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Environmental and energy performance of integrated passenger–freight transport

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ABSTRACT

The first-last mile (FLM) transport of passengers and freight accounts for a significant share of total transport costs, pollution, and energy consumption. According to recent scientific literature and institutional inputs at the European level, operational innovations such as the combination of passenger and freight flows may be an effective approach for promoting sustainable and energy-efficient FLM transport. In this study, the energy and environmental performances of an integrated passenger and freight transport system based on the bus network of Zrenjanin (Serbia) were investigated with different future energy mix and transport policy scenarios. The operational aspects of the integrated system were designed through collaboration with territorial stakeholders and an analysis of local planning documents. The performance was evaluated and compared with current public transport and freight schemes considering vehicle fuel and technology, total mileage, and other relevant endogenous and exogenous factors. The results of our analysis indicate operational benefits and energy savings, mainly due to reduced total mileage and the predisposition to shift to the active modes for the last mile. However, most expected long-term energy savings are the result of technological development of vehicles and modal shifts induced by policy strategies.

1. Introduction

The first and last mile (FLM) legs of passenger and goods movements pose significant for operators and planners. Mobility is vital for economic prosperity and quality of life; however, it accounts for an increasing share of total emissions and other transport externalities (Cavallaro et al., 2013, 2017; Nocera et al., 2017). Many challenges hinder overall transportation efficiency and reliability, especially in dense urban environments where competition for space is strong and the number of overlapping demands is high (Taniguchi and Thompson, 2018). Public authorities and policymakers often address congestion, lack of space, noise, and other transport-related problems in passenger and freight transport in an uncoordinated manner, which may have negative effects on overall mobility (Dablanc, 2007) and social costs (Nocera and Tonin, 2014). The European Commission promotes passenger–freight integration in short-haul operations to improve operational efficiency and sustainability while reducing negative impacts (EC, 2007). Researchers and practitioners have begun to focus on urban and short-distance logistics to reduce excessive transport movements, increase load factors, and improve the social acceptability and financial sustainability of transport operations (Fatnassi et al., 2015). Researchers have argued that mixed passenger–freight FLM operations (MiFLM) may help reduce air pollution, traffic congestion, and road rage (Bruzzone et al., 2021a). In some circumstances, such as with wider use of alternative fuels or introduction of fleet management tools and other technologies, the extent of anticipated environmental benefits may increase, with a positive impact on the energy performance of mobility systems through optimised fuel use, reduced mileage, and more efficient operations. The literature on MiFLM indicates a broad horizon for both urban and rural operations, depending on local mobility-related and policy priorities (Cavallaro and Nocera, 2022). Researchers have studied MiFLM on buses, trams, subways, and metros, as well as water transport (Strale, 2014; Cleophas et al., 2019; Bruzzone et al., 2021a; Cavallaro and Nocera, 2022; Li et al., 2021). The financial and legislative feasibility of integrated passenger–freight systems and their performance have not yet been fully assessed. Similarly, potential integration in future FLM and its impact on future energy and environmental performance have not been discussed. In this study, we build on previous research that developed performance indicators (PIs) for evaluation of MiFLM. We develop an approach to investigate the energy and environmental performance of an MiFLM system based on buses, supported

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Nomenclature

CNG	Compressed Natural Gas
EC	European Commission
FLM	First-Last Mile
GHG	Greenhouse Gases
LPG	Liquid Petroleum Gas
MiFL	Mixed passenger–freight First-Last Mile
MoZ	Municipality of Zrejanin
PI	Performance Indicator
PT	Public Transport
RDA Banat	Regional Development Agency Banat
Vkm	Vehicles*kilometre

by active modes for last-mile distribution. To the best of our knowledge, no previous study has developed a quantitative framework for assessment of energy performances of MiFLM systems; this study represents a step forward. We use the Serbian city of Zrenjanin as a case study and quantitatively evaluate the energy and environmental impacts of MiFLM to verify its effectiveness. Variations in pollution and energy consumption were calculated for several scenarios that considered different technological developments in terms of the vehicle fleet, as well as changes in modal split and penetration level of MiFLM. The remainder of this paper is structured as follows. Section 2 reviews the literature on MiFLM operations. Section 3 presents the proposed methodology. Sections 4 and 5 present and discuss the case study of Zrenjanin. Section 6 presents the conclusions.

2. Previous research

Following the EC's Green Paper on Urban Mobility, calling for passenger–freight integration as a solution to the many challenges of urban logistics, researchers have considered the topic from different perspectives. Two distinctions between MiFLM concepts have been made. The first distinction is between urban and rural applications based on the territorial context of the analysis. Cavallaro et al. (2023) described the characteristics of urban services; Cavallaro and Nocera (2023) described rural specificities. A second distinction is between the sharing of vehicles for passenger and freight transport (sometimes referred to as "cargo hitching" or "freight on transit") (Ardvisson et al., 2016; Cochrane et al., 2016; Monios, 2019; Elbert and Rentschler, 2021), the sharing of transport infrastructure (such as light rail or metro tracks), and the sharing of transport-related public spaces such as stops and stations (Trentini and Mahléné, 2010). The topic of passenger–freight integration is too broad to be fully addressed here. A concept-centric literature review by Cavallaro and Nocera (2022) presents the main research issues related to this topic. The highlights are summarised as follows.

Within the broader MiFLM paradigm, use of buses has been recognised as one of the most promising strategies for improving overall environmental and operational performance, partially overcoming the regulatory/normative constraints that typically affect implementation (Ghilas et al., 2013; Fatnassi et al., 2015). The literature confirms the potential of MiFLM by means of freight on buses, as demonstrated by real-life and simulated case studies. Jansen (2014), Spoor (2015), Ghilas et al. (2016), and Li (2016) suggested that the freight sector (including manufacturers, shippers, carriers, and receivers) generally gains an economic advantage from consolidation of loads and FLM delivery by PT. Furthermore, they showed that PT operators receive economic benefits by making their spare transport capacity available for parcels and/or small goods. Consequently, this benefits funding authorities, reducing the need for subsidies. Similarly, Van Duin et al. (2019) explored the social benefits of MiFLM, highlighting that lower subsidies for PT enable provision of more services for the same cost. Supplementary delivery and PT services, otherwise anti-economic, can be targeted toward shrinking areas to increase their attractiveness to current and future inhabitants, contributing to their quality of life. In addition to the social implications, they also found environmental benefits obtained by reducing the total mileage, resulting in reduced fuel consumption and emissions.

