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Analysis of Modular Autonomous Urban Micro-bus Applications

Pang Qianyue[1,a,*], Chen Yike[1,b], Xiong Le[1,c]

[1]CRRC Electric Vehicle Co., Ltd., Zhuzhou, China
[a]957641369@qq.com, [b]15767300@qq.com, [c]406789617@qq.com
[*]Corresponding author

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Abstract: The article begins by defining Modular Autonomous Urban Micro-Transit (MAUM) and outlining its characteristics. It subsequently analyzes the advantages of applying MAUM from four perspectives: government, technology, operations, and users. While the promotion and implementation of MAUM face a series of challenges and technical hurdles that need to be gradually addressed in practice, it is believed that with ongoing technological development and improvements in the application, it will become a vital component in the urban public transportation sector. It will provide an effective solution for addressing urban traffic congestion and improving urban mobility.

1. Introduction

With the continuous development of the national process of urbanization and electrification, the urban vehicle population is rapidly increasing, leading to increasingly severe urban traffic congestion. In this context, public transportation is considered a key means to alleviate traffic congestion. However, traditional public transportation operates in a 'fixed-supply' manner, with fixed stops, routes, and timetables. This results in poor flexibility for traditional public transport, making it difficult to meet passengers' diverse and personalized travel needs.[1] Future urban residents have increasingly higher expectations for their travel experiences, making it necessary to transform the traditional 'fixed-supply' operation model of public transportation to better meet diverse and personalized travel needs. Otherwise, urban residents will inevitably shift towards private transportation. Therefore, the optimization and reform of traditional public transportation are urgently needed to better adapt to the demands of future urban transportation. MAUM systems offer clear advantages in improving operational efficiency, reducing traffic congestion, reducing energy consumption, and enhancing the travel experience. Therefore, they are expected to be one of the important directions for the future development of public transportation.

2. Definition of MAUM Systems

Modular Autonomous Bus (MAB) is an emerging public transportation mode that fulfills not only the traditional fixed-route passenger-carrying function but also provides flexible, dynamically responsive public transportation services. It operates through an automated, flexible grouping system, offering new possibilities for urban public transportation. The modular electric vehicle solutions provider, Next Future Transportation Inc., has successfully designed an autonomous bus (Figure 1) that can dynamically expand its passenger cabin through modular units and has conducted real-world testing in cities like Dubai.[2]

Figure 1: Dubai’s Modular Autonomous Bus.

2.1. Time-Varying Passenger Cabin Capacity Matching Temporal Passenger Flow Variations

One of the primary features of modular transit is its ability to adjust passenger cabin capacity within the spatiotemporal context dynamically. Traditional public transit, due to its fixed cabin configurations, offers a constant and unchangeable passenger capacity, making it difficult to adapt to fluctuations in temporal passenger flow. This leads to a severe inadequacy of passenger cabin capacity in high-demand routes and oversupply in low-demand routes, which, to a certain extent, hampers the operational efficiency and effectiveness of public transit. MAUM can optimize the utilization of passenger cabin capacity based on the temporal and spatial characteristics of passenger flow on specific routes, thus enhancing the operational efficiency of public transit.

2.2. Customized passenger transport routes enable one-stop travel services

Traditional bus routes are fixed to cover a larger area and serve more city residents. These routes not only increase passenger travel time but also fail to address the 'last mile' problem for passengers. In contrast, MAUM enables passengers to have point-to-point customized routes. Passengers traveling in the same direction and on the same route can transfer to the same vehicle compartment within the bus and proceed directly to their destination, providing one-stop travel services that reduce passenger travel time and solve the 'last mile' challenge.

2.3. Intelligent public transit services enable demand-responsive travel

The reason why modular bus units tend towards compact units resembling modern passenger vehicles is to align with the evolving demand for traditional public transit services transitioning into smart transit services. Ride-hailing, ride-sharing, personalized customization, and demand-responsive transit service models are the directions for transformation and development for traditional public transit enterprises. Ride-hailing transit services allow passengers to pre-book customized travel for different times and destinations. This provides future-confirmed passenger travel data for transit operations, supporting the continuous integration and disintegration of various transit modules based on data, thus achieving passengers' one-stop point-to-point real-time travel services.

3. Application of Modular Autonomous Bus Systems

3.1. Government-led Initiatives

(1) Alleviating Traffic Congestion.

The relentless global urbanization process is leading to the continuous accumulation of urban populations, which in turn has strained urban infrastructure development to meet the growing demands of city residents. In response, China has proposed comprehensive traffic congestion management in urban areas, prioritizing the development of urban public transportation. This approach encourages and guides the adoption of eco-friendly public transit while rationally directing individual motorized travel. MAUM as a form of urban surface public transportation, is expected to attract more urban residents to choose public transit, promoting the development of public transportation systems and mitigating urban traffic congestion.

