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Modular vehicles in freight transport: A systematic literature review of opportunities and challenges

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ABSTRACT

Modular vehicles (MVs), equipped with autonomous driving, communication, and platooning capabilities, are emerging as a promising innovation in transportation, offering the potential to enhance operational efficiency, flexibility, and environmental sustainability. However, challenges and barriers to their successful implementation are not yet fully understood, which limits the realization of these benefits. This literature review synthesizes existing research on MVs across various applications, including passenger and freight transport, to provide a systematic evaluation of state-of-art, opportunities and challenges for modular freight transport systems. The review identifies research gaps in five areas, such as their integration with multimodal transportation, and highlights key deployment challenges including regulatory hurdles, human factors, financial constraints, and operational complexities. Our findings emphasize the need for policy development, system design research and further empirical validation to assess the practical feasibility and impacts of MVs in the freight transport sector.

1. Introduction

Increasing the share of multi-modal freight transport, particularly rail, which is up to four times more fuel efficient than road, offers a path to decarbonization. However, widespread adoption of rail-based freight systems has been hindered by their comparatively lower speed, flexibility, and reliability (AAR, 2024; European Court of Auditors, 2023; Eurostat, 2023). This highlights the need for technological innovations such as MVs, that can enhance multimodal operations. Modularity refers to the ability of a system to separate and recombine its components, enabling greater flexibility and adaptability. In the transport domain, this principle has led to the emergence of MVs, which allows vehicles to be reconfigured based on specific operational needs. This system integrates advanced technologies such as autonomous driving and communication systems for road transport, and virtual coupling and moving blocks for rail systems. Together, these innovations create flexible and scalable MV mobility systems that can better meet diverse transport needs (Pods4Rail, 2024).

MVs can operate independently or in flexible-length platoons on existing road and rail infrastructure, dynamically adjusting to changing travel demands. Their modularity enables seamless intermodal transfers for goods and passengers through detachable-unit designs, as well as the ability to join or split from platoons in alignment with subsequent modes' schedules (see Fig. 1 for details) (Gabele et al., 2024; NEXT, 2024; Nägele et al., 2023). These features offer the opportunity to

optimize infrastructure use and fleet deployment, reduce operational costs, and enhance service flexibility, positioning MVs as a potentially transformative solution for modern multimodal freight transport.

Despite the growing interest in and recognition of the potential of MVs, particularly in freight transport, there is still no comprehensive synthesis of existing research that allows for comparison or highlights consistent trends and discrepancies. Although Lin et al. (2022) provide an informal overview of recent studies on the use of this technology in road passenger transport, their review covers only a limited number of works and application areas. So far, there has been no systematic or comprehensive review of MVs that addresses both passenger and freight applications, system conceptual frameworks, deployment challenges, and future research directions. This paper fills that gap by presenting the first broad review of MV applications in both passenger and freight transport, with a focus on developments related to freight. Such a review is essential for identifying research gaps and guiding future work, ensuring that all key aspects are considered. To achieve this, the study compiles research on MVs in freight transport, covering areas such as system design, modeling, business models, and economic evaluation.

The review is guided by the following research questions:

- RQ1: What is the current state-of-the-art regarding MVs across various application domains, particularly in freight transport?

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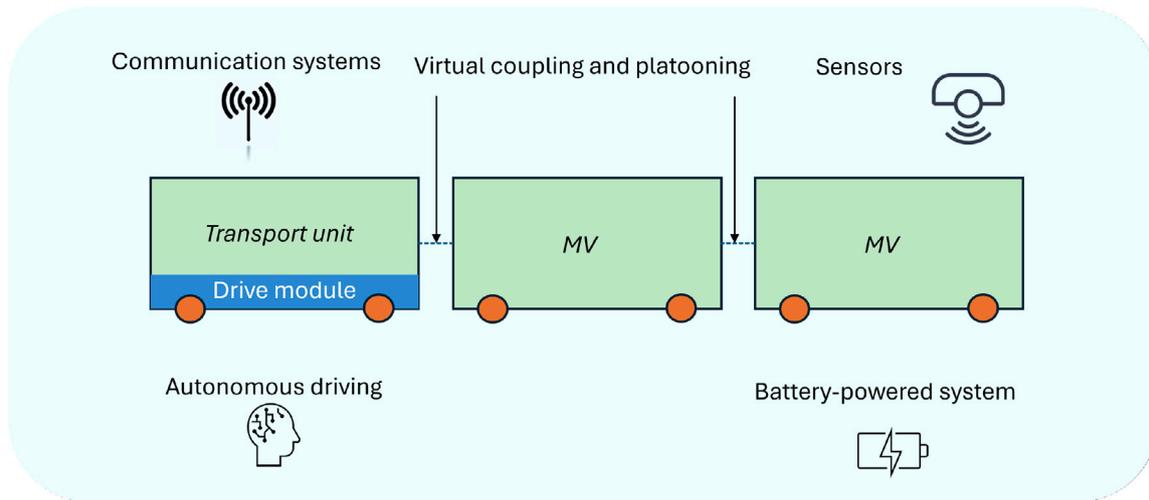


Fig. 1. Sketch of two types of MV: detachable-unit (left) and fixed-unit MV (right two).

- RQ2: What are the main methodological and operational strategies identified in existing research on MV systems?
- RQ3: What are the key barriers and opportunities identified in the literature regarding the practical deployment of MV systems, especially in freight transportation?
- R4: What future research directions can be identified based on the reviewed literature?
- RQ5: What conceptual frameworks can be constructed from the reviewed literature to guide future research and implementation of MV systems?

The structure of the paper is as follows. The MVs concepts and their enabling technologies are introduced in Section 2. Section 3 outlines the methodology employed. Section 4 presents the results of the literature, categorizing the relevant studies into quantitative and qualitative research. Section 5 discusses the impacts of deploying MV systems for freight transport, identifies key challenges and research gaps, and introduces a conceptual model illustrating their operation. Finally, Section 6 summarizes the study, concluding that MV research now spans diverse areas including passenger, freight and mixed use, referring to implementation challenges despite its potentials, and highlighting the need for further comprehensive research on real-world testing.

2. The modular vehicle concept

In the literature, MVs are consistently described with well-defined characteristics (Gabele et al., 2024; NEXT, 2024; Nägele et al., 2023; Pods4Rail, 2024). A modular vehicle consists of a transport unit (TU), which carries passengers and/or freight, and a drive module. These components can be either detachable (as shown on the left of Fig. 1) or built as a single integrated unit (as shown in the two examples on the right of Fig. 1), in which case they form a fixed vehicle (referred to as a pod). Fully autonomous MVs have the ability to couple and travel in platoons, connecting and disconnecting while in motion.

One of the earliest concepts of MVs designed for mixed freight and passenger transport is the HOST Vehicle concept, proposed around two decades ago. This concept was adaptable for services such as ride-sharing, freight delivery, and waste collection, and highlighted potential environmental benefits and increased service efficiency (Orecchini et al., 2005a,b). Since then, technological advancements, including vehicle-to-vehicle communication and autonomous operation, have renewed interest in modularity and its practical value. This has led to a range of pilot projects that explore various applications of MVs. Recent examples of fixed-unit MV designs include the Continental CuBE (Continental AG, 2022a), Bosch Shuttle (Bosch Global,

2020), VW Sedric (volkswagen, 2017), and NEXT (2024). Detachable-unit MVs, on the other hand, enable the selection of transport units tailored to specific freight or passenger needs. Their modular structure also supports transshipment between modes without unloading. Notable concepts in this category include the Rinspeed Snap and microSNAP (Rinspeed AG, 2017), Mercedes Benz Vision Urbanetic (Mercedes-Benz, 2018), Continental BEE (Continental AG, 2022b), DLR MAUDE (Friedrich et al., 2019) and DLR U-shift (DLR Institute of Transport Research, 2021), LiMo (Gabele et al., 2024) and Scania NXT (Scania Group, 2019). Given the novelty of these systems, the only known pilot currently in operation is located in Dubai, UAE (NEXT, 2023).

MVs integrate a range of digital and technological advancements into a single service, significantly improving the performance of transport systems. These advancements can be grouped into three main categories: operation and planning systems, vehicle technologies, and infrastructure.

The **operation and planning system** plays a central role in coordinating the movements of MVs and their interactions with other vehicles, users, and infrastructure. Key functions include mixed-traffic scheduling and rescheduling, which allow flexible assignment of vehicles to meet transport demand; moving block signaling, an advanced train signaling approach where safe zones are dynamically defined in real time based on vehicle locations (Versluis et al., 2024); automated handling and storage systems for efficient vehicle retrieval; information management systems for freight and passenger tracking, ticketing, and pricing; maintenance management systems to ensure vehicle availability; and incident management tools for anticipating and mitigating disruptions.

The **vehicle technologies embedded in MVs** enable their flexible operation and distinguish them from traditional transport modes. These innovations span multiple domains. They include autonomous driving technologies for both road and rail, as well as virtual coupling and platooning systems that dynamically adjust platoon formations. Extensive sensor and camera equipment provides real-time perception and monitoring, while battery-powered systems support clean energy. Advanced vehicle-to-infrastructure communication, precise localization systems, AI-driven decision-support tools, and robust cybersecurity measures ensure safe, efficient, and secure operations.

Finally, while MVs are largely compatible with existing road and rail **infrastructure**, several enhancements are necessary to support their full deployment. These include dedicated energy supplement solutions, remote computing facilities for data processing, advanced communication systems such as V2X for real-time operational updates, and satellite-based positioning technologies to improve navigation and coordination across the transport network.

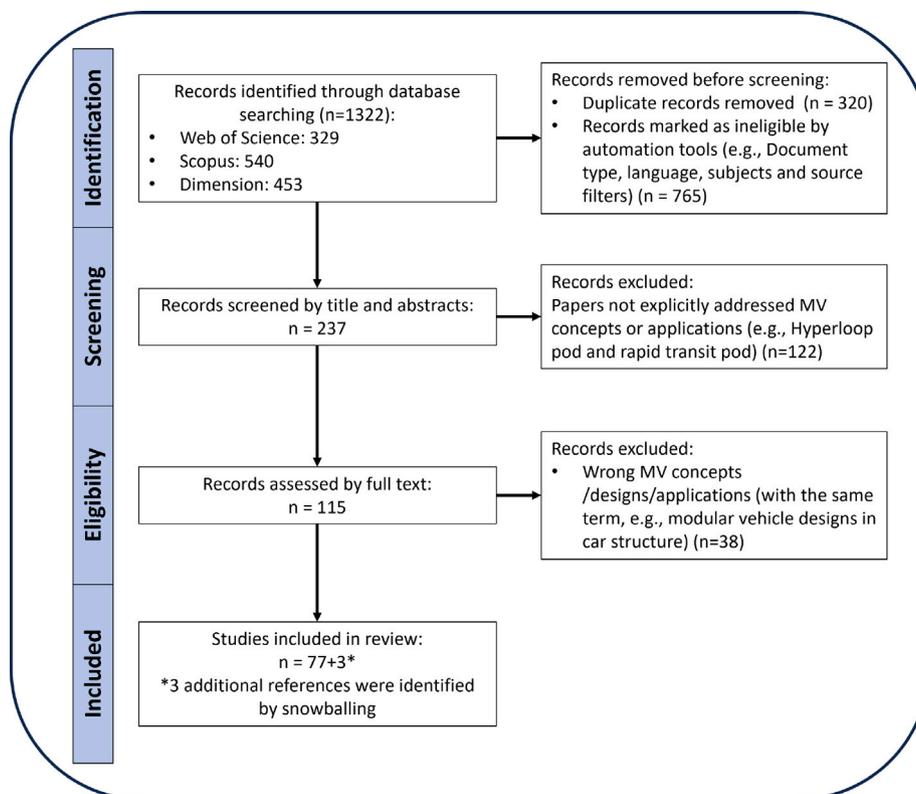


Fig. 2. PRISMA flowchart illustrating the identification, screening, and inclusion process of studies considered in this review.