PT-based crowdshipping has been explored as an integrated solution that is easily implemented. Serafini et al. (2018) assessed the operational potential of crowdshipping by PT in Rome, expanding the MiFLM concept and stressing that operational and environmental benefits could be achieved by reducing the number of trips. Gatta et al. (2019) focused on the Roman subway network and found that by opening additional lines, crowdshipping could significantly increase its potential due to improved proximity and overlapping of passenger and parcel destinations. Further insights into the design of successful crowdshipping services were provided by Fessler et al. (2022), who studied the socioeconomic determinants of user preferences regarding participation and acceptance in PT-based crowdshipping. Considering Singapore as a case study, Zhang et al. (2023) examined the environmental and financial impacts of PT-based crowdshipping in congested cities. They found that it could reduce delivery costs by up to 29 % and polluting emissions by 17 % compared to delivery vans.

MiFLM modelling has also been extensively studied. Savelsbergh and van Woensel (2016) conducted a brief review of MiFLM modelling, considering all modes of people-based logistics. According to them, buses are particularly suitable for MiFLM operations because they typically operate on relatively flexible schedules. Pimentel et al. (2018) developed a mixed-integer programming model to simulate MiFLM on buses, including time and capacity constraints. Integration of passengers and freight positively impacts urban mobility, especially with vehicle innovation. However, they stressed that all stakeholders (authorities, operators, and citizens) must substantially shift their mindset. Masson et al. (2017) proposed an adaptive large-neighbourhood search algorithm to evaluate MiFLM, expanding on previous research by Trentini and Mahléné (2010) and Trentini et al. (2011). Using the Delphi approach, Cochrane et al. (2016) showed that reduced energy use, fuel consumption, and emissions are positive impacts of freight-on-transit operations. Large initial investment, organisational shifts, and conflicts due to additional handling and transfers are perceived as major constraints. Bruzzone et al. (2023) conducted an operational, environmental, and social evaluation of a MiFLM system based on buses in mixed urban/suburban areas in Slovenia. Benefits were identified, particularly in terms of overall mileage and fleet size reduction. The need for normative innovation was suggested.

Several articles have addressed the topic of MiFLM by PT; research on this subject is however limited to the bus mode. Cavallaro and Nocera (2022) compiled a comprehensive review of studies on MiFLM; only 13 focused on bus integration. In another review, Elbert and Rentschler (2021) reported three qualitative and five quantitative studies on this topic. Another study by Ghilas et al. (2018) was split into four publications, each considering a specific aspect of the pickup and delivery problem with time windows and scheduled lines, their mathematical conceptualisation of the MiFLM.

Studies that evaluate MiFLM from an environmental and energy perspective often use performance indicators (PIs) for evaluation alongside conventional approaches such as cost-benefit and multi-criteria analyses (Cavallaro and Nocera, 2022). Little has been written on policy, environmental and sustainability implications, and energy transition. Some EU-funded projects have addressed sustainable FLM (Kijewska, 2017; Bruzzone et al., 2019); a few have also considered integration of passengers and freight. NOVELOG developed a set of PIs to assess the efficiency and sustainability of integrated transport operations (Nathanail et al., 2016). Starting with formal and substantive considerations in defining a set of suitable PIs for evaluation of MiFLM schemes, as indicated by Sinha and Labi (2011), Bruzzone et al. (2021a) collected sources and designed a set of suitable indicators to assess the operational, environmental, and social performances in MiFLM settings. In Section 3, we expand on their work to specify the evaluation context for energy performance assessment.

3. Method and data

The methodology proposed in this study combines scenario analysis and performance measurements using PIs. Although these techniques are not innovative, combination of scenario analysis and PIs for evaluating the contribution of MiFLM to cleaner and more effective mobility has not been explored in the transportation literature. The methodology builds on previous research by Bruzzone et al. (2021a) to define appropriate PIs for evaluating MiFLM settings, on results from the EU-funded SMILE project (Nocera and Bruzzone, 2021), and on other research for scenario analysis. First, we define different passenger–-freight integration scenarios, modal split, and technological development (Section 3.1). Then, we specify an appropriate set of indicators for assessment of MiFLM energy and environmental performance (Section 3.2).

3.1. Scenario analysis

Scenarios help in addressing uncertainty (Kahn, 1962; Erikkson and Weber, 2008) and can support research that considers technological, normative, and societal gains that cannot be fully predicted (Marasco and Romano, 2018). In transport-related literature, scenario analysis has been used for a variety of topics and problems, ranging from traffic flows (Zhong et al., 2015) and related emissions (Ko et al., 2016) to development of transit and sharing services (Räth et al., 2023). Scenario analysis allows predictive estimates that incorporate multiple key drivers and variables without being overly data-intensive. As such, it is appropriate for pre-assessing systems on paper rather than in reality, where stakeholder support and enthusiasm for the system are unknown and incremental implementation of the setting is realistic (Savelsbergh and Van Woensel, 2016). Thus, the study of MiFLM is an appropriate context for scenario analysis.

Twelve scenarios are defined in this study, representing future mobility including the energy mix, vehicle fleet, modal share, and changes in transportation infrastructure in different MiFLM conditions. Methodologically, we develope scenarios based on two main concepts: the characteristics of future mobility and levels of MiFLM uptake (Table 1).

The characteristics of future mobility include a context-specific estimate of the modal split, vehicle fleet characteristics (fuel type and emission class), and the impacts of mobility management and policy-making. Four alternatives are proposed for the future horizon: 0-BAU, 1-Pessimistic, 2-Moderate, and 3-Optmistic. They consider policy and technological components, with particular reference to fleet composition (fleet age, type of vehicles, and type of fuel) and fleet use (affecting modal share and distance travelled). In Scenario 0, the motorisation rate, vehicle type, and modal choice follow the business-as-usual (BAU) pattern. Scenario 1 predicts a shift toward cleaner urban mobility. However, no structural changes to vehicle fleets or available modes are considered, resulting in a pessimistic overview of the energy and environmental performances of mobility in the considered time horizon. In Scenario 2, exogenous factors lead to partial evolution of choice toward more sustainable modes. New fuels and technologies contribute to reduced vehicle emissions. In Scenario 3, both modal choice and vehicle fleet assume more sustainable values than in the other scenarios. Scenarios can be modelled using the Urban Transport Roadmaps Tool (de Stasio et al., 2016). The main entries to the Roadmap Tool include context-specific statistical data, survey-based data, and measured data on traffic flows and levels. The outputs of the Urban Transport Roadmap Tool, verified by transport and urban planning tools and supported by statistical sources and traffic counts, allow the vehicle fleet composition in each of the 12 scenarios to be determined. Moreover, the tool allows determination of vehicles-kilometre (vkm) for each fleet type. Based on these outputs, emissions can be modelled using appropriate software. For unavailable categories, emission factors can be obtained from the scientific literature. Depending on the geomorphological, infrastructural, and mobility-related specificities of the context, alternative emission modelling tools and sources can be used, such as WRI (2015), ISPRA (2021), EPA (2022), and the Handbook on Emissions Factors (HBEFA; Notter et al., 2019, 2022).

