Planning a Swarm-Based Mobility System with Autonomous Vehicles for Sustainable and Flexible Transportation in Rural Areas

Emergent Research Forum (ERF) Paper

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Abstract

Rural areas face significant mobility challenges due to low population density, limited public transportation, and a high dependence on private vehicles, leading to restricted access for non-vehicle owners and environmental issues. This paper presents a decision support system (DSS) currently developed within the NeMo.bil project, which explores a swarm-based, on-demand mobility system using autonomous vehicles to address these challenges. The DSS integrates strategic fleet planning with real-time operational planning to optimize resource allocation and demand response. A sample use case illustrates how the tool is intended to support decision-making for fleet sizing and configuration in rural regions. As this research is ongoing, we present a preliminary concept of the DSS and outline future research directions.

Keywords

On-demand transportation, autonomous vehicles, rural mobility, decision support system.

Introduction

Addressing challenges in rural mobility requires innovative solutions that leverage automation and digitalization to enhance efficiency and sustainability. While recent research on new mobility systems has demonstrated the potential of shared and autonomous mobility services in urban settings (Butler et al., 2020), their applicability in rural regions remains an open challenge. This paper presents a decision support system developed within the NeMo.bil project[1], which investigates a swarm-based, on-demand mobility system using autonomous vehicles to address mobility needs in rural areas. The DSS, as part of the overall NeMo.bil system, integrates strategic fleet planning with real-time operational decision-making to optimize resource allocation and demand response. To illustrate the application of the DSS, we present a sample use case in which the tool supports decision-making for fleet sizing and configuration in a rural region. The remainder of this paper begins with a review of the background and related work, followed by a description of the NeMo.bil mobility system and the embedded DSS, and it concludes with a summary and an outlook on future work.

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[1] https://nemo-bil.de/

Background

Evolution of Mobility Systems

Mobility systems are evolving from traditional fixed-route public transport toward more flexible, on-demand solutions, driven by advances in information and communication technology (ICT) such as mobile apps and GPS, which enable real-time passenger-to-driver matching (Agatz et al., 2012). Automation, including autonomous driving, further enhances system flexibility and cost-effectiveness (Golbabaei et al., 2021), while convoy-based mobility, where groups of vehicles drive coordinately, offers additional efficiency gains through reduced energy consumption and improved traffic flow (Nahavandi et al., 2022). Although much of this innovation has focused on urban areas, rural regions—characterized by low population density, long travel distances, and limited public transport—could greatly benefit. On-demand autonomous mobility holds promise for improving rural accessibility, but challenges remain in adapting these technologies to dispersed and variable demand patterns (Schasché et al., 2022; Imhof et al., 2020).

Planning Tasks in On-Demand Mobility Systems

Designing and operating on-demand mobility systems involves both strategic and operational planning tasks (Zardini et al., 2022). Strategic planning focuses on long-term decisions such as fleet sizing—balancing vehicle numbers to meet demand and service quality—and fleet composition, which includes vehicle types, capacities, propulsion, and technologies aligned with operational and sustainability goals. It also addresses infrastructure needs like charging station placement and parking allocation. Operational planning manages real-time system performance through dispatching, routing, rebalancing, and ride-sharing. Dispatching assigns requests to vehicles for optimal fleet use, while routing minimizes travel time and distance. Rebalancing moves idle vehicles based on predicted demand to maintain service availability. Ride-sharing matches multiple passenger requests to a single vehicle, requiring efficient coordination to maintain service reliability and minimize detours. Operational planning also includes tasks such as scheduling vehicle charging and routine maintenance to ensure continuous system performance.

Need for Integration of Strategic and Operational Planning

Effective on-demand mobility systems require the integration of both strategic and operational planning (Ma & Fang, 2022). These two levels of planning are closely interlinked: strategic decisions shape operational performance, while real-time operations can inform strategic adjustments. Without integration, inefficiencies may arise, such as poor vehicle utilization or service coverage gaps. In rural areas, where demand is sporadic and infrastructure is limited, this integration is especially critical. Decision support systems play a key role in enabling such integration by helping operators align strategic goals with operational needs. The DSS introduced in this paper supports this process.