A major benefit of MVs lies in their ability to form platoons, which is a capability extensively studied in the context of truck transport (Hou et al., 2023). This concept can also be extended to rail freight, with significant potential for improving single wagonload transport concept (Guglielminetti et al., 2017; Krauth and Haalboom, 2022). For example, modular flat wagons with detachable loading units can be consolidated into flexible-length platoons at hubs, improving operation efficiency and eliminating the need for traditional transshipment processes (Gronalt et al., 2019; Pods4Rail, 2024). Together, these developments lay a strong foundation for integrating MVs into the broader freight transport ecosystem.

3. Methodology

This study employs a systematic review methodology based on the protocols outlined by Kitchenham et al. (2007), Denyer and Tranfield (2009) and Durach et al. (2017), which have been successfully applied across a range of research fields. The research approach is structured in four stages (a summary of the search process is provided in Fig. 2): (1) defining research questions, identifying data sources and search keywords; (2) formulating search strings, defining selection criteria, and identifying relevant literature; (3) analyzing and synthesizing the results; (4) reporting the findings.

(1) Defining research questions, identifying data sources and search keywords: The guiding questions and scope are articulated in the previous section. Web of Science and Scopus were selected as the main databases due to their broad coverage of high-impact, peer-reviewed journals in transportation, logistics, operations research, and management sciences, ensuring a robust and high-quality literature base. This selection is further complemented by the Dimensions database (Dimensions, 2024), which provides integrated online visualization and analytical tools to support the verification and presentation of findings. Keywords related to the research questions, starting with “modular vehicle”, “freight” and “transport” and were refined in stage

2. Moreover, considering the unified design of MVs, the potential to use a homogeneous fleet for integrated freight and passenger transport, and the significant work already conducted on the application of MVs for passenger transport, the scope of keywords has been extended to include this domain.

(2) Formulating search strings, defining selection criteria, and identifying relevant literature: The core keywords identified in the first step were further expanded to incorporate related terms and abbreviations. For example, the target technology term “modular vehicle” was extended to include “pod” and “flexible vehicle”, while application-specific terms such as “freight” and “passengers” were broadened to include “cargo” “goods*”, “parcel*” and “people”. Boolean operators were then applied to create structured search expressions, such as (“modular vehicle” OR “pod system”) AND (“freight” OR “cargo” OR “logistics”). Several pilot searches were performed to refine the strings and improve relevance, resulting in the final search query: (“MV*” OR Pod OR “flexible vehicles”) AND (freight OR cargo OR delivery OR good* OR package OR parcel OR shipment* OR passenger OR people) AND (transport* OR logistics* OR mobility). Searches were conducted on titles, keywords, and abstracts without time restrictions given the innovative nature of modular mobility systems, returning 1322 articles.

Studies were then filtered based on several inclusion and exclusion criteria. Subject area filters were tuned to remove irrelevant disciplines such as arts, medicine, and chemistry. Document type and source filters were adjusted to retain only publications in peer-reviewed journals, conference proceedings, academic book chapters, and scientific reports. Only English-language publications were considered, and keywords (filters) were evaluated for their relevance to MVs, transportation, logistics, operations research, engineering, or management science. Duplicates (320) and irrelevant papers (765) were systematically removed, yielding approximately 237 studies. After an initial relevance screening: titles and abstracts were reviewed manually to ensure that each paper explicitly addressed MV technologies or applications, 115

Table 1
Article selection criteria.

Criteria	Description
Scientific databases	Web of science, Scopus, and Dimensions covering peer-reviewed transport and logistics research.
Year of publication	No time restriction due to the emerging nature of MV studies.
Type of publication	Peer-reviewed journal articles, conference papers, and book chapters; non-indexed sources excluded.
Language	Only English-language publications were included.
Inclusion criteria	Studies explicitly addressing MVs in transportation, logistics, operations research, or related fields.

articles were retained for further assessment. The specific inclusion and exclusion criteria are outlined in [Table 1](#).

The 115 shortlisted studies are then evaluated in full-text to determine their relevance to MVs in transportation. This two-step process involved: (1) manual screening of each paper to ensure MV-related content (38 studies were excluded); and (2) backward snowballing to identify additional relevant studies not captured in the initial search. Through this process, 3 additional studies were added, resulting in a final sample of 80 articles.

(3) Analysis and synthesis: The synthesis of findings employs a method of descriptive analysis suggested by [Schick-Makaroff et al. \(2016\)](#), which is suitable for integrating qualitative, quantitative, conceptual, and theoretical research. This approach involves a detailed descriptive analysis of the selected articles, categorizing articles by publication geography, year, and research type (quantitative vs. qualitative).

(4) Reporting of results: The final step involves interpreting the synthesized results from the analysis to delineate the current state of the art. This stage aims to highlight the prevailing challenges and propose future research directions.

4. Results

The results of the review are provided below. A descriptive analysis is provided firstly. Research is then categorized into qualitative and quantitative work (Sections 4.2 and 4.3), where we describe their specific applications, characteristics, and methodologies.

4.1. Descriptive analysis

A descriptive analysis based on the identified studies regarding their research approaches, geographical distribution and publication years is conducted. The analysis covers studies published between 2005 (the earliest identified paper) and March 2025 (the most recent), distinguishing between quantitative and qualitative studies. Quantitative research involves collecting and analyzing numerical data to identify patterns, test hypotheses, and make predictions, while qualitative research focuses on understanding concepts, policies, experiences, or phenomena through non-numerical data like interviews, observations, and textual analysis. Notably, there has been a clear increase in the total number of publications over the past five years, indicating an emerging research interest in this subject. Additionally, the amount of quantitative research has grown in recent years, particularly from 2019 onwards. Conversely, qualitative studies have maintained a relatively stable presence throughout the examined period. Overall, 65% of the studies are published after 2021.

The geographical distribution of the research is analyzed based on the affiliation of each publication's first author, which is assumed to represent the location where the research was funded and conducted. The results show active engagement from only 14 countries, each contributing at least one publication. China leads the research output with 27 publications, followed by the USA with 15, Germany with 11, Singapore with 5, Sweden and Tunisia with 4, the Netherlands, and UAE and Italy with 3 each. Other countries like Greece, the UK, Luxembourg, and Switzerland engage only sporadically in this area.

4.2. Qualitative research

Qualitative research primarily concentrates on the conceptual development of MV systems, including aspects of system design, business models, and supporting policies. Such studies provide the foundational basis for understanding and evaluating MV feasibility, especially during early-stage exploration. In this review, qualitative studies are broadly defined to include conceptual analyses, theoretical frameworks, scenario-based discussions, and methodological descriptions, which do not primarily rely on numerical data or quantitative modeling. This section provides partial insights toward answering RQ1.

Qualitative research represents 11 out of the 80 reviewed articles, as summarized in [Table A.3](#) in [Appendix](#). The first investigation into MVs dates back to 2005, when [Orecchini et al. \(2005b\)](#) introduced a human-oriented sustainable transport prototype. This was followed by a significant surge of interest beginning in 2019, particularly driven by the cross-institutional "Next Generation Car" meta-project led by the German Aerospace Center (DLR). A series of contributions from this initiative ([Friedrich et al., 2019](#); [Ulrich et al., 2019b,a](#); [Münster et al., 2020](#); [Gabele et al., 2024](#)) explore vehicle concepts, operational strategies for different use cases, emerging business models, and supporting technical specifics.

Building on these conceptual and strategic foundations, [Gao et al. \(2022\)](#) propose three application scenarios for MV-based transit systems, demonstrating how dynamic capacity adjustment and en-route passenger transfers can be realized in practice. In parallel, [Friedrich et al. \(2019\)](#) are the first to suggest blending on-road and on-rail modules into a unified mobility framework, a vision currently being piloted under the European Pods4Rail project ([Pods4Rail, 2024](#)). [Gecchelin and Webb \(2019\)](#) extend the modular paradigm into ride-sharing, showing how detachable units coupled with autonomous vehicles form a Modular Dynamic Ride-Sharing (MDRS) system can flexibly match demand in real time.

Complementing this technology-centric trajectory, [Lin et al. \(2022\)](#) offer an early informal review of MV applications in passenger transport, demonstrating their promise for last-mile mobility. Recognizing that technical innovation must be matched by resilience, [Zohner and Lazeski \(2023\)](#) then identified key cybersecurity challenges: dynamic key management, secure vehicle interfaces, and remote integrity verification. These must be addressed before large-scale MV fleets can operate safely in smart cities. Finally, [Mazzarino et al. \(2022\)](#) embed the NEXT modular system within Padua's urban transport ecosystem, showing through stakeholder engagement and policy analysis how cargo hitching can simultaneously support both passenger and freight flows.

In summary, the qualitative studies emphasize the necessity for holistic approaches to successfully deploy MVs and provide foundational insights into the conceptual design, operational strategies, potential business models, and policy frameworks for MVs. These studies highlight critical aspects such as stakeholder engagement, business models, cybersecurity concerns, technological feasibility, and urban policy implications, emphasizing the importance of integrating both passenger and freight transport into unified modular systems. Together, these insights lay the groundwork for subsequent quantitative modeling efforts and to inform practical implementation of MV solutions.

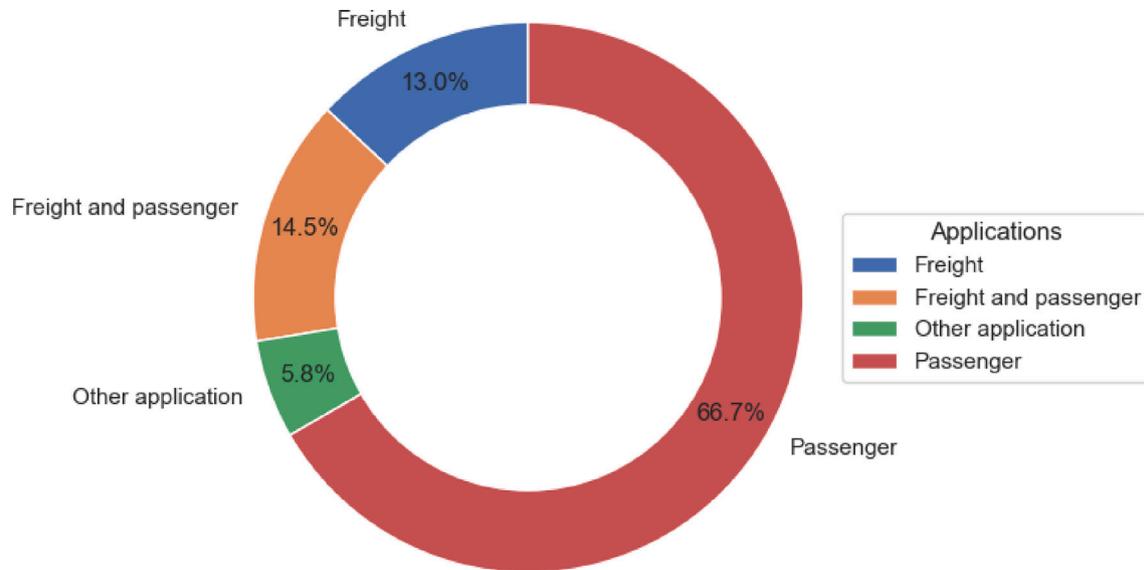


Fig. 3. Applications of quantitative research.