For MiFLM uptake, future scenarios 0, 1, 2 and 3 are further specified by the integrated passenger–freight component, according to Bracale (2016), Mazzarino and Rubini (2019), and Bruzzone et al. (2021a). Three alternatives are presented: MiFLM is not implemented ("No-MiFLM", *N*); MiFLM is applied to a few categories of goods ("Low-MiFLM", *L*); MiFLM is applied to more categories of goods ("High-MiFLM", *H*). Combination of the general mobility trends with the MiFLM settings produced 12 alternative scenarios: 0 N, 0 L, 0H, 1 N, 1 L, 1H, 2 N, 2 L, 2H, 3 N, 3 L, and 3H (Table 1).

Table 1
Structure of proposed scenario analysis.

Scenarios to be evaluated		Level of passenger/freight integration		
		N	L	H
Mobility and technological development	0	0N	0L	0H
	1	1N	1L	1H
	2	2N	2L	2H
	3	3N	3L	3H

3.2. Performance indicators

Formal and substantive aspects should be considered in defining appropriate PIs for MiFLM. Formally, PIs compare an ex-post state (A) with an ex-ante state (B), and must provide comparable, objective, and unbiased measures (Sinha and Labi, 2011). They must have the following five characteristics: suitability, measurability, defensibility, realism, and universality. In addition, PIs should be able to evaluate the system from freight and passenger transport operator, customer and citizen, management authority, and other stakeholder perspectives (Posset et al., 2010). In this context, we go beyond the ex-ante and ex-post conditions and use PIs to evaluate the 12 scenarios. We propose four PIs indicated as I_n, where I stands for indicator and n is a number between 1 and 4. The PIs are based on previous research and EU-funded projects and specified for energy assessment. They consider both the general characteristics of the mobility system (PT, freight transport, and private transport) and the specificities of the MiFLM system, focusing only on PT and freight transport (specified by n.1, see Table 2). To this end, we divided the vehicles into four main classes, labelled *a*–*d*: a – PT; b – light commercial vehicles and medium trucks, FT; c–private traffic, PV; d–heavy vehicles/articulated trucks, HT. For a general indicator, all four classes were evaluated; only classes a and b were evaluated when only the MiFLM component was considered. To facilitate comparison of results between different scenarios, the values are normalised using the 0 N scenario as a reference.

I_1 – Total mileage

Indicator I_1 analyses the total distance covered by all motorised vehicles using the road network in a specific scenario x. For our purposes, we refer to the daily temporal horizon; however, more aggregate evaluations may be made on a monthly or yearly basis. This indicator is defined as (Equation (1).

$$I_{1_x} = \frac{\sum_{i=a}^{d} (vkm_i)_x}{\sum_{i=a}^{d} (vkm_i)_{0N}} \tag{1}$$

where $(vkm_i)_x$ is the vehicle-kilometres run by class i in the temporal horizon considered in the analysis of scenario x (Table 1).

Table 2
Energy and environment PIs for MiFLM setting.

Category	Indicator	Description	Source
Operations	I_1 – Total mileage	Normalised distance covered, expressed as the ratio of the value in a scenario to the value in 0 N	Bruzzone et al. (2021a)
Energy	I_2 – Energy consumption	Normalised total energy required for the mobility system (public + freight + private), expressed as the ratio of the value in a scenario to the value in 0 N	Elaboration on Bruzzone et al. (2021a)
	$I_{2.1}$ – Energy for MiFLM	Normalised energy required for MiFLM (light and medium trucks + public transport), expressed as the ratio of the value in a scenario to the value in 0 N	Bruzzone et al. (2021a)
Environment	I_3 – Total GHG emissions	Normalised GHG emissions (CO_2 + CH_4 + N_2O) of the mobility system (public + freight + private), expressed as the ratio of the value in a scenario to the value in 0 N	Elaboration on Nathanail et al. (2016)
	$I_{3.1}$ – GHG emissions of MiFLM	Normalised GHG emissions (CO_2 + CH_4 + N_2O) of MiFLM system (public transport + light and medium trucks), expressed as the ratio of the value in a scenario to the value in 0 N	Elaboration on Nathanail et al. (2016)
	I_4 – Local pollutant emissions	Normalised NO_x emissions of the mobility system (public + freight + private), expressed as the ratio of the value in a scenario to the value in 0 N	Elaboration on Nathanail et al. (2016)
	$I_{4.1}$ – Local pollutant emissions of MiFLM	Normalised NO_x emissions of the MiFLM system (public transport + light and medium trucks), expressed as the ratio of the value in a scenario to the value in 0 N	Elaboration on Nathanail et al. (2016)

I_2 – Energy consumption

Indicator I_2 considers the variation in energy consumption (MJ/day) of the entire transport system. It is intended to show the overall energy performance of the mobility system, considering the modal split and fuel and technological advancements in different scenarios compared to scenario 0 N.

$$I_{2_x} = \frac{\sum_{i=a}^{d} (J_i)_x}{\sum_{i=a}^{d} (J_i)_{0N}} \tag{2}$$

Indicator I_2 may also be limited to the components of the MiFLM service, focusing on the variation in energy consumption for delivery of parcels (LT) and provision of PT, as shown in Equation (3). This evaluation is specific to the evaluation system.

$$I_{2.1_x} = \frac{\sum_{i=a}^{b} (J_i)_x}{\sum_{i=a}^{b} (J_i)_{0N}} \tag{3}$$

where J is the energy consumption; the other indexes are as previously defined.

I_3 – GHG emissions

This indicator expresses the total GHG emissions of the mobility system based on vehicle type, vkm, and fuel type. First, GHG pollutants must be selected. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) constitute the majority of GHG emissions (more than 90 %, according to EEA, 2022) and may be suitable for our evaluations. These pollutants must be reported in comparable units of measurement. The Global Warming Potential (GWP) converts each GHG emission into a CO_2 equivalent (CO_{2eq}) using a specific factor (IPCC, 2021a, Equation (4). The GHG emissions for each traffic component in each scenario were summed and compared to scenario 0 N (Equation (5).

$$GHG = CO_2 + CH_4 \cdot GWP_{CH_4} + N_2O \cdot GWP_{N_2O} \tag{4}$$

$$I_{3_x} = \frac{\sum_{i=a}^{d} (GHG_i)_x}{\sum_{i=a}^{d} (GHG_i)_{0N}} \tag{5}$$

Similar to Indicator 2, it is possible to limit the analysis with Indicator 3.1 to the MiFLM scheme under evaluation (Equation (6).

$$I_{3.1_x} = \frac{\sum_{i=a}^{b} (GHG_i)_x}{\sum_{i=a}^{b} (GHG_i)_{0N}} \tag{6}$$