(2) Fostering Green Mobility.

Enhancing energy efficiency, emissions reduction, and pollution control within the transportation system, and advocating for green and low-carbon travel concepts, represents a critical future direction for China's road transportation system. Micro-transit achieves miniaturization of large-capacity public transit cabins, resulting in a form of lightweight public transit vehicles. Lightweight design effectively improves overall vehicle fuel efficiency and handling stability, which is of great significance in reducing transportation emissions. Simultaneously, the use of new energy sources, such as fuel cells, compared to traditional fuel-based propulsion methods, decreases energy consumption and reduces environmental pollution, aligning more closely with the theme of green and low-carbon urban travel.

(3) Aligning with Future Urban Planning Trends.

In 2013, the European Union introduced the 'Sustainable Urban Mobility Plan,' proposing a novel concept in future urban planning known as the 'mobility concept.'[3] This document emphasizes a shift in future urban planning towards more widespread and comprehensive mobility strategies, with a greater focus on the development of ground-based public transit modes and enhanced accessibility across different urban areas. MAUM through in-vehicle transfers, not only achieves point-to-point transportation but also facilitates the integration of various transportation modes. It can replace several existing public transit methods, thus maximizing the benefits and cost-effectiveness of ground-based public transit development, aligning seamlessly with the mobility-oriented principles of future urban planning.

3.2. Technical Support

Technology serves as a critical foundation for the realization of MAUM systems. Research on autonomous modular transit control technology, vehicle-infrastructure cooperation methods in modular transit systems, and other related technologies has been a focal point for many scholars in recent years. The significant advancements in these technologies have made the implementation of MAUM increasingly feasible.

3.2.1. Autonomous Modular Transit Control Technology

The prerequisite for harnessing the advantages of MAUM is the ability to allow individual units to freely form and disband on roadways. This necessitates precise positioning and communication systems between these unit modules, enabling real-time information exchange and synchronization among vehicles to ensure the accuracy of their relative positions and velocities. Furthermore, MAUM must possess autonomous driving technology and intelligent control systems, allowing it to independently perform coupling and separation operations. Simultaneously, the size, mass, and structure of unit modules must meet the requirements for coupling and separation, complete with appropriate mechanical and electrical interfaces to facilitate safe and reliable connections and disconnections.

Regarding free modular public transit control technology, various scholars have examined multiple dynamic vehicle coupling and separation methods, including vehicle convoy reconfiguration, dynamic platooning control, fleet formation using reinforcement learning algorithms, and multi-vehicle convoy control based on cooperative adaptive cruise control. These approaches can be applied to MAUM systems to achieve dynamic platooning and separation.

3.2.2. The Modular Bus System Vehicle-Road Coordination Approach

To fully leverage the advantages of MAUM, an optimization model focused on passengers' comprehensive travel time, the minimal number of operational vehicles, and the least energy consumption must be established. This model termed the collaborative optimization model for static multi-route scheduling, is designed to generate vehicle scheduling, rearrangement, separation, and charging plans for various routes.

The static multi-route vehicle collaborative scheduling primarily addresses the temporal and spatial imbalances in passenger flows across multiple routes. It unifies the allocation of public transit capacity to facilitate resource sharing among various routes. This helps overcome issues in public transit route operations, such as idle vehicles during off-peak hours and inadequate capacity during peak times, ultimately leading to cost savings for public transit companies.[4] The optimization goals are determined based on data models. Optimization algorithms are applied to obtain the best solutions, which are then used to generate vehicle schedules, reconfigurations, separations, and charging strategies for individual routes. This optimization process aims to minimize passenger comprehensive travel times, minimize the number of operational vehicles required, and reduce energy consumption. Model validation and adjustments are performed based on real-world conditions to ensure the model's accuracy and reliability.

On the other hand, the dynamic multi-route vehicle-road cooperative control, enabled by intelligent connected vehicle technologies, serves as a technical foundation for vehicle-road collaborative control. Research by Xu Hui and others involved information sharing and cooperative control between vehicles and traffic signal control systems. This approach employs fuzzy logic control to manage vehicle speeds by considering vehicle status, traffic conditions, signal light statuses, and more. This strategy facilitates the smooth operation, efficient scheduling, and speed control optimization of public bus fleets. Simulation experiments confirmed the feasibility and effectiveness of this approach, offering a novel solution for public bus fleet management.

3.3. Operation services

For operators, the MAUM system will disrupt traditional public transportation operational models and emerge as a novel urban surface transportation mode that integrates ride-sharing, car-sharing, public transit, and taxis.