4.3. Quantitative research

The majority of studies (69 out of 80) approach this problem from a quantitative point of view. These studies are categorized and discussed according to their application areas, design choices, and data used. A summary of these classifications is provided in Table A.2 in Appendix. This section contributes to answering both RQ1 and RQ2.

4.3.1. Application

The quantitative research collected can be classified into various applications by passenger transport, freight transport, combined freight and passenger transport, and other applications, as illustrated in Fig. 3. Passenger transport accounts for the largest share, with 46 out of 69 studies. This is followed by research on combined passenger and freight systems (10 out of 69), and freight-only applications (9 out of 69). Additional applications include unique sectors such as emergency medical services and vehicle-to-vehicle charging, and control (2) focuses on platoon formation through coordinated speed adjustments. Although this review focuses on the potential of MVs to improve (multi-modal) freight transport, the limited number of freight-oriented studies necessitates insights from passenger-focused and integrated systems research as well. By analyzing these related works, we seek to identify transferable principles, operational strategies, and design choices that could be applicable to the freight context.

Freight transport In the context of freight transport using MVs, research predominantly focuses on fleet sizing and routing problems within road-based applications. A group of studies (Aggoune-Mtalaa et al., 2015; Rezgui et al., 2018, 2019b,a, 2017; Zhou et al., 2025; Shafiee et al., 2024) address variants of the vehicle routing problem for urban freight distribution. These works examine two types of operational strategies: (1) the use of multiple modular units towed by a cab module, where the units are non-autonomous; and (2) the ability of MVs to dock or detach en route at customer locations, enabling dynamic platoon formation or separation to better meet customer-specific requirements. These studies employ various search methods to address the complex problem of vehicle routing and fleet sizing for MVs. Key findings across these studies include reduced fleet sizes, lower operational costs, and enhanced delivery performance. On the rail side, Liao et al. (2024b) propose a demand-driven MV system for freight pickup and delivery, enabling in-motion platoon reconfiguration, which demonstrates improvements in transport cost efficiency and capacity utilization.

Moreover, Liao et al. (2024a) investigate scheduling of MVs in a rail-based freight system, emphasizing the autonomous assignment of drive modules to transport units and the formation of route-overlap-based platoons, which contributes to reduced makespan and improved capacity utilization.

Combined passenger and freight transport Out of 10 studies addressing combined freight and passenger transport using MVs, with 5 specifically focusing on the Pickup and Delivery Vehicle Routing Problem (PDVRP). Chen et al. (2022a), Hatzenbühler et al. (2022) and Kortekaas et al. (2023) investigate the mixed single and multi-purpose PDVRP, considering body-swapping with detachable-unit MVs (Fig. 1). This allows for the swapping of transport units at service points when the next assigned task requires a different demand type, leading to significant reductions in total system costs and fleet sizes compared to conventional single-purpose fleets. Building on this, Hatzenbühler et al. (2023) extend the work by allowing MVs to form platoons at depots and consolidating passenger and freight requests within one MV, resulting in further cost reductions compared to single-purpose fleets in a case study conducted in Stockholm. Meinhardt et al. (2022) find on-demand MVs can serve dual purposes without significantly compromising passenger service quality, while potentially offering significant operational cost savings for freight services. Lin and Zhang (2024) address urban rail scheduling, exploring scheduling challenges of MVs along a bi-directional urban rail transit corridor. Notable operational cost savings are achieved through efficient docking/undocking at stations and comodality (combined freight and passenger transport, but not in a shared space like Hatzenbühler et al., 2023). Additionally, Zheng et al. (2025) analyze an urban comodal passenger-freight system using MV, formulating optimization models for both transit operators and freight carriers to derive their reservation price functions and comparing four market mechanisms (operators-led Stackelberg, carriers-led Stackelberg, iterative bargaining and full cooperation) through game-theoretic equilibrium analysis.

The remaining three studies in this category do not directly deal with operation problems. Österle et al. (2022) conduct a cost-benefit analysis of using MVs for freight and passenger transport, finding that the benefits outweigh the costs. Deineko et al. (2023) perform an exploratory analysis (the initial phase of analyzing a transportation system to gain insights into its structure and functioning and identify key factors that influence the system's performance) using continuum approximation methodology to model and analyze urban transportation

systems deploying MVs for both passenger and goods transport. Ulrich et al. (2023) apply a life cycle analysis to compare conventional automated vehicles with U-shift (on-road MVs for passenger and cargo transportation) in a use case of S-Vaihingen, considering seven impact categories.

Passengers transport There are 46 studies targeting on different practical aspects of passengers transport. The covered domains are bus system, demand responsive transport and urban rail system.

(1) Bus system: Of the 46 studies, 29 focus on MV applications in bus systems on fixed routes. Romea and Estrada (2021) analyze modular bus on fixed routes in Barcelona, examining the effects of service parameters such as headways and stop spacing on its operation. Zermasli et al. (2023) studies feeder modular bus network design for Athens metro, optimizing fleet size, routes, and station capacities. Similarly, studies by Liu et al. (2023), Xia et al. (2023), Tian et al. (2023), Ji et al. (2021), Wang et al. (2023), Hong et al. (2025), Liu et al. (2020), Tian et al. (2022) and Chen et al. (2019, 2020) examine the operational efficiency of modular bus systems on fixed routes, including scheduling, timetabling, and flexible platoon formation. Their work shows significant improvements in demand–supply matching, reducing operator and passenger costs. Tian et al. (2025) extends these by developing a real-time learning-based operational framework to optimize MV platoon formations, reducing operational expenses, passenger waiting times, and congestion. Moreover, Dakic et al. (2021) uses a three-dimensional macroscopic fundamental diagram (3D-MFD) to optimize modular bus units in Zurich, integrating human-driven and MVs. Tang et al. (2024), Liu et al. (2021), Zou et al. (2024) and Wang et al. (2025) propose a platoon-based bus operation system with decoupling for targeted door-to-door service in the area surrounding the mainline, significantly reducing total system costs. Pei et al. (2021) develops a dispatching model for modular bus networks, optimizing route assignments and platooning configurations based on demand. Xia et al. (2024) introduces a model combining fixed-route bus services and demand-responsive transport (DRT) using MVs, dynamically adjusting bus formations to meet fluctuating demands and reducing operational costs.

Gong et al. (2021) proposes a transfer-based customized modular bus system with passenger-route assignment optimization, aiming to integrate modular fleets within network designs, enhancing route efficiency and vehicle utilization. Furthermore, Wu et al. (2021) explores planning of modular buses at intersections, showing reductions in passenger transfers and travel time, with energy consumption similar to conventional bus systems. Guo et al. (2017) demonstrates that switching between fixed-route and on-demand modular buses could reduce costs by 72%, while Khan and Menendez (2022), Khan et al. (2023), Liu et al. (2024) and Zhang et al. (2024) focus on the coupling-decoupling strategy, superior to traditional methods in reducing bunching effects and passengers' waiting times.

Two studies focus on traffic flow rather than operational aspects. Wang et al. (2024) proposes a heterogeneous demand traffic assignment model for multimodal transportation, integrating private vehicles, public transit, and MVs, and introduces a dynamic equilibrium framework to model choice behaviors. Li et al. (2025) analyzes flow equilibrium between modular bus and private vehicles during morning commutes, showing that modular buses can reduce congestion and societal costs with high coupling efficiency and optimized passenger loads.

(2) Demand responsive transport (DRT): Nine out of the 46 studies relate to the pickup and delivery vehicle routing problem (PDVRP) or demand-responsive transport (DRT) services, which do not follow fixed or corridor-based lines; in these cases, passenger demand can be picked up or dropped off at predefined stops or anywhere within the network. Caros and Chow (2021) investigate the utilization of MVs for DRT services, implementing a two-sided day-to-day learning framework to assess various operational strategies using empirical data. This

research highlights that en-route transfers among MVs can substantially improve operational efficiency and user experience by enabling dynamic reassignment of passenger and optimizing travel routes. This approach also reduces the fleet's overall travel distance, particularly in hub-and-spoke operational designs. Then Fu and Chow (2023), Maiti et al. (2024) and Yuan et al. (2025) extended their research to explore the MV platooning in DRT services, including the in-motion transfer of passengers between MVs within a platoon, eliminating the need to stop at designated transfer points. Their findings show significant reductions in both operational costs and service times across synthetic and real-world scenarios. In Sun et al. (2025), a reservation-based first-and-last-mile service for metro station using MVs is proposed, where MVs dynamically assemble to match demand at depot. The problem is modeled as a stochastic semi-Markov decision process and solved via a multi-agent RL algorithm. Results on a real Singapore network show near-optimal performance and improvements in profit and service quality over fixed-capacity baselines. Additionally, a series of studies (Zhang et al., 2020; Guo et al., 2023b; Gao et al., 2023; Guo et al., 2023a) explore the on-demand modular customized bus (CB) system, which utilizes modular buses that can be detached and reattached to bus platoons at stations or depots based on passenger demand. These studies focus on optimizing platoon formation, routing, charging and passenger-to-vehicle assignments, showcasing the high potential of MVs in enhancing flexibility and reducing overall system costs in transport services.

(3) Urban rail system: out of 46 studies, 8 specifically address line- or corridor-based urban rail systems involving MVs, in which the MVs operated solely along fixed routes. Chen and Li (2021), Chen et al. (2022b), Pei et al. (2023) and Zhuo et al. (2024) explore the scheduling of MVs along urban rail corridor or metro line, emphasizing station-wise or depot-wise docking to uncover operational cost reductions and enhanced vehicle utilization compared to traditional fixed-formation operations. Shi et al. (2020) and Shi and Li (2021) analyze MVs for variable-composition operations at depots in urban rail environments, demonstrating significant operational cost savings. Additionally, Yin et al. (2022) examine the scheduling of MVs and passenger flow in rail transit, incorporating a trip reservation system that allows for advance booking by passenger and real-time demand-based schedule planning by operators to boost operational efficiency and fairness. And Wu et al. (2024) propose a Dynamic Autonomous Non-stop Rail Transit (DANRT) system utilizing MVs to enable carriages to attach and detach from trains without requiring the trains to stop at stations, which reduces passenger travel time significantly compared to traditional urban rail systems.

Other applications Two additional applications targeting operational-level planning problems with MVs have been identified. Hannoun and Menendez (2022) investigate the application of MV technology in emergency medical services (EMS) to reduce response times and transport times to hospitals. They achieve this by optimizing MV assignments, enabling coupling and decoupling during en-route patient transfers to improve overall efficiency. Furthermore, Fu and Chow (2024) introduce an innovative concept where a fleet of MVs serves as electricity suppliers, transferring power to other electric vehicles while moving in platoons en route. This approach minimizes detours and charging times at stations, resulting in significant reductions in total costs and travel time.

Moreover, Li and Li (2022, 2023) focus exclusively on control aspects related to efficient docking and platooning operations of MVs on road intersections. These studies emphasize the development of trajectory planning strategies to enhance safety, reduce congestion, and improve operational efficiency. Both highlight the potential of MVs to revolutionize transportation by optimizing space utilization and traffic flow on roadways.

4.3.2. Design choices

The design and modeling of MV systems in the literature cover a range of aspects, including platooning strategy, passenger transfers, charging operation, vehicle fleet rebalancing, time requirements, station storage capacity, stochastic elements, network structure, modeling approaches, objective functions and solution approaches. The following sections give an overview of the studies that specifically address each of these design choices. The main directions and gaps, derived from this review are summarized in Section 5.

Platooning strategy Platooning where multiple MVs travel together to dynamically adjust capacity in response to demand and reduce transportation costs is a defining feature of MV systems. As shown in Table A.2 in Appendix, 55 quantitative studies (excluding the two focused on traffic flow analysis) incorporate dynamic platooning strategies across passenger, freight, or mixed-use transport settings. These strategies can be classified into two main categories: depot-based and station-wise.