I_4 – Local pollutant emissions

This indicator expresses the local pollutant emissions generated by the mobility system based on the vehicle type, vkm, and fuel type of the vehicle fleet. To calculate this indicator, we used nitrogen oxides (NO_x). The contribution of transportation to these emissions is widely acknowledged (IPCC, 2021b). Together with particulate matter, they represent the primary targets of several policies aimed at reducing local pollution. I_4 was calculated using Equation (7). Other indicators may refer only to the MiFLM scheme under evaluation (Equation (8).

$$I_{4_x} = \frac{\sum_{i=a}^{d} (NOx_i)_x}{\sum_{i=a}^{d} (NOx_i)_{0N}} \tag{7}$$

$$I_{4.1_x} = \frac{\sum_{i=a}^{b} (NOx_i)_x}{\sum_{i=a}^{b} (NOx_i)_{0N}} \tag{8}$$

Using these indicators, it was possible to estimate the main expected energy and air pollution impacts of MiFLM, within the general mobility system and in comparison with conventional PT and logistics, excluding other traffic components. The proposed scenario analysis considers different future conditions, providing a solid picture of MiFLM impacts with different technological advancements. IPFT is beneficial for each index if $I_n < 1$. If I_n 1, no significant benefits or additional effects can be expected from implementing the MiFLM system. Conversely, if $I_n > 1$, the MiFLM solution is inferior to the status quo in terms of the evaluated dimensions.

The readability of the results was ensured through ratio R_n (Equation (9):

$$R_n = \frac{I_{nx}}{I_{n.1x}} \tag{9}$$

R_n allows quick assessment of the MiFLM contribution with respect to the overall condition of the mobility system in a given scenario x.

4. Case study: MiFLM in Zrenjanin (SRB)

The Serbian city of Zrenjanin was considered as a case study using the previously defined method. The city is associated with the local Regional Development Agency (RDA Banat), which demonstrated interest in the topic of this research. Along with Iuav University of Venice and other international partners, RDA Banat participated in the Adrion EU-funded project SMILE and its follow-up SMILE Plus. The main goal of SMILE (firSt and last Mile Inter-modal mobiLity in congested urban arEas of Adrion Region) was to develop future mobility scenarios as a methodological and planning tool to promote post-pandemic transition to zero-emission multi-modal integrated mobility (SMILE, 2023). Integration of passenger and freight transport is a potential solution to achieve this target, making Banat a solid case study to test our research hypothesis. Section 4 is divided into subsections for improved clarity. Section 4.1 presents the area of the case study; Section 4.2 defines the scenarios and the evaluation setting for the specific case; Section 4.3 presents the results. A discussion is presented in Section 5.

4.1. Case study description

Zrenjanin is located in the Banat region of Serbia, with approximately 80,000 inhabitants in a densely populated urban core and some sprawl along the main roads to the flat countryside. The total population

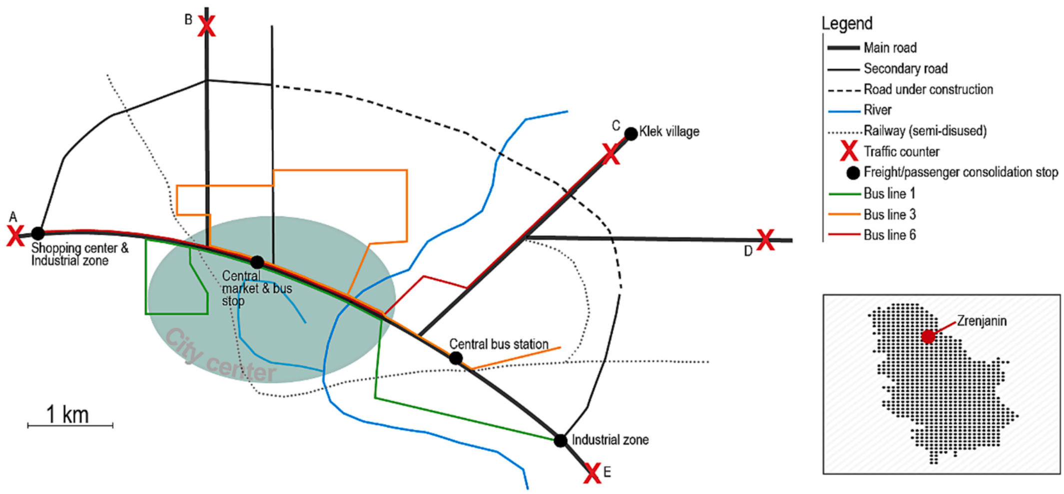

Fig. 1. Mobility in Zrenjanin (our elaboration).

including its suburbs is 123,362 (2018 data; RDA Banat, 2019). The city is historic, but carefully planned. The compact central residential area is surrounded by linear infrastructure including roads, railways, inland waterways, and commercial and industrial areas (Fig. 1).

The Begej River is canalised and navigable, providing important infrastructure for freight transport. The local railway is in poor condition, with low operating speeds and loading gauge. No passenger services are available. The road network is local, making Zrenjanin relatively poorly accessible and disconnected from the rest of the country (RDA Banat, 2019). Fig. 1 illustrates the main elements of the Zrenjanin area, including the main roads, location of traffic counters used to collect the input data for scenario modelling, the main local bus routes, river, railway, and central bus stations.

Table 3 presents the modal split of internal mobility calculated in 2019 (RDA Banat, 2019). Local mobility is primarily based on private vehicles (representing almost 50 % of movement). Buses account for approximately one-fifth of trips; pedestrian mobility also plays a major role (30 % of the modal split).

As of 2017 (most recent data collection), the motorisation rate in Zrenjanin was 272 cars per 1,000 inhabitants. Local statistics indicate that private cars cover 413,306 vkm/day and commercial vehicles cover 11,026 vkm/day within the 176-km local road network; light and medium trucks account for 6,270 vkm/day. Buses serving three major local routes (Fig. 1) and approximately 10 low-frequency urban and suburban routes (depending on the day and time) and longer-distance connections, drive for 4,656 vkm/day at a commercial speed of 13.4 km/h (MoZ, 2005; RDA Banat, 2019). Of these, 3,392 vkm/day were operated on high-frequency bus routes 1, 3, and 6, with 64 daily departures on weekdays and 14 buses in service.

In this study, we assume that the goods to be transferred to buses are consolidated and loaded in three facilities located near bus terminals in the west (shopping centre and industrial area), north (Klek village industrial area), and southeast (industrial area) of Zrenjanin. The main bus terminal and market stops can also be used for transfer and storage of goods (Fig. 1). From the consolidation points, local buses on lines 1, 3, and 6 deliver parcels to all regular stops; customers pick them up directly or in dedicated lockers. In the most positive scenarios, cargo e-bikes complement buses for freight transport. Some assumptions were made to evaluate the MiFLM setup. We assume that there was sufficient spare capacity on buses in all scenarios without any relevant increase in the number of services or vkm. This seems to be a reasonable assumption as most of the local buses are high-floor coaches that can accommodate luggage and parcels in under-floor compartments. The amount of goods to be transported on buses is determined from comparison with previous studies, as discussed in Section 4.2. Furthermore, we do not consider time constraints in our simulation. Loading and unloading of parcels can increase travel time and reduce the attractiveness of transit. In our case study, this is counterbalanced by expected extensive implementation of bus lanes and priority in the main transit corridors in Zrenjanin (RDA Banat, 2019).