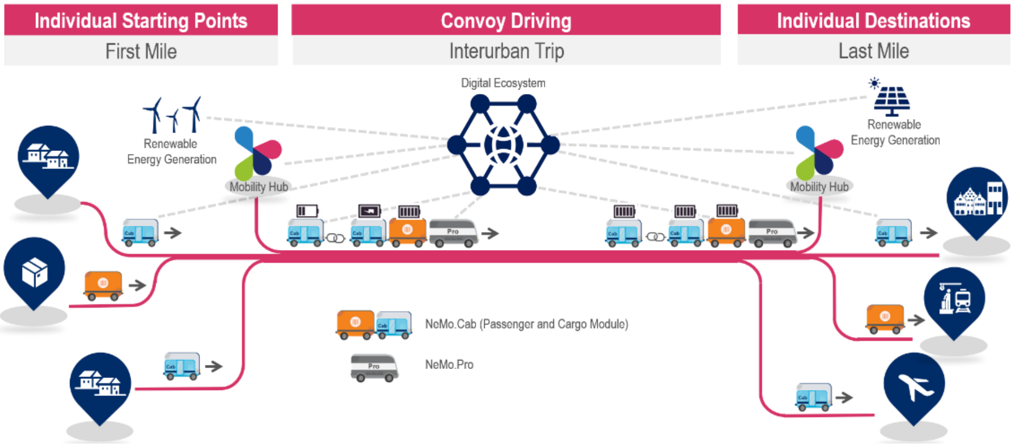

Figure 1. Concept of the Swarm-Based Mobility System “NeMo.bil”

Swarm-Based Mobility System "NeMo.bil"

The mobility system developed in the NeMo.bil research project addresses the lack of efficient mobility solutions in rural areas through a scalable fleet of two autonomous vehicle types: NeMo.Cab and NeMo.Pro (Ostermann et al., 2023). The system's key innovation is a swarm-based convoy mode (see Figure 1), dividing transport into first mile, interurban, and last mile segments. NeMo.Cab is a lightweight, electric vehicle designed for autonomous door-to-door service in the first and last mile. For longer interurban trips, NeMo.Cabs form convoys led by a hydrogen-powered NeMo.Pro, which offers higher speed and power but no passenger capacity. This formation reduces air resistance for trailing vehicles, lowering energy consumption, and enables en-route charging, as the NeMo.Pro serves as a mobile charging unit. Hydrogen is supplied at mobility hubs powered by renewable energy sources, ensuring sustainability.

Decision Support System for "NeMo.bil"

Planning Process and Design

The DSS for NeMo.bil has two main objectives: (1) to identify high-performing vehicle fleets across multiple objectives using integrated fleet and operational planning, and (2) to support decision-makers through an interactive dashboard for analyzing proposed fleets. As illustrated in Figure 2, the DSS comprises four components that enable iterative integration of strategic and operational planning.

The *demand generator* initiates planning by creating a demand scenario based on empirical data—either from historical ride requests of existing shuttle services or forecasts tailored to NeMo.bil. Each scenario includes pick-up/drop-off locations and times, passenger counts, and lead times. Parameterized scaling factors allow demand density adjustments, enabling flexible modeling of diverse conditions and forming the foundation for subsequent planning activities.

In the *fleet planning* component, various fleet configurations are computed and evaluated for a given demand scenario. These configurations vary in vehicle types (e.g., battery size) and quantities. Each configuration is assessed using key performance indicators (KPIs) that reflect two typically opposing perspectives: the operator's (e.g., minimizing costs) and the passenger's (e.g., maximizing coverage). The selection of KPIs depends on the optimization objectives specified by the decision-maker and may include metrics such as total fleet cost, number of rejected requests, and other metrics relevant to both efficiency and service quality. Since no single fleet configuration satisfies all objectives equally well, the output consists of a set of non-dominated solutions that represent trade-offs between opposing objectives, aiming to be as close as possible to the Pareto front. The fleet planning follows a heuristic approach, starting with an initial fleet and iteratively refines it by running the operational planning algorithm, evaluating KPIs, and adjusting fleet composition until a termination criterion is met (e.g., number of iterations).

