptations highlight the importance of considering local traffic conditions and urban development patterns when implementing lane management strategies.

The impact of new social trends on lane management strategies is significant. The increasing presence of CAVs needs dedicated lanes to ensure safety and efficiency. The initial stages of CAV adoption require careful design to avoid disrupting traffic flow. There is also a growing preference for sustainable and non-motorised modes of transport, such as biking and walking. Integrating these preferences into lane management requires innovative strategies like narrower lanes to accommodate bicycle lanes without significantly impacting vehicle flow. Modern urban planning emphasises multimodal transport integration and reducing car dependency. Strategies like BLIP and ITSs are being implemented to align with these evolving concepts, promoting efficient and sustainable urban mobility.

ITS technologies enable the development of advanced multimodal MaaS solutions. By integrating carpooling services with park-and-ride facilities, these solutions can significantly enhance the connectivity between suburban areas and public transport stations (bus or rail) along metropolitan corridors. This approach addresses the critical challenge of limited parking spaces at these transport interchanges, promoting efficient and sustainable commuting options. The combination of ITS technologies and MaaS optimises parking space usage and reduces traffic congestion and environmental impact, fostering a seamless and integrated urban mobility ecosystem.

The analysis highlights that lane management strategies significantly contribute to addressing the challenges of metropolitan corridors by enhancing traffic flow, reducing congestion, and minimising emissions. However, these benefits come with challenges that must be addressed through innovative solutions and adaptive planning. The spatial context and evolving social trends play pivotal roles in shaping the effectiveness of these strategies. Effective implementation requires a comprehensive understanding of local conditions, technological advancements, and changing commuter behaviours.

Future research should focus on several key areas. Integrating emerging technologies, such as CAVs and ITSs, in lane management should be further explored to enhance traffic efficiency and safety. Additionally, the implications of the increasing share of electric vehicles on lane management, including the feasibility of wireless charging lanes, need to be investigated. Developing adaptive lane management strategies that can dynamically respond to changing traffic patterns and commuter behaviours, leveraging machine learning and real-time data analytics, is also crucial. Lastly, assessing the socioeconomic impacts of lane management strategies, particularly on lower-income communities, is essential to ensure equitable access and benefits across all user groups. This assessment should include facilitating convenient transfers to rail and bus stops, ensuring that all population segments can benefit from enhanced connectivity and efficient transportation options.

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