4.2. Energy use and environmental evaluation

According to the method presented in Section 3, our goal is to evaluate the energy performance of 12 scenarios of future mobility, with use of luggage compartments on existing high-floor buses and e-bikes to deliver some parcels arriving in Zrenjanin. The MiFLM system was evaluated for the year 2030 for two reasons: 1) MiFLM can be evaluated with no structural changes to the public transport system introduced (e.g., start of new rail services); 2) it corresponds to the tactical planning horizon in Zrenjanin and to sustainability and innovation targets set at local and European levels.

Table 4 provides an overview of the specifics of each scenario in Zrenjanin, modelled by the Regional Development Agency Banat in the Interreg Adrion SMILE project, adapted according to the method presented in Section 3. To define the characteristics of each scenario and calculate the PIs, we followed previous research by RDA Banat and used the Municipality of Zrenjanin web tools, including their webGIS and the city's statistical, planning, and development documents (MoZ, 2005; RDA Banat, 2019; MoZ, 2022). When relevant, the data sources used as the input in the modelling tool are reported in Table 4. In Scenario 0, the motorisation rate, vehicle type, and modal choice follow the business-as-

Table 3
Modal split of internal mobility in Zrenjanin in 2019 (data source: RDA Banat).

Mode choice	Modal split (%)	Additional notes
Pedestrians	30.9	/
Bike	1.7	The bike network covers approximately 8 % of the total road network length.
Private car	47.4	Pay parking is rare and costs approximately 0.33 €/hour
Motorbike	0.9	/
Bus	19.1	Priority lanes for buses are negligible (<5% of total road network length)

Table 4
Overview of characteristics in scenarios 0 N to 3 N (without MiFLM).

Scenario	Vehicles	Modal split (%)	vkm/day [1]	Input data and source	Other notes
0 (BAU)	Private cars	67.8	502,371 (conventional fuel) [2]88,653 (alternative fuels) [3]	Statistics Serbia (2021): motorisation rate, population trends. EC (2022). RDA Banat (2019)	
	Buses	8.1	4,656	Requirement for urban services (2019 timetable) and traffic counts (suburban/long distance traffic)	
	Commercial vehicles	n.a.	11,026 (total)6,270 (light and medium trucks only)	Traffic counts. Our elaboration on data from WebGIS Zrenjanin	[4] [5]
1 (Pessimistic)	Private cars	50.9	436,727 (conventional fuel)145,576 (alternative fuel)	Statistics Serbia (2021): motorisation rate, population trends. EC (2022); RDA Banat (2019)	
	Buses	18.5	4,336	Requirement for urban services (2019 timetable) and traffic counts (suburban/long distance traffic) RDA Banat (2019). Own elaboration on data from WebGIS Zrenjanin	
	Commercial vehicles	n.a.	5,960 (total)3,582 (light and medium trucks only)	Traffic counts Our elaboration on data from WebGIS Zrenjanin	[4] [5]
2 (Moderate)	Private cars	29.8	242,527 (conventional fuel)130,591 (alternative fuel)	Statistics Serbia (2021): motorisation rate, population trends. EC (2022); RDA Banat (2019)	
	Buses	33.6	4,986	Requirement for urban services (2019 timetable) and traffic counts (suburban/long distance traffic). RDA Banat, 2019. Our elaboration on data from WebGIS Zrenjanin	
	Commercial vehicles	n.a.	4,094 (total)3,856 (light and medium trucks only)	Traffic counts. Our elaboration on data from WebGIS Zrenjanin	[4] [5]
3 (Optimistic)	Private cars	11.1	141,075 (conventional fuel)115,425 (alternative fuel)	Statistics Serbia (2021): motorisation rate, population trends. EC (2022). RDA Banat (2019)	
	Buses	26.7	4,691	Requirement for urban services (2019 timetable) and traffic counts (suburban/long distance traffic). RDA Banat (2019). Our elaboration on data from WebGIS Zrenjanin	
	Commercial vehicles	n.a.	4,094 (total)3,856 (light and medium trucks only)	Traffic counts. Effect of structural infrastructure improvements and e-commerce. Our elaboration on data from WebGIS Zrenjanin	[4] [5]

[1] In each scenario, we assume that all vehicles of one kind cover the same distance, regardless of age and emission class. We also assume that commercial vehicles are loaded uniformly and that the vkm reduction is directly proportional to the fleet size reduction. [2] Conventional fuels: petrol, diesel. The subdivision of vehicles by type of fuel and emission class is modelled based on data from Statistics Serbia (2021) and from countries with similar fleet composition (Slovakia, Romania; Velten et al./EEA, 2020). EC (2022) is used to validate modelled scenarios. [3] Alternative fuels: CNG, LPG, hybrid, battery-electric, hydrogen-fuel cell. The subdivision of vehicles by type of fuel and emission class is modelled based on data from Statistics Serbia (2021) and from Velten et al./EEA (2020) on countries with similar fleet composition (Slovakia, Romania). EC (2022) is used to validate modelled scenarios. [4] In scenarios 2 and 3, city bypass opens, eliminating heavy-truck traffic (RDA Banat, 2019). [5] In scenarios 2 and 3, light and medium trucks cover 5 % more vkm than in scenario 1 due to more deliveries within the general context of reduced demand for personal mobility (Buldeo Rai et al., 2019; Trent and Joubert, 2022).

usual (BAU) pattern derived from statistical and academic sources between 2001 and 2021. In Scenario 1, a positive effect due to EU-wide efforts toward cleaner urban mobility was observed. However, neither improvements in public transport nor relevant technological changes to the vehicle fleet were considered, indicating that mobility impacts remain higher than what is expected by international and local agreements, strategies, and plans. In Scenario 2, exogenous factors (EU-wide and national policies and norms, and structural modifications to the mobility system, including opening of new roads and protection of bus lanes) led to partial evolution of modal choice toward more sustainable modes. Moreover, new fuels and technologies contributed to reduced vehicle emissions. In Scenario 3, alongside policy and infrastructural innovation, positive trends and policies led to optimistic conditions, with private motorised transportation playing a marginal role.

Fig. 2 graphically presents the considered vehicle types according to the Roadmap Tool outputs in the 2030 horizon. Private cars and light trucks use several types of fuel; heavy-duty vehicles (buses and trucks) are powered by diesel, natural gas, and hybrid engines. Businesses are powered by electric and hydrogen fuel cells.