The majority of studies (37) adopt station-wise platooning, a node-based approach in which MVs arrive at designated stations or nodes where platoon compositions can be reconfigured before proceeding. Seventeen studies implement depot-based platooning, where platoon structures are fixed at the depot and remain unchanged throughout the route. Ten studies do not explicitly address platooning strategies. However, three of them (Chen et al., 2022a; Hatzenbühler et al., 2022; Kortekaas et al., 2023) explore body-swapping mechanisms instead, where detachable-unit MVs (illustrated in Fig. 1) switch between passenger and freight units at predefined locations to accommodate varying demand types.

To tackle the complexities of platooning, a wide range of methods have been applied, with mathematical optimization being the most prevalent. These models typically build on traditional routing and scheduling decisions, notably incorporating flexible platooning decisions. These platooning decisions generally fall into two types:

1. **Variable-size platooning**, where a single MV consisting of n connected units travels as a unified platoon: the size of the platoon can vary.
2. **Coordinated platooning**, where more than one independent MV, each operating separately, are synchronized spatially and temporally to operate as a platoon: individual MVs to couple or decouple as needed.

A key challenge in both cases lies in determining the optimal platoon size, with the second approach requiring more complex coordination of timing and location.

Recent studies (Liu et al., 2024; Sun et al., 2025) model platooning as an SMDP and apply deep RL to optimize platoon formation. Liao et al. (2024a) propose a simulation framework for detachable-unit MVs (Fig. 1) that addresses sequenced platoon formation alongside transport unit and drive module assignment decisions.

Passenger transfers Gong et al. (2021) explore passenger transfers at stations, where passengers are required to disembark in order to switch between different MV platoons. In contrast, several studies (Wu et al., 2021; Fu and Chow, 2023; Caros and Chow, 2021; Maiti et al., 2024; Yuan et al., 2025; Zermasli et al., 2023; Pei et al., 2021; Zou et al., 2024; Wang et al., 2025) investigate en-route passenger transfers, which allow passengers to move between MVs within a platoon at specific locations without disembarking. These approaches consider the interactions between multiple vehicles, enabling transfers while in motion, thereby reducing detours and eliminating the time typically required at transfer stations. Specifically, Hannoun and Menendez (2022) apply the concept of en-route transfers in emergency medical transport, where patients can be transferred between a life-support vehicle and a medical transport vehicle at predetermined transfer points.

To support such transfer strategies, simulation frameworks (e.g., the two-sided simulation in Caros and Chow (2021)) and optimization-based methods have been employed. These approaches must ensure

that MVs and their onboard passengers are synchronized in both time and space to facilitate successful in-motion transfers. Similar conditions to those used in platooning apply here, with the added complexity of determining which passengers should be transferred.

Charging operation Since MVs are typically battery-electric, charging operations emerge as a critical design consideration across different transport contexts. Several studies (Guo et al., 2023b; Gao et al., 2023; Chen et al., 2022a; Aggoune-Mtalaa et al., 2015; Rezgui et al., 2018, 2019b,a, 2017; Yuan et al., 2025; Sun et al., 2025) investigate strategies for determining when, where, and how much to charge, ensuring that vehicles remain sufficiently powered to meet service demand.

These charging decisions are often integrated into routing and scheduling optimization frameworks. In particular, some studies formulate the problem as a semi-Markov decision process (SMDP), with reinforcement learning applied in Sun et al. (2025) to enable adaptive charging scheduling for MVs at depots.

Vehicle fleet rebalancing Vehicle rebalancing refers to the process of relocating and storing MVs efficiently after the completion of tasks, which is essential in a demand-driven MV system. Studies such as (Tian et al., 2023; Xia et al., 2024; Tian et al., 2022; Wang et al., 2025) incorporate repositioning as part of operational planning for passenger transport, addressing decisions regarding which MVs and how many MVs should be relocated to which locations.

Optimization techniques are employed to determine cost-effective rebalancing strategies, aiming to maintain an appropriate balance between vehicle supply and demand across the network.

Time requirements Time requirements are commonly considered in the modeling of MVs for passenger, freight, and mixed-use transport systems. One of the most prominent time-related aspects is the incorporation of time windows, especially in problem settings related to vehicle routing problems (VRPs) (Chen et al., 2022a; Hatzenbühler et al., 2022, 2023; Kortekaas et al., 2023; Guo et al., 2023b; Gao et al., 2023; Aggoune-Mtalaa et al., 2015; Rezgui et al., 2018, 2019b,a, 2017; Sun et al., 2025; Liao et al., 2024b).

Among these studies, only hard time windows are considered, meaning that each passenger or freight request must be served strictly within its designated time window. Soft time windows, which allow for delayed service with penalties, are not used.

Beyond time windows, broader time requirements are also relevant, particularly in public transport systems such as urban rail or bus services. In these cases, each demand (passenger or freight) is typically associated with a ready time and an implicit requirement to minimize the transport duration from origin to destination. This duration can be affected by passenger waiting times, MV detours to serve other demands, delays due to shared routing, or waiting for platooning opportunities.

Station storage capacity To fully exploit the potential of MVs, especially in studies that implement station-wise platooning, abandoned or idle MV units are often stored at intermediate stations. Most of the existing literature assumes that the storage capacity at such stations is sufficiently large and does not impose any constraints.

However, this assumption does not always hold in practical scenarios. For instance, Xia et al. (2024) explicitly introduce constraints that limit the number of idle MVs that can be stored at each station over discrete timesteps. Similarly, Tian et al. (2022) incorporate station location planning, including docking and undocking functionality, and station capacity planning as part of their optimization framework, treating them as decision variables to enhance operational feasibility.

Stochastic elements In transportation systems, many key inputs, such as passenger demand patterns, vehicle dwell and travel times, and real-time forecasts, are inherently uncertain, often rendering deterministic plans suboptimal or infeasible. To address this, several studies explicitly incorporate stochastic elements into the modeling of MV systems.

For example, Xia et al. (2024, 2023) apply distributionally robust optimization with Wasserstein- and discrepancy-based ambiguity sets to hedge against demand estimation errors in fixed-route and scheduling contexts involving MVs. Sun et al. (2025) model first/last-mile services as a semi-Markov decision process and employ multi-agent deep Q-networks with mean-field approximations to adaptively respond to stochastic passenger request arrivals and cancellations.

In another example, Liu et al. (2024) capture modular bus-bunching dynamics under random boarding and traffic delays using a continuum model, and learn split/merge control policies via a specialized deep Q-network that includes replay-buffer enhancements. Meanwhile, Tian et al. (2025) embed a convolutional neural network (CNN)-based proxy within a rolling-horizon control framework to instantly predict near-optimal headways and modular formations in response to noisy, time-varying demand.

These approaches reflect a growing recognition that robust MV system design must account for stochastic variability to ensure reliable and adaptive service in real-world settings.

Network structure As summarized in Table A.2 in Appendix, research on transport network structures within the MV domain is evenly divided across different network types. Specifically, 31 studies focus on networked service models, particularly those involving the Vehicle Routing Problem (VRP) to support unscheduled, demand-responsive services.

The remaining 32 studies consider single-line or multi-line structures (including two studies on multiple-line systems), which are generally oriented toward providing scheduled services along predefined routes. Notably, four studies (Tang et al., 2024; Liu et al., 2021; Zou et al., 2024; Wang et al., 2025) labeled as “single line with PD” in Table A.2 in Appendix propose a unique hybrid structure in which platoons operating along a single baseline route are allowed to temporarily decouple and provide targeted, door-to-door pickup and delivery services within local segments adjacent to the main route.

Modeling approaches Based on the data summarized in Table A.2 in Appendix, the predominant method used to study MV systems is mathematical optimization, which is applied in 51 out of the 62 quantitative studies to address various aspects of MV planning and control.

In addition to optimization, simulation techniques are employed in five studies (Khan et al., 2023; Caros and Chow, 2021; Meinhardt et al., 2022; Guo et al., 2017; Liao et al., 2024a) to evaluate system behavior under different scenarios. Furthermore, seven studies adopt alternative modeling approaches to provide broader insights into the efficiency and sustainability of MV systems. These include cost-benefit analysis (Österle et al., 2022), life-cycle assessment (Ulrich et al., 2023), and exploratory modeling (Deineko et al., 2023) for combined passenger and freight MV transport. Additionally, traffic flow equilibrium analysis with discrete choice modeling is used in Li et al. (2025) and Wang et al. (2024) to study mode choice behavior between MVs and other forms of public transport. Moreover, Liu et al. (2024) and Sun et al. (2025) model the operational problem as a semi-Markov decision process (SMDP) and apply deep reinforcement learning to derive optimal policies under uncertainty. Meanwhile, Tian et al. (2025) utilize a convolutional neural network (CNN) as a machine learning proxy to approximate near-optimal decision-making in a rolling-horizon framework. Interestingly, Zheng et al. (2025) use a game-theoretic equilibrium framework to model negotiations between transit operators and freight carriers in a passenger-freight corridor with MVs.

Objective functions A variety of objective functions are employed in mathematical optimization and reinforcement learning models within MV-related research, reflecting different stakeholder perspectives. From the **operator’s perspective**, the primary objective in most studies (45) is to minimize operational costs, including transportation and dispatching costs. Less frequently addressed cost components include

module-swapping costs (Chen et al., 2022a; Hatzenbühler et al., 2022; Kortekaas et al., 2023), freight handling costs (Lin and Zhang, 2024), and vehicle repositioning costs (Tian et al., 2023; Xia et al., 2024). Some studies also incorporate ownership or vehicle purchase costs related to fleet sizing (15 studies), penalties for unmet demand (9 studies), and vehicle charging costs (7 studies).

Beyond cost minimization, several studies target service performance and system efficiency. For instance, Zhang et al. (2020) aims to maximize service rate, Ji et al. (2021) minimizes the number of empty seats, Tian et al. (2025) reduces in-vehicle congestion, Yin et al. (2022) seeks to minimize disparities in passenger utility (i.e., fairness), and Sun et al. (2025) maximizes service profits by balancing operational costs and customer service revenue.

From the **passenger’s perspective**, the most commonly modeled objectives involve minimizing in-vehicle travel time and waiting time (27 studies), which are sometimes converted into equivalent monetary costs. In addition, the number of passenger transfers, viewed as a form of disutility, is incorporated into the objective functions in Yuan et al. (2025) and Wu et al. (2021).

Other objective functions appearing in the literature include infrastructure investment costs (Tian et al., 2022; Romea and Estrada, 2021), emergency response times in medical transport systems (Hannoun and Menendez, 2022), and control-based objectives such as minimizing squared acceleration and deviation distance for trajectory optimization (Li and Li, 2022, 2023).

Solution approaches The solution approaches adopted in mathematical optimization and semi-Markov decision process (SMDP) research (53 studies). These approaches can generally be categorized into heuristics (29), exact methods (20), and AI-based methods (4).

Customized heuristics: These methods tackle large MV problems by decomposing them into smaller, more manageable subproblems. For instance, Wu et al. (2021) apply a two-stage A^* algorithm, and Yin et al. (2022) use nested heuristics to separate timetable design, platoon formation, and passenger flow control. Lagrangian relaxation techniques in Guo et al. (2023b,a) partition the task into routing, vehicle-assignment, and platoon-assembly subproblems, while Fu and Chow (2023) combines a tailored routing subproblem with a neighborhood-search-based platooning heuristic. Column generation is also employed in Gao et al. (2023) to iteratively refine the solution space.