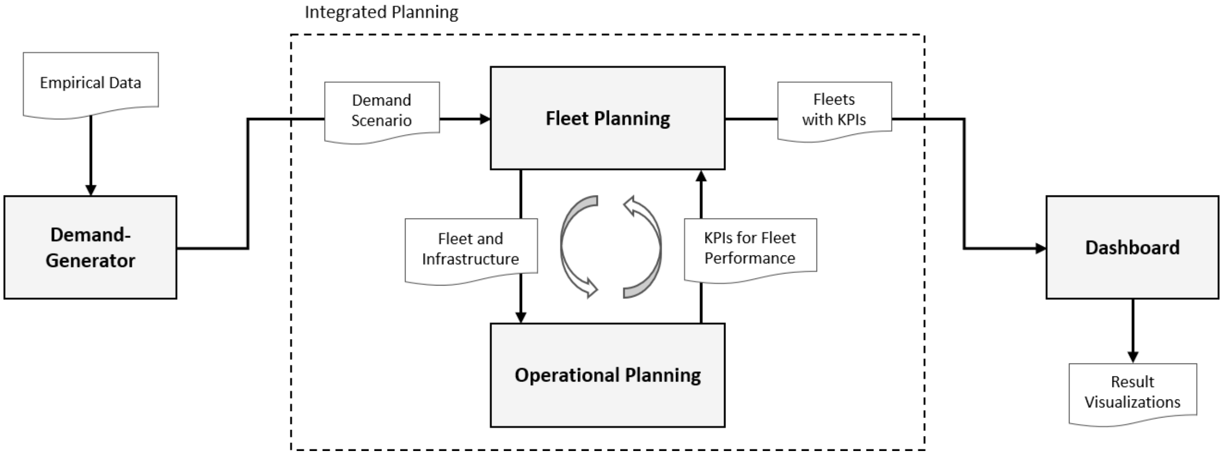

Figure 2. Design of the Decision Support System for "NeMo.bil"

The *operational planning* component simulates how a specific fleet handles incoming requests over the planning horizon. Using a configurable operating policy—including dispatch rules, charging strategies, and convoy logic—it accounts for real-world constraints like vehicle range, charging infrastructure, and traffic. The resulting performance data (KPIs) are fed back into fleet planning for further refinement.

Finally, the *dashboard* interactively visualizes the results of the planning process, showing inputs (e.g., demand scenarios) and outputs (e.g., approximated Pareto fronts of fleet configurations). It allows decision-makers to explore trade-offs between operator and passenger perspectives, compare options, and perform sensitivity analyses. While the decision-maker still needs to decide which fleet configuration to choose and implement in practice, the DSS helps quantify the main advantages and disadvantages of different options. The dashboard is highly customizable, supporting adjustments to optimization objectives, demand scenarios, and other parameters.

Towards Practical Application: A Sample Use Case

To illustrate the functionality of the DSS, we present a sample use case that demonstrates how a mobility planner interacts with the system to configure and evaluate a NeMo.bil-based rural mobility solution. The DSS is a software-based tool applied to support design decisions regarding fleet sizing and configuration. The primary actor in this use case is a municipal mobility planner responsible for selecting a suitable vehicle fleet and infrastructure setup. Secondary actors, such as policy-makers and technical experts, contribute system constraints and detailed technical knowledge but do not interact directly with the system.

The planner's goal is to identify the fleet configuration that best balances operating efficiency and service quality, based on a given demand pattern and regional characteristics (e.g., infrastructure). The DSS supports this through several core functions. It processes user-defined inputs such as geographical data (e.g., road network), demand forecasts, vehicle specifications, and planning objectives. Based on these inputs, the system simulates and evaluates a variety of fleet configurations and operational strategies. Each configuration is assessed using key performance indicators (e.g., rejected ride requests, fleet costs). The results are then visualized through an interactive dashboard that highlights trade-offs between competing objectives, helping the planner make informed decisions.