We modelled the energy consumption and tank-to-wheel emissions (specifically CO_2, CH_4, N_2O, and NO_x) in each scenario using the HBEFA handbook (Notter et al., 2019, 2022). However, this tool does not cover all types of power sources. For missing values, we used appropriate conversion rates for the EFs of other types of sources in the literature. We determined the factors affecting LPG car emissions based on the results of Opresnik et al. (2012), Mingolla and Lu (2021), and Chatzipanagi et al. (2022). We also investigated the fuel consumption of hybrid heavy-duty vehicles, adapting the related emission levels according to Sun et al. (2021) and the CO_2 emissions of hybrid cars according to Peters et al. (2021). The outputs of Zahabi et al. (2014) were used as the main sources of emissions for hybrid cars (gasoline vehicles were used as benchmarks). Determination of emission factors for hydrogen fuel-cell vehicles is problematic. The literature provides inconsistent results, ranging from very optimistic estimates to life-cycle emissions 2.7 times greater than those of battery/electric counterparts (Logan et al., 2020). For this reason, considering the small numbers involved (maximum of 3.4 % of all vehicles in Zrenjanin in scenario 3H), we assigned the same emissions factors to hydrogen vehicles and battery/electric vehicles of the same type (car, bus, light truck).

Scenarios involving MiFLM (L and H) require determination of the quantity of freight that can be served by transit vehicles. According to previous research (Jansen, 2015; Nathanail et al., 2016), this is context-dependent and influenced by the system uptake by public and private investors. Optimisation of the operational performance of MiFLM was not within the scope of this study. Based on previous studies and the current organisation of the local transport system including the bus network, we determined conservative estimates for light and medium trucks that considered substitution by buses and e-bikes. These estimates investigate the percentage of third-party goods in frequent categories, those with repetitive and easy-to-manage deliveries. According to MiFLM case-studies reported by Jansen (2014), Nathanail et al. (2016), Mazzarino and Rubini (2019), and Bruzzone et al. (2021a), we consider

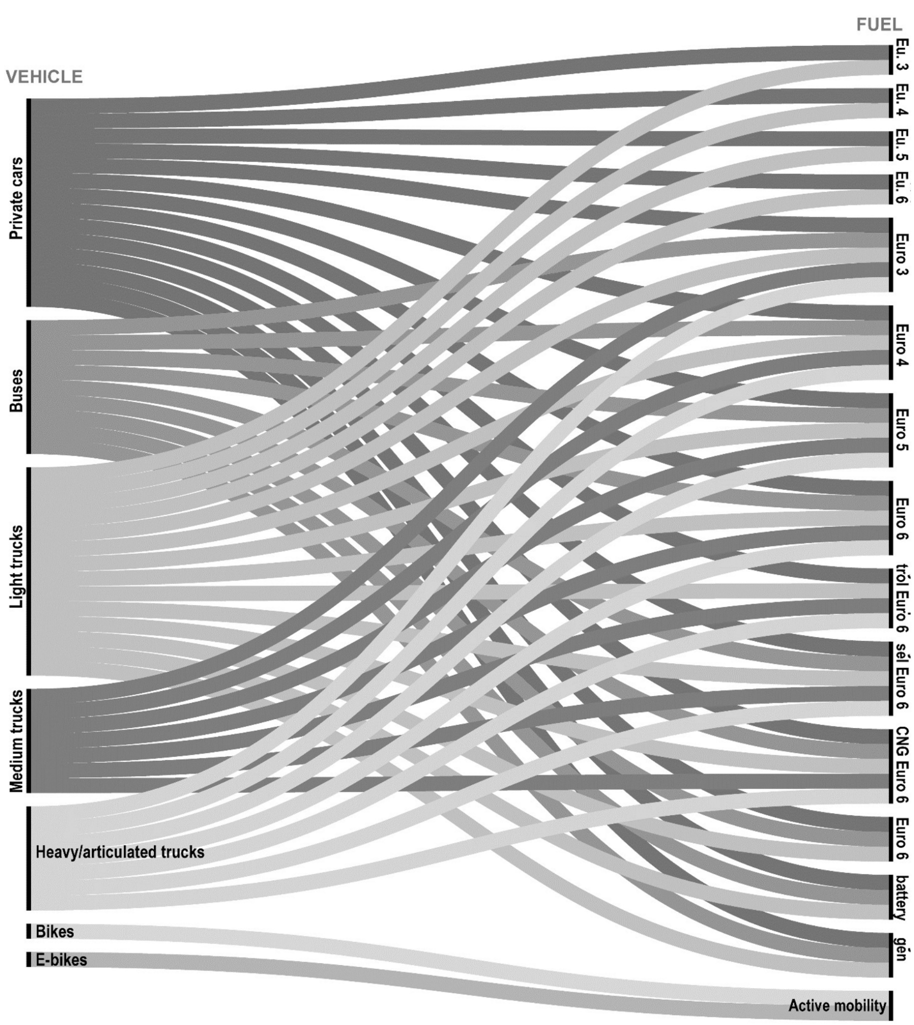

Fig. 2. Vehicles and fuel types in mobility scenarios.

Table 5
Energy and environmental absolute values in different scenarios for 2030.