A subset of studies hybridize heuristics with exact solvers to balance speed and optimality. For example, Shi and Li (2021) use dynamic programming for MV scheduling followed by a solver for passenger-vehicle matching; Lin and Zhang (2024) similarly split rail scheduling and platoon adjustment across two stages. In Tian et al. (2022), a surrogate model reduces the station-selection problem before exact optimization, and Zhang et al. (2020) applies recursive graph partitioning to cluster passengers and solve each cluster with CPLEX in parallel.

Metaheuristics: Population-based algorithms include particle swarm (Gong et al., 2021) and genetic algorithm (Zermasli et al., 2023; Rezgui et al., 2019a), which evolve solution populations via selection, crossover, and mutation. Single-solution methods such as variable neighborhood search (Rezgui et al., 2019b), tabu search (Zhou et al., 2025), and adaptive large neighborhood search (Xia et al., 2024; Hatzenbühler et al., 2023) iteratively destroy and repair solutions using adaptive operator selection.

Exact methods: Exact approaches solve smaller MV formulations directly. Commercial solvers address bus scheduling (Ji et al., 2021; Pei et al., 2021), request assignment (Kortekaas et al., 2023), and platoon planning (Liao et al., 2024b; Pei et al., 2023). Classical techniques include branch-and-cut (Xia et al., 2023), dynamic programming (Chen et al., 2019), and continuum approximation (Chen et al., 2022b), ensuring optimality when problem size permits.

AI-based methods: Reinforcement learning and learning proxies enable real-time decision-making under uncertainty. Tian et al. (2025) train a CNN proxy offline to predict near-optimal MV headways and

formations; Sun et al. (2025) apply multi-agent deep hierarchical RL for day-ahead MV reservation and charging operation; and Liu et al. (2024) use a DQN with multiple replay buffers to learn split-merge policies that prevent modular bus bunching.

4.3.3. Data used

Beyond the predominance of synthetic datasets employed in 24 of the 69 quantitative studies to test new algorithms under controlled conditions, a substantial body of work draws on real-world transport data to validate model realism. These empirical sources fall broadly into two categories: individual vehicle traces (e.g. taxi GPS logs and ridesharing dispatch records) and public transit smartcard or AVL/AVL (automated vehicle location) feeds from bus and metro operators. For example, several studies use multi-day taxi trip records from Beijing or New York City to calibrate on-demand MV routing heuristics (Zhang et al., 2020), while others leverage AFC (automated fare collection) data from Singapore's DRT pilot (Tian et al., 2022, 2023, 2025) and AVL traces from Athens Metro feeder services to fine-tune station-level assembly and disassembly models (Zermasli et al., 2023).

Geographically, these empirical investigations are heavily clustered in China, the United States, and Western Europe, reflecting both data availability and institutional partnerships. Consequently, modeling assumptions often implicitly mirror the travel patterns, regulatory environments, and infrastructure characteristics of these regions. To broaden the applicability of MV research, future work should seek to incorporate datasets from under-represented contexts such as landlocked or developing country networks where network density, demand volatility, and infrastructure constraints differ markedly. Developing open-access benchmark datasets for MV operations would further enhance reproducibility, facilitate cross-study comparisons, and accelerate the transition from synthetic proof-of-concept to real-world deployment.

4.3.4. Summary

The components discussed above can be reorganized into three interlinked dimensions of an MV system: transport assets, operations management, and transport demand. Network structure, vehicle equipment, and infrastructure (transport Assets) set the physical, financial and operational limits for platoon size, charging station placement, and vehicle rebalancing, directly shaping operational decisions. In turn, transport operations management (e.g. platooning, passengers transfer, charging operations, vehicle rebalancing, objective functions, and algorithmic approaches) must be designed around the temporal and spatial characteristics of demand, ensuring schedules and routing abide by time windows and passenger or freight flows. Finally, observed demand patterns (transport demand) considering stochasticity can feed back into asset planning by indicating where additional network capacity or charging infrastructure is most needed. Each design choice not only serves its primary function but also guides and constrains the others, ultimately determining the overall performance of MV systems.

These elements provide a strong foundation for developing a conceptual framework for the MV mobility system (Section 5.3; Fig. 5 details the interconnections among components).

5. Discussion

Building on the analysis in earlier sections, this section examines the opportunities MVs offer for improving freight transportation, identifies the gaps that must be addressed to realize this potential, and outlines future research directions and policy recommendations to support wider deployment. Integrating MVs into the freight transport system as a seamless component is challenging, especially given the sector's multimodal and multi-stakeholder nature. With these challenges in mind, and drawing on insights from the literature review, a conceptual model is proposed as a foundational framework.

5.1. Opportunities of MVs for freight transport

This section identifies and discusses the opportunities of MVs for freight transport in response to RQ3. For freight transport, MVs enable dynamic configuration adjustments in routing to match demand, thereby enhancing operational flexibility and reducing costs through improved alignment of supply and demand. Initially, the most tangible benefits of MVs in freight transport have emerged from research directly related to freight operations. These benefits are for instance related to reduction of fleet size and transport costs (Aggoune-Mtala et al., 2015; Rezgui et al., 2018, 2019b,a, 2017; Zhou et al., 2025) required for urban freight deliveries using MVs compared to conventional vehicles. These findings are supported by the research on MVs in combined passenger and freight transport (Chen et al., 2022a; Hatzenbühler et al., 2022; Kortekaas et al., 2023; Hatzenbühler et al., 2023), identifying additional advantages such as decreased transport distance, reduced trip duration and lower empty vehicle kilometers. These studies also highlighted savings from the consolidation of passenger and freight demands, using shared space within a single vehicle, thereby enhancing vehicle utilization and potentially meeting stringent scheduling requirements more effectively. Furthermore, Meinhardt et al. (2022) demonstrate the potential to significantly reduce idle times of MVs by incorporating freight deliveries with passenger transport. This integration not only simplifies logistics by minimizing the need for varied fleet sizes but also streamlines maintenance, operations, and procurement processes, leading to considerable cost savings for freight operators.

Although key performance indicators (KPIs) differ between freight and passenger applications, with freight KPIs primarily focusing on economic outcomes, the impacts of MVs on freight transport can still be inferred from their use in passenger transport and other sectors, such as medical services. This is made possible by the shared design principles and similar operational methods of MVs across these domains. Key benefits often include reductions in energy consumption due to MV platooning, a concept extensively explored in the context of truck and rail platoon studies. Moreover, MVs help reducing in-vehicle travel time and waiting times at service points, crucial for adhering to the tight delivery schedules demanded in logistics, thereby effectively minimizing delivery delays (Hatzenbühler et al., 2023). These aspects can apply to both freight and passenger transport.

Studies on passenger transport show that en-route transfers within an MV platoon reduce required transfer stops and allow sharing of excess capacity among vehicles in a platoon (Fu and Chow, 2023), thereby saving transfer time and using fleet capacity more efficiently. This mechanism could be adopted by analogy for freight operations, assuming that each MV is equipped with personnel or autonomous conveyor systems to facilitate freight transfers between vehicles in a platoon. However, unlike passenger transfers, which require minimal time and space, en-route freight transfers demand significantly more space due to the presence of onboard personnel, transfer equipment, and the physical handling of goods. This limits the possibility of frequent reassignment of freight requests to individual vehicles within a platoon during transit, which is arguably more feasible in the case of passenger transport. Additionally, these operations could reduce the vehicle's net carrying capacity and require more handling time than passenger transfers. Therefore, while en-route transfers are technically feasible for freight, their practicality and benefits for freight transport are expected to be more limited and the feasibility and potential impacts thereof should be subject of further research. Moreover, the schedules for various MV platoons at passenger transfer stations, enabling passenger transfers, have been explored by Pei et al. (2021) and Gong et al. (2021), providing valuable insights for efficient freight transfer.

Potential advantages for freight transport also encompass space savings and the potential to free up capacity on constrained infrastructures such as railways, ports, and freight handling terminals, primarily due to the compact design of MVs and more flexible fleet management

for rail freight (Gabele et al., 2024; Liao et al., 2024b,a). These MVs also enable substantial time savings for freight and passenger trains by reducing the time spent in changing compositions at shunting yards, thanks to the automation and MVs' ability to dynamically adjust configurations while in transit. Additionally, the capacity of MVs to modify compositions on the move helps eliminate unnecessary stopping times at each service station (Wu et al., 2024; Khan and Menendez, 2022; Khan et al., 2023; Zhang et al., 2024), as only those MVs assigned specific tasks at stations need to detach from the platoon and halt, allowing others to continue uninterrupted. This feature significantly reduces travel time for freight delivery, enhancing overall logistics efficiency. Furthermore, rail freight, traditionally aimed at bulk and mining products like metal ore (Eurostat, 2024), has the potential to tailor to smaller shipments, thus expanding its service scope like parcels delivery by adopting MVs (van de Lande et al., 2024). MVs also have the potential to enhance intermodal connectivity, making it easier to transfer goods between different modes of transport without the need for costly and time-consuming reloading processes (Nägele et al., 2023). Their autonomous operation further alleviates the industry's pressing issue of driver shortages (EUobserver, 2023; IRU, 2022).

Finally, optimization, simulation, and artificial intelligence techniques, which are extensively validated in passenger MV applications, provide a robust methodological foundation for freight use cases. These methods can be tailored to freight-specific constraints to accelerate real-world deployment of MVs in freight transport systems.

5.2. Challenges and barriers for deployment

The MVs concept has been studied for some years, yet it has not fully transitioned into a practical reality, with actual implementation cases still limited. Responding to RQ3, this section identifies the key barriers and challenges hindering MV deployment.

The successful implementation of MVs primarily relies on technological advancements. Thanks to progress in technologies such as vehicle-to-vehicle (V2V) communication, autonomous driving, AI, platooning, and virtual coupling in railways (Felez and Vaquero-Serrano, 2023), the application of MVs on existing transport infrastructures is becoming more feasible, moving towards higher technical maturity. However, more research and real experiments on technologies still have to be done in order to enhance the informational, decisional, and learning ability which will, in turn, improve the reliability of MV operations. Additionally, many of the concepts of MVs in transportation are still theoretical, with only 1 ongoing pilot experiment in Dubai, UAE (NEXT, 2023). Therefore, while core enabling technologies have reached sufficient readiness levels demonstrated by successful platooning trials and autonomous vehicle prototypes, the integration of these components into a fully automated MV system remains at a demonstration stage. Targeted pilot deployments across diverse environments are thus essential to validate interoperability, safety, and system resilience before large-scale technical rollout can be considered.

A second challenge relates to operations and regulations involving the separate or integrated handling of passenger and freight demands within MVs. Such integration, as highlighted by recent initiatives such as the EU's Pods4Rail project (Pods4Rail, 2024), remains legally and operationally complex in many regions. Freight and passenger services are typically governed by distinct regulations and providers which imposes operational complications in loading and unloading procedures when combined, may disrupt passenger boarding and alighting, and compromise the safety and security of both passengers and freight. Equally, managing dynamic platoon reconfiguration in transit without causing delays or blocking rail and road systems poses a significant operational hurdle. Addressing these issues will require not only further research on technologies but also targeted policy action. At the EU level, instruments such as the intelligent transportation system directive (2010/40/EU and its revision COM 2021/0813) (European Union,

2010; European Commission, 2021), the Vehicle General Safety Regulation (EU 2019/2144, EU 2022/2236) (European Union, 2019; European Commission, 2022), and the rail interoperability framework of Technical Specifications for Interoperability (TSI, Directives 2016/797 and 2016/798) (European Union, 2016a,b) with ongoing calls to update TSI for lightweight MVs provide a model for harmonized rules on data sharing, safety standards, and cross-border operations. Ensuring regulatory feasibility for MVs will require alignment of national regulations with these directives, simplification of approval processes, and tailored certification pathways for mixed-use MVs. Future work should engage with these regulatory directives to develop clear guidelines for integrated MV freight-passenger services.