3.3.1. Operational Services in Travel Scenarios of Different Distances

Vehicle dispatch based on passenger demand responsiveness involves adopting different operational strategies for scenarios with varying travel distances to enhance operational efficiency for the enterprise.[5] In cases where the origin and destination are distributed within the central urban area, the MAUM can provide services akin to urban center-based ride-hailing and taxi services. Passengers can transfer within the vehicle during the journey, thereby reducing the passenger's travel time, lowering both the passenger's travel costs and operator operational expenses, and ultimately increasing operational efficiency. The provided operational services are depicted in Figure 2.

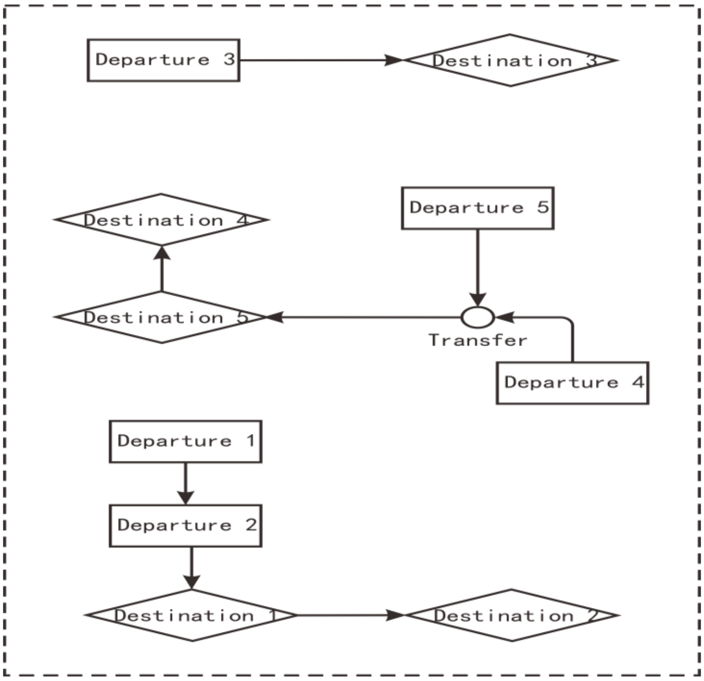

Figure 2: Short-distance travel service model.

For large cities, where urban coverage is extensive and commuter distances exceed the central urban area, operators can provide a solution to the 'last-mile' issue in intermodal travel. This service complements the fixed rail routes, as shown in Figure 3. Users no longer need to walk, drive, or bike to stations from their departure points. Instead, MAUM transports passengers from different origins to rail stations, and upon reaching the destination station, buses or transit units near the station take passengers directly to their final destinations, offering seamless interconnection services.

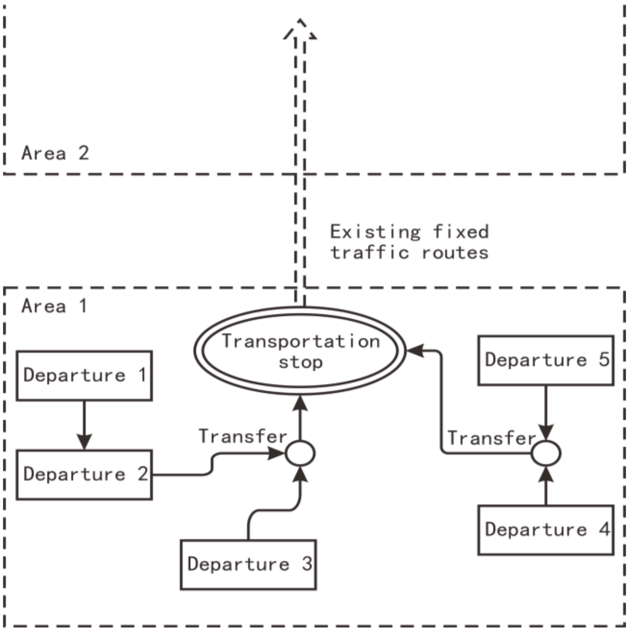

Figure 3: The mid or long-haul intermodal travel mode.

In addition, for passengers who still opt for ground transportation for their commutes, operators can also offer a one-stop transportation service, as shown in Figure 4. First, passengers are transported from their departure points to a transit hub. Then, a fleet consisting of multiple transit units proceeds to the central urban area's transit hub, where passengers are individually transported to their respective destinations. This system resembles park-and-ride or multimodal commuting services. It offers greater convenience to passengers, providing a one-stop solution from home to the workplace. Passengers only need to change seats during the fleet's operation to complete the transfer.