Indicator (unit of measure) - scenario		0N	0L	0H	1N	1L	1H	2N	2L	2H	3N	3L	3H
I1	a	502,371	502,371	502,371	436,727	436,727	436,727	242,527	242,527	242,527	141,076	141,076	141,076
(vkm)	b	88,654	88,654	88,654	145,576	145,576	145,576	130,591	130,591	130,591	115,425	115,425	115,425
	c	3,725	3,725	3,725	3,469	3,469	3,469	2,493	2,493	2,493	0	0	0
	d	931	931	931	867	867	867	2,493	2,493	2,493	4,692	4,692	4,692
	e	2,822	2,455	2,257	1,816	1,580	1,452	1,801	1,567	1,080	1,589	1,382	953
	f	314	273	251	202	176	161	318	276	191	530	461	318
	g	2,947	2,652	2,505	1,490	1,341	1,266	1,478	1,330	1,256	1,304	1,173	1,108
	h	188	169	160	166	149	141	261	235	222	435	391	369
	i	4,471	4,471	4,471	2,140	2,140	2,140	202	202	202	178	178	178
	j	285	285	285	238	238	238	36	36	36	59	59	59
	k	0	0	0	0	0	0	0	0	425	0	0	425
	tot	606,707	605,986	605,610	592,690	592,262	592,038	382,199	381,750	381,516	265,287	264,838	264,604
I2	a	969,544	969,544	969,544	842,855	842,855	842,855	468,129	468,129	468,129	272,003	272,003	272,003
(MJ)	b	153,148	153,148	153,148	156,343	156,343	156,343	157,842	157,842	157,842	141,556	141,556	141,556
	c	30,198	30,198	30,198	26,522	26,522	26,522	15,590	15,590	15,590	0	0	0
	d	5,998	5,998	5,998	3,799	3,799	3,799	9,050	9,050	9,050	21,675	21,675	21,675
	e	6,627	5,766	5,302	4,267	3,713	3,413	4,229	3,679	2,537	3,729	3,244	2,237
	f	648	442	406	468	407	374	610	531	366	974	847	584
	g	6,922	6,230	5,884	3,455	3,149	2,974	3,470	3,123	2,950	3,065	2,758	2,605
	h	443	399	376	384	346	326	608	547	517	1,006	905	855
	i	35,904	35,904	35,904	17,154	17,154	17,154	1,620	1,620	1,620	1,422	1,422	1,422
	j	2,231	2,231	2,231	1,859	1,859	1,859	279	279	279	465	465	465
	tot	1,211,663	1,209,860	1,208,992	1,057,106	1,056,146	1,055,620	661,427	660,390	658,880	445,895	444,876	443,403
I3	a	69,993,681	69,993,681	69,99,3681	60,847,725	60,847,725	60,847,725	33,787,893	33,787,893	33,787,893	19,623,893	19,623,893	19,623,893
(g)	b	7,545,483	7,545,483	7,545,483	7,068,659	7,068,659	7,068,659	8,068,003	8,068,003	8,068,003	7,093,058	7,093,058	7,093,058
	c	2,112,486	2,112,486	2,112,486	1,855,293	1,855,293	1,855,293	1,090,571	1,090,571	1,090,571	0	0	0
	d	379,750	379,750	379,750	127,057	127,057	127,057	254,115	254,115	254,115	961,418	961,418	961,418
	e	463,623	403,352	370,898	301,683	262,464	241,316	298,941	260,079	179,365	263,568	229,304	158,141
	f	33,722	29,338	26,978	29,799	25,925	23,836	32,919	28,639	19,751	50,412	43,859	30,247
	g	484,228	435,806	411,594	244,344	219,910	207,663	242,308	218,077	205,961	214,006	192,605	181,905
	h	31,000	27,900	26,350	24,452	22,007	20,781	40,002	36,002	34,002	62,702	56,431	53,297
	i	2,511,558	2,511,558	2,511,558	1,199,937	1,199,937	1,199,937	113,327	113,327	113,327	99,492	99,492	99,492
	j	156,328	156,328	156,328	130,180	130,180	130,180	19,530	19,530	19,530	32,539	32,539	32,539
	tot	83,711,859	83,595,682	83,535,106	71,829,128	71,759,157	71,722,447	43,947,610	43,876,237	43,772,519	28,401,089	28,332,600	28,233,991
I4	a	125,349	125,349	124,611	108,970	108,970	108,970	57,387	57,387	57,387	31,126	31,126	31,126
(g)	b	1,571	1,571	1,571	2,193	2,193	2,193	2,623	2,623	2,623	2,688	2,688	2,688
	c	8,777	8,777	8,777	7,743	7,743	7,743	3,334	3,334	3,334	0	0	0
	d	482	482	482	149	149	149	299	299	299	1,196	1,196	1,198
	e	1,746	1,519	1,397	971	845	777	856	745	514	657	572	394
	f	34	30	27	34	29	27	36	31	21	56	49	34
	g	1,824	1,642	1,550	902	829	782	913	822	776	728	656	619
	h	50	45	43	28	25	24	53	47	45	65	58	55
	i	9,748	9,748	9,748	4,657	4,657	4,657	440	440	440	347	347	347
	j	233	233	233	194	194	194	29	29	29	48	48	48
	tot	149,815	149,396	148,439	125,841	125,635	125,517	65,968	65,756	65,466	36,912	36,740	36,510

Letters in second column indicate type of vehicle and fuel. a = Conventional private cars; b = Alternative private cars; c = Conventional buses; d = Alternative buses; e = Conventional light trucks; f = Alternative light trucks; g = Conventional medium trucks; h = Alternative medium trucks; i = Conventional heavy trucks; j = Alternative heavy trucks; k = e-bikes (excluded from energy assessment due to limitation of HBEFA). Values in italics define categories of vehicles directly involved in MiFLM operations such as buses and light and medium trucks.

Table 6
PIs of MiFLM in Zrenjanin for 2030.

Indicator/Scenario	0N	0L	0H	1N	1L	1H	2N	2L	2H	3N	3L	3H
I_1 – Total mileage	1	0.999	0.998	0.977	0.976	0.976	0.630	0.629	0.629	0.437	0.436	0.436
I_2 – Total energy	1	0.999	0.998	0.872	0.872	0.871	0.546	0.545	0.544	0.368	0.367	0.366
$I_{2.1}$ – Energy of MiFLM	1	0,965	0,947	0,765	0,746	0,736	0,660	0,640	0,610	0,599	0,579	0,550
I_3 – Total GHG emissions	1	0,999	0,998	0,858	0,857	0,856	0,525	0,524	0,522	0,339	0,338	0,337
$I_{3.1}$ – GHG emissions of MiFLM	1	0,967	0,950	0,737	0,717	0,706	0,559	0,539	0,509	0,443	0,423	0,395
I_4 – Total emissions of local pollutants	1	0.997	0.991	0.840	0.839	0.838	0.440	0.439	0.437	0.246	0.245	0.244
$I_{4.1}$ –Emissions of local pollutants in MiFLM	1	0.968	0.951	0.761	0.745	0.736	0.425	0.409	0.386	0.209	0.196	0.178