Financial challenges also represent major obstacles. Transitioning to MV-based systems demands substantial investments in vehicle design, manufacturing, and infrastructure upgrades (such as V2X retrofits and modular moving platforms). The economic scalability of MVs is also constrained by the need to equip each unit with its own powertrain and digital control systems, contributing to high initial capital expenditure. Innovative financing mechanisms, such as public-private partnerships and scalable cost-sharing models, will be essential to reduce risk and attract investor confidence. Explicit cost-benefit studies could also clarify the economic case for MV deployment.

Finally, human-related challenges are pivotal. The introduction of MVs impacts a variety of stakeholders, requiring the involvement of diverse social components in the deployment process. According to the EU-funded Pods4Rail project (Nägele et al., 2023; Nägele et al., 2025), 10 stakeholder groups can be considered essential for MV deployment: rail and road infrastructure managers; urban and regional authorities; freight forwarders; public transport operators; vehicle and component manufacturers; Mobility-as-a-Service platforms; standardization bodies (e.g., the European Committee for Standardization (Comité Européen de Normalization)); regulatory authorities; and end users. Each brings distinct and sometimes conflicting views on safety, interoperability, data sharing, infrastructure adaptation, and business models. To reconcile these perspectives, we recommend structured, ongoing engagement through workshops, design reviews, and pilot trials that enables regulators to refine legal frameworks, infrastructure managers to plan upgrades, manufacturers to validate specifications, operators to ensure commercial viability, and users to voice needs and concerns related to comfort, safety, and operational challenges. Behavioral feasibility hinges on end users' (such as shippers and passengers) willingness to use, making early public outreach and user-centered design critical. Likewise, organizational feasibility depends on multi-stakeholder coordination establishing multi-agency/company governance structures, training staff for mixed-use operations, and integrating disparate management systems to ensure that MV services can be delivered smoothly.

5.3. Future research directions

In response to RQ5, and based on the descriptive and content analysis as well as the identified deployment challenges, this section outlines five key future research directions essential for advancing the understanding, design, and implementation of MV mobility systems (summarized in Fig. 4). Each direction is further divided into specific research areas to offer clear guidance for future studies.

5.3.1. Application areas

Although MV research has largely concentrated on passenger services, it presents promising applications in other demand categories, such as rail freight transport and integrated transport of passenger and freight, where research remains relatively limited.

Freight transport: While MV research has largely concentrated on passenger services, freight applications remain underexplored, with only 8 studies addressing this area. The unique characteristics of freight transport, such as the varied sizes of the shipment, flexible delivery

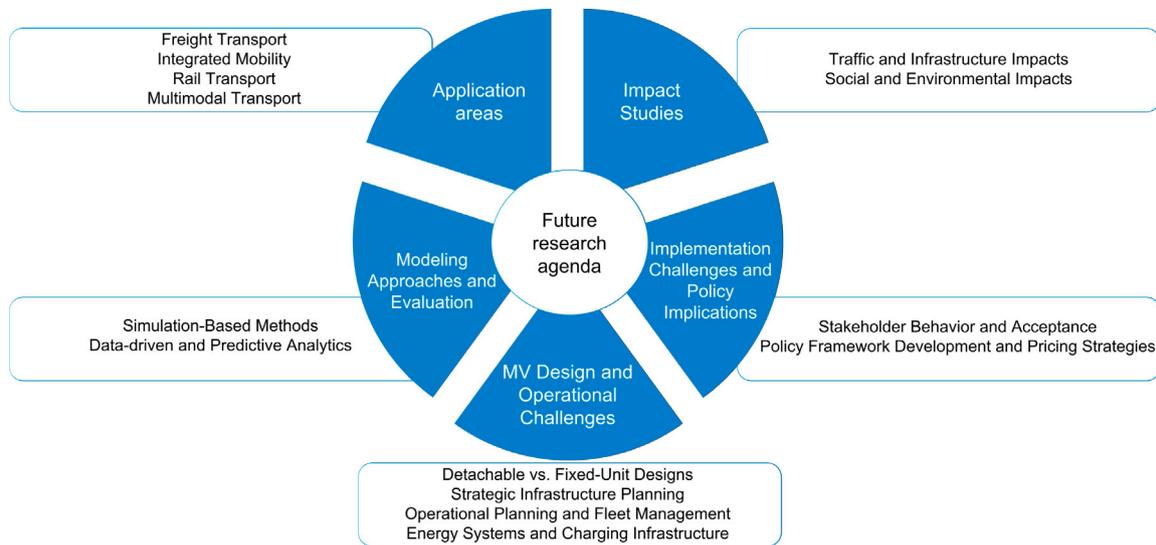


Fig. 4. Future research directions.

windows, and complex routing needs, offer significant opportunities for MVs to improve efficiency and adaptability. Future research should focus on dedicated MV solutions for urban and regional freight logistics.

Integrated mobility: Only 10 studies have investigated combined freight and passenger systems in urban contexts, highlighting a significant gap in understanding the role of MVs in supporting integrated mobility. MVs offer the potential to flexibly accommodate both passenger and freight needs within a unified system, enhancing efficiency through demand consolidation, especially during off-peak periods or when using shared infrastructure. Future research should focus on developing network-level coordination strategies for integrated services, particularly for interurban and regional settings with careful attentions (e.g. the compatibility between the two types of demands), to fully realize the operational and economic advantages of integrated modular transport.

Rail transport: Most existing rail-related MV studies have centered on single-line scheduling for passenger applications, leaving network-level scheduling and rail freight scenarios largely unexplored. Only 3 studies (Lin and Zhang, 2024; Liao et al., 2024b,a) have addressed MV applications in rail freight or mixed-use contexts. To bridge this gap, future work should investigate MV scheduling across entire rail networks, optimizing platoon coordination and service routing to enhance efficiency and capacity utilization.

Multimodal transport systems: Most research investigates isolated MV systems, rather than integration within current transportation ecosystems. Since the adoption of MV mobility systems is likely to be gradual, future studies should explore how MVs interact with conventional transport modes (such as rail, bus, and private cars) and examine the coordinated operations of road- and rail-based MVs. Emphasis should be placed on multimodal integration and transshipment processes, which have the potential to increase network coverage and improve overall transport efficiency. So far, only one study (Xia et al., 2024) has examined a combined bus and demand-responsive transport (DRT) service, highlighting the need for more research on multimodal integration.

5.3.2. MV design and operational challenges

Current research on MVs largely focuses on fixed-unit designs, with limited study of detachable-unit alternatives. Strategic infrastructure planning, operational fleet management, including platooning and vehicle repositioning, and efficient energy and charging systems also remain underexplored and require further investigation.

Detachable vs. Fixed-unit designs: Research predominantly focuses on fixed-unit MVs, with limited exploration of detachable-unit

designs (Chen et al., 2022a; Hatzenbühler et al., 2022; Kortekaas et al., 2023). Future research should systematically compare the operational benefits, design complexities, and scalability potential of detachable and fixed-unit MVs (illustrated in Fig. 1).

Strategic infrastructure planning: Limited research addresses strategic infrastructure decisions such as network planning, station/hub location placement, idle MV storage capacity (Tian et al., 2022), and freight loading/unloading equipment requirements. Further studies should address these gaps, facilitating large-scale MV implementation.

Operational planning and fleet management: Platooning algorithms that enable efficient and real-time formation changes especially for station-wise platooning of MVs on both road and railway remain absent in current literature and represent a critical area for future research. Additionally, vehicle repositioning within MV systems has been minimally addressed (Tian et al., 2023; Xia et al., 2024; Tian et al., 2022; Wang et al., 2025). Future work should focus on developing comprehensive algorithms and strategies for dynamic MV allocation, repositioning, and real-time platooning management to enhance system adaptability and operational efficiency.

Energy systems and charging infrastructure: As MVs are battery-powered, future research should focus on development of energy system and charging strategies under various scenarios (Guo et al., 2023b; Gao et al., 2023; Chen et al., 2022a; Aggoune-Mtala et al., 2015; Rezgui et al., 2018, 2019b,a, 2017), including dynamic and static charging infrastructure, as well as the integration of vehicle-to-grid (V2G) and vehicle-to-vehicle (V2V) technologies (Liu et al., 2013; Fu and Chow, 2024).

5.3.3. Impact studies

Existing research on MVs has scarcely addressed their impacts on traffic congestion, infrastructure utilization, and environmental sustainability. Very few studies explicitly explore congestion and traffic flow implications, particularly within urban and logistical environments. Additionally, social and environmental factors, including emissions comparisons and societal benefits, remain understudied and need comprehensive future analysis.

Traffic and infrastructure impacts: Few studies have examined the impacts of MV on congestion and infrastructure use, despite their potential benefits in reducing congestion through platooning and compact sizing (Gabele et al., 2024). Only four studies have explicitly assessed congestion (Dakic et al., 2021; Li et al., 2025) and traffic flow impacts (Li et al., 2025; Wang et al., 2024). More research should address these impacts comprehensively, particularly in constrained urban environments, railways, and logistics hubs.

Social and environmental impacts: Limited studies (Guo et al., 2023b; Österle et al., 2022; Ulrich et al., 2023; Pei et al., 2023) have evaluated environmental factors, such as emissions, comparing MVs to conventional transportation systems. Future research should extensively explore environmental sustainability and broader societal implications, including potential societal benefits from widespread MV adoption.

5.3.4. Implementation challenges and policy implications

Research on MVs currently lacks comprehensive policy frameworks addressing data governance, regulatory standards, operational guidelines, and public-private partnerships, especially in mixed freight and passenger contexts. Future studies should establish clear policies on safety, infrastructure investment, liability, and equitable MV access. Additionally, pricing strategies, including congestion-based and dynamic pricing models, are critically unexplored and require further investigation to support informed decision-making and incentivize MV adoption.

Stakeholder behavior and acceptance: Public perception and social acceptance of MVs remain unexplored, particularly in freight logistics contexts where stakeholder priorities may differ from passenger scenarios. Choice modeling and behavioral analyses have been extensively applied to mode/route choice in traditional freight transport, yet their application to MVs remains unexplored. Future research should examine user behavior, equity impacts, and potential modal shifts resulting from MV deployment. This includes investigating stakeholder decision-making processes and attitudes toward MV adoption.

Policy framework development and pricing strategies: Given the data-intensive nature of MV operations, clear policies regarding data governance, privacy, and information sharing are required. Current literature lacks a comprehensive normative policy framework for MVs, especially regarding mixed freight and passenger scenarios. Future research must focus on developing policy frameworks addressing regulatory needs, standards, operations, and public-private partnerships. Policymakers require clear guidelines for adapting transportation policies to incorporate MVs effectively, considering infrastructure investments, safety standards, liability, data governance and equitable access to MV systems. Furthermore, more cost-benefit analyses need to be done to support informed decision-making and justify public and private investments in MV technologies.

Moreover, pricing strategies are critical yet remain unexplored. Research should focus on pricing models that incentivize the adoption and efficient utilization of MVs, considering user behaviors, economic feasibility, and social equity. Evaluating various pricing scenarios, including congestion/sustainability pricing and dynamic pricing based on demand fluctuations, could provide valuable insights to stakeholders and policymakers.

5.3.5. Modeling approaches and evaluation

Current MV research primarily employs mathematical optimization, with limited application of simulation-based methods. Future studies should leverage simulation techniques to enhance realism in evaluating MV operations and network performance. Additionally, integration of data-driven methods, including stochastic modeling, real-time analytics, and AI, remains scarce.