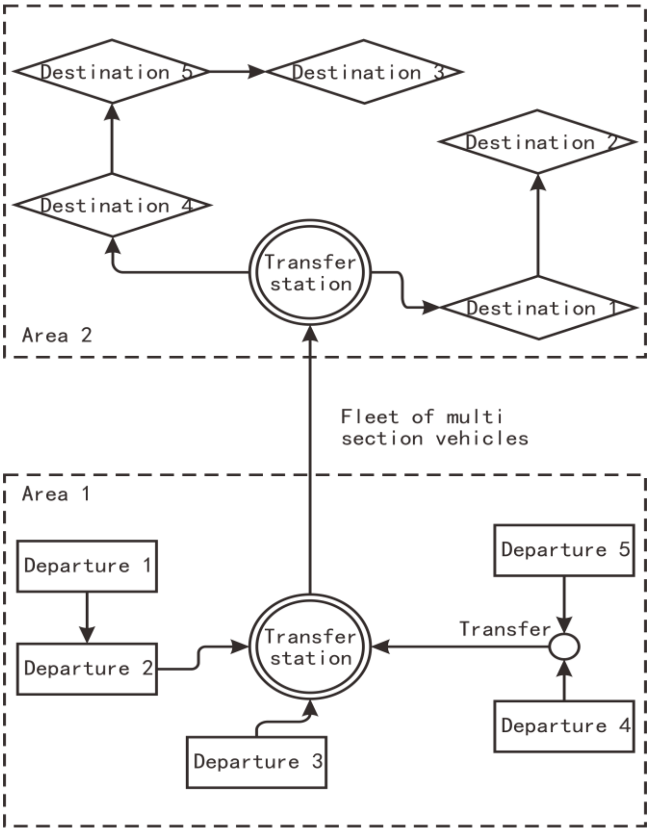

Figure 4: The one-stop travel mode for mid or long-distance journeys.

3.3.2. Operational services under different business models

(1) Leasing Model: Operators can lease MAUM units to other companies or individuals, such as large enterprises, property management firms, residential communities, etc. These companies or individuals can use MAUM to provide more convenient transportation services for their employees or residents.

(2) Sharing Model: Operators can operate MAUM as a form of shared mobility, similar to shared bicycles and car-sharing services. Users can book and use MAUM through a mobile app.

(3) Customization Model: Operators can offer customized services to governments or businesses, tailoring MAUM vehicles according to specific needs.

(4) Advertising Model: Operators can place advertisements on MAUM vehicles and generate revenue from advertising fees.

These business models all have the potential to generate income for operators, especially the sharing and advertising models. Additionally, if operators can successfully introduce MAUM to the market and capture a significant market share, they may also gain additional income through brand value and brand premiums.

3.4. User Experience

Providing passengers with an integrated travel experience, connecting the 'pre-trip, in-trip, post-trip' scenarios, offering end-to-end travel chain planning, reservation services, contactless payments, real-time information, and system evaluations are pivotal in shaping the future of travel services.[6]

MAUM as an on-demand travel service, allows users to select routes and provide travel information through mobile applications before embarking on their journey, offering personalized travel options. Addressing the 'first and last-mile' challenges, interchange issues, and personalization of travel, smaller modular cabins are designed to minimize transfers, reduce congestion, and deliver personalized services.[7] MAUM achieves comprehensive coverage of the entire travel scenario, making passenger travel a service scenario. Continuous optimization of service touchpoints enhances passenger travel continuity and satisfaction.

Compared to traditional public transportation, MAUM offers passengers a better travel experience in the following ways:

(1) Improved Riding Comfort: The design of MAUM is adapted to urban road conditions, ensuring a smoother and more stable ride, reducing bumps and sways, and enhancing passenger comfort.

(2) Increased Travel Efficiency: Autonomous driving technology enhances road safety and stability while optimizing routes and traffic flow, reducing congestion and wait times, and improving travel efficiency. Additionally, modular design allows for flexible adjustments according to different travel needs and traffic conditions, better meeting user requirements.

(3) Providing More Personalized Services: MAUM can be equipped with smart terminals, offering users personalized, customized travel services.

(4) Reduced Travel Costs: Due to the adoption of autonomous driving technology and modular design, MAUM can effectively lower operational costs, enabling operators to offer more cost-effective travel options and reducing user travel expenses.

4. Conclusion

The emergence of MAUM aligns with current social and urban development trends, offering an effective solution to alleviate urban traffic pressures, enhance transportation efficiency, and realize intelligent, eco-friendly mobility. However, this new technological product is still in its nascent stage of development, necessitating further research and development efforts and broader dissemination. Moreover, it relies on substantial support and collaboration from governments and public transportation operators to facilitate its wider adoption and proliferation.

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