In the primary process, the planner explores these trade-offs using the dashboard and selects a fleet configuration that best balances the mobility system's efficiency and service quality in line with the specified optimization objectives. Figure 3 illustrates this process, showing a heatmap of ride request distribution (input) and a trade-off curve between fleet costs and rejected requests (output). Contingency paths may arise if no configuration meets the defined efficiency and service targets. In such cases, the planner may revise optimization objectives, modify vehicle types, or adjust charging strategies before re-running the integrated planning to identify a more suitable solution.

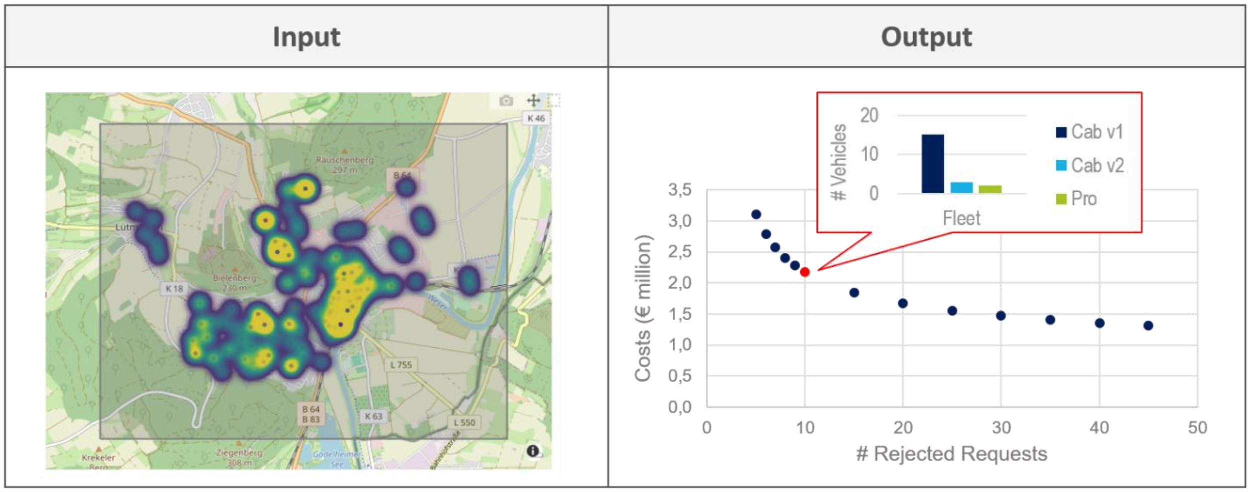

Figure 3. Exemplary Input and Output of the DSS

Conclusion

The NeMo.bil Decision Support System represents a significant advancement in integrating strategic and operational planning for fleet management. By combining empirical data, simulation, and optimization, the system enables informed decision-making that enhances efficiency and reduces operational costs. The iterative approach ensures that optimal fleet compositions are identified while balancing operator and customer perspective. Through its structured methodology, the DSS provides valuable insights into demand patterns and key performance indicators, enabling transport operators to make data-driven adjustments. The visualization of results via the dashboard allows for intuitive assessment and scenario comparisons, supporting proactive fleet planning. The sample application of the DSS demonstrates how it is intended to support actors in achieving their goals by utilizing its functions of simulating, evaluating, and visualizing various fleet configurations and trade-offs. Future developments may focus on refining the system's predictive capabilities, incorporating real-time data, and extending its applicability to diverse transport scenarios. As part of the planned validation, the tool will be provided to project partners for testing in real-world planning scenarios where the NeMo.bil system is intended to be introduced. By continuously improving decision support mechanisms, the NeMo.bil DSS contributes to more sustainable and efficient rural mobility solutions.

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