Simulation-based methods: While mathematical optimization models dominate current research on MV systems, simulation-based approaches remain underutilized. Only a limited number of studies have employed simulation to evaluate MV operations, system behavior, or network performance. Simulation, whether used on its own or in hybrid frameworks with optimization, offers valuable opportunities to test design assumptions and explore real-world variability. Future research should utilize simulation to complement optimization, enabling more realistic assessment of MV performance across diverse transport environments.

Data-driven and predictive analytics: The integration of stochastic or real-time data in MV research remains limited, with only five studies (Guo et al., 2023b,a; Sun et al., 2025; Liu et al., 2024; Wang et al., 2025) incorporating such methods. Notably, Guo et al. (2023a) apply AI for real-time passenger demand forecasting, while Sun et al. (2025) and Liu et al. (2024) adopt reinforcement learning to manage uncertainties in traffic, such as travel time and demand, enabling adaptive platoon formation and more reliable service delivery. Given the dynamic nature of MVs operation, future research should further explore the use of stochastic/real-time data, rolling horizon framework and AI-driven decision-making to strengthen the resilience and responsiveness of MV operations.

5.4. Conceptual framework for MV freight mobility systems

In response to RQ5, building on the literature and identified challenges, Fig. 5 presents a conceptual framework for the MV mobility system in freight transportation, structured around three primary blocks aligned with 3 design groups identified in Section 4.3.4: transport demand, transport operations management, and transport assets. The MV freight mobility system is envisioned as demand-driven, where operational decisions and asset utilization are dynamically aligned with real-time freight demand patterns.

Represented by the transport demand block, customers (e.g. shippers) submit freight requests in real time, providing details such as origins, destinations, volumes, and time windows, etc. These inputs are inherently variable such as changes in schedules and volumes, reflecting fluctuating demand patterns. Subsequently, the real-time requests are conveyed to the transport operations management block for storage and processing (arrow 4).

The transport assets block encompasses traditional freight transport modes, i.e. trains and trucks, and road/railway infrastructures. Trains, representing a multiple-unit mode, are treated as fixed-formation entities that cannot be altered once they leave the depot. In contrast, trucks represent a single-unit mode, operating as independent units. These represent a broader range of assets in terms of capacity, autonomy, and fuel type. The proposed MV solution operates in a range between these two extremes due to its ability to flexibly reconfigure formations and the type of demand it addresses. Through sensors and communication systems, information pertaining to MVs and their operating environment (such as MV's location, status, and traffic/infrastructure conditions) is collected and transferred to the transport operations management block for processing (arrow 2).

Within the transport operations management block, the integrated decision-making system leverages real-time information (arrows 2 and 4) to make strategic, tactical, and operational decisions for MVs. Strategic decisions include fleet sizing, hub placement, capacity planning and depot selection. Tactical and operational decisions pertain to short term (to real-time) scheduling, routing, transfers, request-vehicle assignment, composition adjustments, and pricing strategies for MVs. These decisions then lead to service-related actions (arrow 3), such as routing MVs within the transport assets block, allowing for real-time adjustments in the number of units in platoon and enabling a more effective match between supply(MVs) and demand(freight). In addition, customer-related decisions (arrow 5), such as pricing, order acceptance and estimated arrival time, are communicated directly back to the customers, e.g. via a booking system. Moreover, in the transport operations management block, internal information flows (arrows 6 and 7) represent the continuous feedback loop in which all decisions are assessed against key performance indicators (KPIs) in terms of sustainability, economy and society. The outcomes of these evaluations in turn influence and refine subsequent decision-making strategies (considering different objectives/KPIs). Finally, service-related information, such as tracking details (arrow 1), is provided to customers to enhance visibility and transparency throughout the freight transportation process.

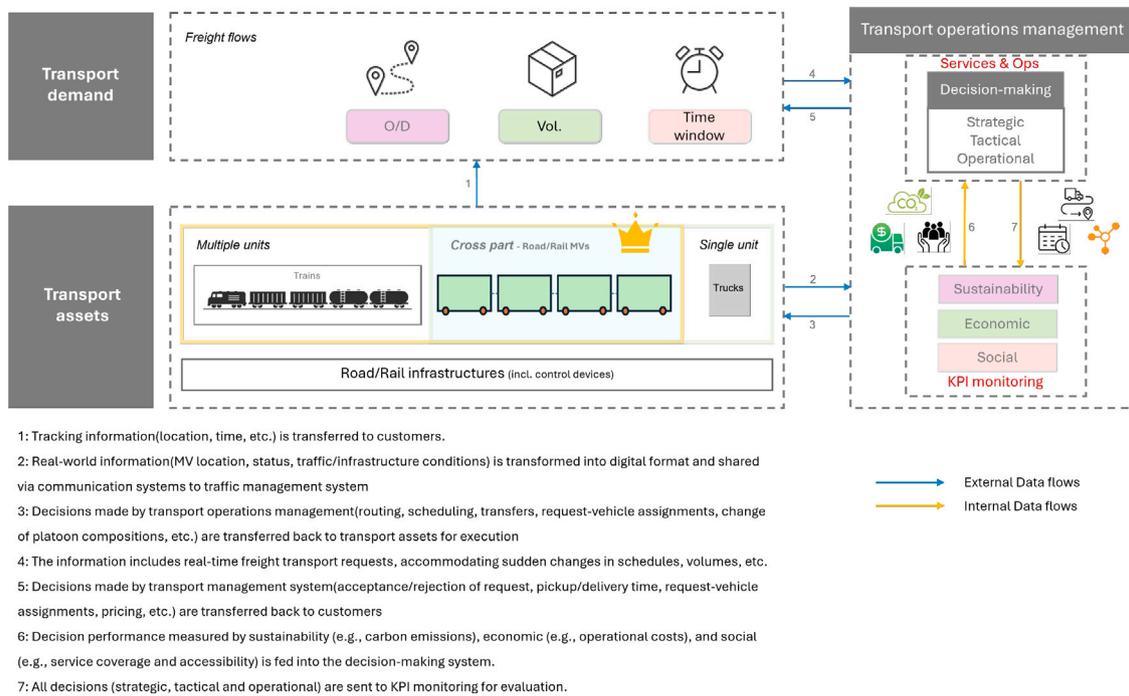


Fig. 5. Conceptual framework of MV mobility system.

This comprehensive framework links and integrates the essential features of an MV freight mobility system across three blocks, offering the foundation for understanding, designing, and further implementing MV systems for freight transport as well as, crucially, its integration within the broader freight transport system. This framework is also applicable to MV operations in the context of passenger transport. With minor adjustments to the key performance indicators (KPIs) and the decision making process, a similar structure can be employed for passenger services. This adaptability makes it a generic and versatile framework for operating MVs in combined passenger and freight transport.

6. Conclusion

This review contributes to the literature by exploring the state of knowledge on the modeling, impacts and feasibility of MVs in the freight transport sector and presents a conceptual model for MV freight mobility system. In this review, qualitative research focuses on the conceptual development of MVs for passenger and freight transport, while quantitative research, using mathematical models, emphasizes operational and cost efficiencies in detailed planning and control. Our findings suggest that MVs offer a promising solution to several pressing issues in freight logistics, including operational inefficiencies, costs, and the rigidities of traditional freight systems.

Looking forward, this review highlights five future research directions that are essential for advancing MV deployment. These include: (1) expanding MV applications beyond passenger-focused systems toward rail freight, and multimodal use cases; (2) addressing design and operational challenges such as platooning configurations, infrastructure planning, fleet management, and energy systems; (3) evaluating the broader system impacts of MVs on traffic, environment, and society; (4) developing regulatory and policy frameworks that support safe and scalable adoption; (5) and advancing modeling approaches by integrating simulation, real-time data, and AI to capture complexity and uncertainty in MV operations.

The potential of MVs remains largely theoretical without extensive empirical research and real-world testing. At the same time, the adoption of MVs in freight or combined freight and passenger transport

faces multiple challenges, including technological hurdles, operational and regulatory barriers, stakeholders acceptance and the need for infrastructure adaptation. From a policy and practice standpoint, the successful implementation of MV systems therefore demands coordinated action across regulators, industry, users, and researchers to translate technological potential into operational reality. Furthermore, pilot projects and public-private partnerships play a critical role in validating feasibility under real-world conditions and in closing the gap between research and practice.

In conclusion, while the deployment of MVs in freight transport presents considerable advantages, realizing these benefits necessitates targeted research efforts, pilot projects, and collaborative industry initiatives. These should ensure that MVs mobility systems become practical, scalable solutions for the freight transport sector, contributing to a more sustainable and efficient transportation landscape.

CRedit authorship contribution statement

Ximeng Liao: Writing – original draft, Writing – review & editing, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lóránt Tavasszy:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Oded Cats:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Mahnám Saednia:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Summary of research

See Tables A.2 and A.3.

Table A.2
Summary of quantitative research.

Paper	Focus	Application	Design choices											Data	
			Platooning	Passenger transfer	Charging operation	Vehicle fleet rebalancing	Time requirement	Station storage capacity	Stochastic elements	Network structure	Modeling approach	Objective function	Solution approach		
Wu et al. (2021)	Bus system	Passenger	En-route	✓	×	×	×	×	×	×	Single road	NLP	Minimize passenger transfers and vehicle movements	CH	Synthetic data
Khan et al. (2023)	Bus system	Passenger	Station-wise	×	×	×	×	×	×	×	Single line	Simulation	–	–	Synthetic data
Xia et al. (2023)	Bus system	Passenger	Station-wise	×	×	×	×	✓	×	×	Single line	MILP	Minimize passenger and operator costs	Exact	Beijing bus line 469
Chen et al. (2022b)	Urban rail system	Passenger	Station-wise	×	×	×	×	×	×	×	Single line	MILP	Minimize passenger and operator costs	Exact	Synthetic & Batong line of Beijing Subway
Chen and Li (2021)	Urban rail system	Passenger	Station-wise	×	×	×	×	×	×	×	Single line	MILP	Minimize operational costs	Exact	Synthetic data
Zermasli et al. (2023)	Bus system	Passenger	Station-wise	✓	×	×	×	×	×	×	Network	NLP	Minimize operational, procurement, and unsatisfied demand costs	MH	Athens metro system
Guo et al. (2017)	Bus system	Passenger	×	×	×	×	×	×	×	×	Network	Simulation	–	–	Synthetic data
Liu et al. (2021)	Bus system	Passenger	Station-wise	×	×	×	×	✓	×	×	Single line with PD	MILP	Minimize operational costs, passenger waiting and travel times, and unmet demand costs	CH	Wangjiang region, Beijing
Liu et al. (2023)	Bus system	Passenger	Station-wise	×	×	×	×	✓	×	×	Multiple lines	MILP	Minimize passenger waiting times and vehicle operation costs (including coupling and decoupling)	Exact	Beijing Public Transport system
Yin et al. (2022)	Urban rail system	Passenger	Depot	×	×	×	×	✓	×	×	Single line	MILP	Minimize passenger travel and vehicle scheduling costs and ensure fairness in Passenger flow utility	CH	Batong line, Beijing Subway

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Table A.2 (continued).

Tian et al. (2023)	Bus system	Passenger	Station-wise	×	×	✓	✓	×	×	Single line	MILP	Minimize passenger waiting times and vehicle operation costs (including module repositioning)	MH	DART line 1, Singapore
Zhang et al. (2020)	DRT	Passenger	Station-wise	×	×	×	×	×	×	Network	MILP	Maximize service rate	CH	NYC taxi system
Guo et al. (2023b)	DRT	Passenger	Depot	×	✓	✓	×	×	×	Network	MILP	Minimize transportation and dispatch costs	CH	Beijing area
Dakic et al. (2021)	Bus system	Passenger	Depot	×	×	×	✓	×	×	Multiple lines	MILP	Minimize vehicle operation and passenger travel time costs	CH	Traffic network in Zurich
Chen et al. (2019)	Bus system	Passenger	Depot	×	×	×	✓	×	×	Single line	MILP	Minimize energy costs and passenger waiting times	Exact	Beijing Metro and Tampa shuttle systems
Guo et al. (2023a)	DRT	Passenger	Station-wise	×	×	×	×	×	×	Network	MILP	Minimize transport, departure, and unserved demand costs	CH	Beijing area
Tang et al. (2024)	Bus system	Passenger	Station-wise	×	×	×	✓	×	×	Single line with PD	NLP	Minimize ownership, operating, and maintenance costs, and passenger waiting, walking, and in-vehicle times	Exact	Bus line 28 in Dalian
Tian et al. (2022)	Bus system	Passenger	Station-wise	×	✓	✓	✓	×	×	Single line	NLP	Minimize operator, passenger, and infrastructure costs	CH	Dynamic autonomous road transit in Singapore
Ji et al. (2021)	Bus system	Passenger	Depot	×	×	×	✓	×	×	Single line	MILP	Minimize empty seats and passenger waiting time	Exact	Bus Route 622 in Fuyang District, Hangzhou
Liu et al. (2020)	Bus system	Passenger	Depot	×	×	×	×	×	×	Single line	ILP	Minimize fleet size	–	Dynamic autonomous road transit in Singapore
Pei et al. (2021)	Bus system	Passenger	Station-wise	✓	×	×	×	✓	×	Network	NLP	Minimize operator and passenger costs	Exact	Guangzhou bus lines

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Table A.2 (continued).

Fu and Chow (2023)	DRT	Passenger	Station-wise	✓	×	×	×	✓	×	Network	MILP	Minimize vehicle travel costs and passenger service times	CH	Synthetic data
Caros and Chow (2021)	DRT	Passenger	×	✓	×	×	×	×	×	Network	Simulation	–	–	Ridership data from UAE
Zhang et al. (2024)	Bus system	Passenger	Station-wise	×	×	×	✓	×	×	Single line	MILP	Minimize vehicle ownership usage and energy consumption costs, and passenger in-vehicle and penalized waiting time costs	Exact	Bus line in Dandong
Shi et al. (2020)	Urban rail system	Passenger	Depot	×	×	×	✓	×	×	Single line	MILP	Minimize passenger waiting time and vehicle operation costs	Exact	Pinellas County, Florida
Shi and Li (2021)	Urban rail system	Passenger	Depot	×	×	×	✓	×	×	Single line	MILP	Minimize passenger waiting time and vehicle operation costs	CH	Synthetic data and Beijing UTS Line 6
Gao et al. (2023)	DRT	Passenger	Depot	×	✓	×	✓	×	×	Network	MILP	Minimize operator costs	CH	Bus line in Zhengzhou
Gong et al. (2021)	Bus system	Passenger	Depot	✓	×	×	✓	×	×	Network	MILP	Minimize operator and passenger costs, as well as unserved demand	MH	Taxi data in Chengdu
Romea and Estrada (2021)	×	Passenger	Depot	×	×	×	×	×	×	Single line	–	Minimize operator and infrastructure costs, and passenger costs	–	Bus line in Barcelona
Wu et al. (2024)	Urban rail system	Passenger	Station-wise	×	×	×	✓	×	×	Single line	MILP	Minimize passenger waiting time	Exact	Batong line, Beijing Subway
Xia et al. (2024)	Bus system	Passenger	Station-wise	×	×	×	✓	✓	✓	Single line	MILP	Minimize operator and passenger costs	MH	Beijing bus line
Pei et al. (2023)	Urban rail system	Passenger	Station-wise	×	×	×	✓	×	×	Single line	MILP	Minimize passenger waiting and train operation costs	Exact	Metro line 4, Shenzhen
Zhuo et al. (2024)	Urban rail system	Passenger	Depot	×	×	×	✓	×	×	Single line	MILP	Minimize passenger waiting time	Exact	Metro line in Beijing
Khan and Menendez (2022)	Bus system	Passenger	Station-wise	×	×	×	×	×	×	Single line	Simulation	–	–	–

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Table A.2 (continued).

Wang et al. (2023)	Bus system	Passenger	Station-wise	×	×	×	✓	×	×	Single line	NLP	Minimize passenger waiting time and fleet size	MH	Nantong bus line
Maiti et al. (2024)	DRT	Passenger	Station-wise	✓	×	×	×	×	×	Network	MILP	–	AI	NYC taxi system
Tian et al. (2025)	Bus system	Passenger	Depot	×	×	×	×	✓	✓	Single line	MILP	Minimize passenger waiting time, in-vehicle congestion, and operator transport costs	AI	Bus line in Beijing and Auckland
Wang et al. (2024)	Bus system	Passenger	×	×	×	×	×	×	×	Single line	TAM and DCM	–	CH	Chicago city
Li et al. (2025)	Bus system	Passenger	×	×	×	×	×	×	×	Single line	TFM	–	–	Synthetic data
Yuan et al. (2025)	DRT	Passenger	Station-wise	✓	✓	×	✓	×	×	Network	MILP	Minimize fleet sizing, vehicle travel time, charging, transfer inconvenience, and passenger travel time costs	MH	Synthetic data
Sun et al. (2025)	DRT	Passenger	Station-wise	×	✓	×	✓	✓	×	Network	SMDP	Maximize service profit	AI	Synthetic data
Liu et al. (2024)	Bus system	Passenger	Station-wise	×	×	×	✓	✓	×	Single line	SMDP	Minimize passenger waiting and bus operation costs	AI	Synthetic data
Hong et al. (2025)	Bus system	Passenger	Depot	×	×	×	✓	×	×	Single line	MILP	Minimize passenger waiting and bus operation costs	Exact	Synthetic data
Zou et al. (2024)	Bus system	Passenger	Station-wise	✓	×	×	✓	×	×	Single line with PD	MILP	Minimize passenger travel time and vehicle travel distance	MH	Bus line in Shanghai
Wang et al. (2025)	Bus system	Passenger	Station-wise	✓	×	×	✓	×	×	Single line with PD	MILP	Minimize passenger transfer costs, operation costs and unmet demand costs	CH	Bus line in Beijing

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Table A.2 (continued).

Aggoune-Mtala et al. (2015)	Distribution	Freight	Station-wise	×	✓	×	×	✓	×	Network	MILP	Minimize travel, charging, and vehicle acquisition costs	MH	Synthetic data
Rezgui et al. (2017)	Distribution	Freight	Station-wise	×	✓	×	×	✓	×	Network	MILP	Minimize travel, charging, and vehicle acquisition costs	MH	Synthetic data
Rezgui et al. (2018)	Distribution	Freight	Station-wise	×	✓	×	×	✓	×	Network	MILP	Minimize travel, charging, and vehicle acquisition costs	MH	Synthetic data
Rezgui et al. (2019a)	Distribution	Freight	Station-wise	×	✓	×	×	✓	×	Network	MILP	Minimize travel, charging, and vehicle acquisition costs	MH	Synthetic data
Rezgui et al. (2019b)	Distribution	Freight	Station-wise	×	✓	×	×	✓	×	Network	MILP	Minimize travel, charging, and vehicle acquisition costs	MH	Synthetic data
Shafiee et al. (2024)	Distribution	Freight	Station-wise	×	×	×	×	×	×	Network	MILP	Minimize travel and vehicle acquisition costs	Exact	Synthetic data
Zhou et al. (2025)	Distribution	Freight	Station-wise	×	×	×	×	×	×	Network	MILP	Minimize transport costs	MH	Synthetic data
Liao et al. (2024a)	×	Freight	Station-wise	×	×	×	×	×	×	Network	Simulation	–	–	Synthetic data
Liao et al. (2024b)	Urban rail system	Freight	Station-wise	×	×	×	✓	×	×	Network	MILP	Minimize transport and demand rejection costs	Exact	Synthetic data
Meinhardt et al. (2022)	DRT	Freight and passenger	×	×	×	×	×	×	×	Single line	Simulation	–	–	Berlin
Österle et al. (2022)	×	Freight and passenger	×	×	×	×	×	×	×	Network	CBA	–	–	Stuttgart
Deineko et al. (2023)	×	Freight and passenger	×	×	×	×	×	×	×	Network	Exploratory analysis	–	–	–
Ulrich et al. (2023)	×	Freight and passenger	×	×	×	×	×	×	×	Network	LCA	–	–	S-Vaihingen
Chen et al. (2022a)	DRT	Freight and passenger	×	×	✓	×	✓	×	×	Network	MILP	Minimize vehicle acquisition, labor, energy, and module-swapping costs	MH	Synthetic data

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Table A.2 (continued).

Hatzenbühler et al. (2022)	DRT	Freight and passenger	×	×	×	✓	×	×	×	Network	MILP	Minimize vehicle acquisition, travel time, energy, module-swapping, and unserved demand costs	MH	Stockholm
Hatzenbühler et al. (2023)	DRT	Freight and passenger	Depot	×	×	×	×	×	×	Network	MILP	Minimize travel distance and time costs, vehicle acquisition, and unserved demand costs	MH	Stockholm city
Kortekaas et al. (2023)	DRT	Freight and passenger	×	×	×	✓	×	×	×	Network	MILP	Minimize travel distance, vehicle acquisition, and unserved demand costs	Exact	Synthetic data
Lin and Zhang (2024)	Urban rail system	Freight and passenger	Station-wise	×	×	×	✓	×	×	Single line	MILP	Minimize vehicle operation, passenger waiting, freight handling, and station operation costs	CH	Transit line in Hong Kong
Zheng et al. (2025)	Urban rail system	Freight and passenger	Depot	×	×	×	×	×	×	Single line	MILP and game theory	Minimize transit operators' capita costs and carriers' delivery costs	Exact	Synthetic data
Hannoun and Menendez (2022)	DRT	Other application	Station-wise	✓	×	×	×	✓	×	Network	MILP	Minimize response time and travel time to hospital	Exact	Synthetic data
Fu and Chow (2024)	×	Other application	Station-wise	×	×	×	✓	×	×	Network	MILP	Minimize total energy consumption and travel time	MH	–
Li and Li (2023)	×	Control	Station-wise	×	×	×	×	×	×	Single road	MILP	Minimize cumulative distance and squared acceleration	CH	Synthetic data
Li and Li (2022)	×	Control	Station-wise	×	×	×	×	×	×	Single road	MILP	Minimize squared acceleration and squared jerk	CH	Synthetic data

Note: CH: customized heuristics; MH: metaheuristics; Exact: exact approach; LCA: lifecycle analysis; Single line with PD: pickup and delivery service around a single line; DRT: demand responsive transport/pickup and delivery vehicle routing problem; AI: artificial intelligence; TAM: traffic assignment model; SMDP: semi-Markov decision process; DCM: discrete choice model; TAF: traffic flow model.

Table A.3
Summary of qualitative research.

Reference	Country	Focus	Application
Orecchini et al. (2005a)	Italy	Concept	Freight and passenger
Ulrich et al. (2019b)	Germany	Concept	Freight and passenger
Ulrich et al. (2019a)	Germany	Concept	Freight and passenger
Münster et al. (2020)	Germany	Concept	Freight and passenger
Lin et al. (2022)	USA	Review	Passenger
Zohner and Lazeski (2023)	Germany	Security analysis	–
Gecchelin and Webb (2019)	Italy	Concept	Passenger
Friedrich et al. (2019)	Germany	Concept and business models	Freight and passenger
Mazzarino et al. (2022)	Italy	Stakeholder and policy analysis	Freight and passenger
Gao et al. (2022)	China	Concept	Passenger
Gabele et al. (2024)	Germany	Concept	Freight and passenger

Data availability

Data will be made available on request.

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