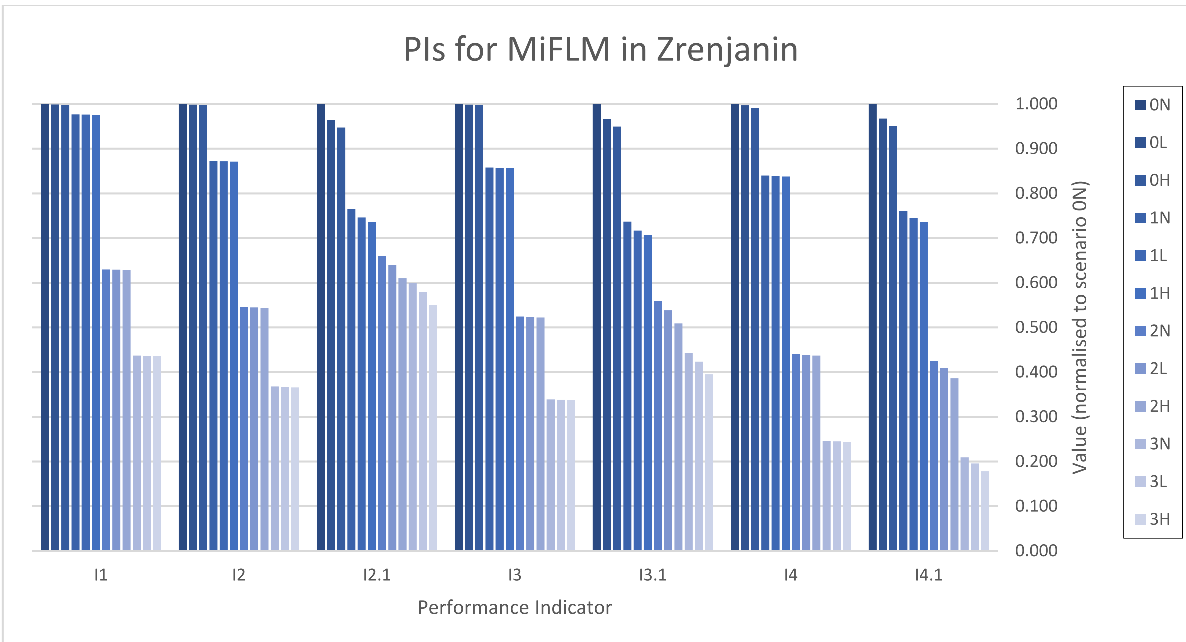

Fig. 3. PIs of MiFLM in Zrenjanin for 2030.

that in the "Low-MiFLM" (L) condition, 13 % of light trucks and 10 % of medium trucks are not needed as their load is transported by bus. These numbers increase to 20 % and 15 % in the "high-MiFLM" (H) scenarios. In H3, an additional 20 % of light trucks are replaced by bikes and e-bikes for last-mile delivery, consistent with the indications of the EC (2022).

4.3. Results

Using the PIs defined for MiFLM as explained in Section 3.2 and the presented scenarios, we calculated each indicator according to the local setting and specifics in the case study area. In the HBEFA simulation, we considered an urban road with a speed limit of 50 km/h, flat terrain, and free traffic flow, consistent with most roads in the city of Zrenjanin. Table 5 provides an overview of the results, showing the absolute value of each indicator for each scenario, normalised to 0 N. Each indicator was presented individually to highlight the findings.

I_1 - Total mileage

Indicator I_1 analyses the total distance covered by all vehicles in Zrenjanin in the 12 scenarios, as shown in Equation (1). The results of our calculations indicate slight reductions in the overall mileage comparing each L and H to the respective N. However, owing to the envisioned modal shift and reduced private car travel, the overall distances covered in scenarios 2L, 2H and 3L, 3H were approximately 64 % and 44 % of those covered in scenarios 1L and 1H, respectively. In 1 N, 592,690 vkm/day were covered by all vehicles, compared to 592,038 vkm/day in 1H, 381,516 vkm/day in 2H, and 264,604 vkm/day in 3H. In 0 N, the overall distances were 606,707 vkm/day, 2.3 % higher than in 1 N. Thus, the contribution of MiFLM is minor for indicator I_1. However, the overall performance largely benefits from the exogenous factors assumed for development of mobility toward 2030. Modal-shift policies allow a considerable reduction in total mileage in the area.

I_2 – Total energy consumption

The results for indicator I_2 show that MiFLM contributes only marginally to overall energy savings; however, the overall energy requirement is decreased by approximately 63 % in scenario 3 owing to evolution of vehicle fleets from a 0 N value of 1,211,663 to 443,403 MJ/day in 3H, the least energy-consuming scenario. In scenarios L and H, even with MiFLM, the overall required energy was very similar compared to the respective scenario N, indicating that the reduction in commercial vehicle mileage induced by MiFLM did not produce energy savings. This can be explained by the different energy mixes used by the vehicle fleets. In this case, greater energy use is due to CNG and LPG vehicles; both have higher energy consumption factors than conventional-fuel vehicles according to the HBEFA handbook (Notter et al., 2022).

$I_{2.1}$ – Energy consumption for MiFLM

Indicator $I_{2.1}$ measures the amount of energy required by the MiFLM system (PT; light and medium trucks). For $I_{2.1}$, scenario 0 N required 50,836 MJ/d, whereas 3H required 27,956 MJ/d. Energy consumption in relation to 0 N decreased by 26 % in scenario 1H, by 39 % in scenario 2H, and by 45 % in scenario 3H. The contribution of more energy-efficient electric and fuel-cell vehicles was evident, particularly in scenario 3H, with a $I_{2.1}$ value of 0.55, compared to 0.58 in 3 L and 0.60 in 3 N (see Table 6). In addition to transport of freight on buses, the energy performance can be improved by shifting to different bus fleet technologies. The 1 N, 2 N, and 3 N scenarios required 39 GJ/day, 34 GJ/day, and 30 GJ/day, respectively, decreases of 24 %, 34 % and 40 % from 0 N; 1 L and 1H indicated decreases of 2 % and 3 %, respectively, compared to 1 N.

I_3 – Total GHG emissions

GHG emissions were determined using Equation (5): the results show that scenarios 1L and 1H produced a slight decrease in GHG emissions compared to 1 N, from 71,829 kg/d without MiFLM to 71,759 and 71,722 kg/d (-0.3 %). Great reductions were achieved in 2 N, 2L and 2H (around −48 %) and in 3 N, 3H and 3L (approximately −65 %). Like in Scenario 1, L and H slightly outperformed N in scenarios 2 and 3, with small reductions (-0.1 % to −0.7 %). Similarly, scenarios 0L and 0H produced a marginal decrease compared to scenario 0 N. Thus, we conclude that the overall technological shift in vehicles is more efficient than MiFLM in reducing GHG emissions.

$I_{3.1}$ – GHG emissions of MiFLM

Considering only the performances of vehicles directly involved in transit and freight delivery operations, the system is expected to reduce GHG emissions between 2 % and 4 % in each L and H compared to the respective N scenario (e.g., from 1,959 kg/day in 2 N to 1,784 kg/day in 2H), and up to 60 % in 3H compared to 0 N, from 3,505 kg/day in 0 N to 1,385 kg/day in 3H due to renewal of bus and commercial vehicle fleets.

I_4 – Total local pollutant emissions

Indicator I_4 (Equation (7) indicates that reductions in NO_x emissions are achievable, up to 76 % in 3H (36,510 g/day) compared to 0 N (149,815 g/day) and up to 71 % compared to 1 N (125,841 g/day). Most of these benefits are derived from substitution of diesel-powered vehicles. For this reason, scenario 3, where 100 % of the bus fleet is either electric, fuel-cell, or CNG, scored particularly well; scenario 2H produced a 56 % reduction in NO_x emissions (65,466 g/day) compared to 0 N.

$I_{4.1}$ –Local pollutant emissions of MiFLM.

The reduction in NO_x emissions excluding heavy trucks and private cars (MiFLM conditions) was higher than the overall performance described by I_4 (-82 % as opposed to −76 % in 3H, compared to 0 N). $I_{4.1}$ indicates that implementation of MiFLM could favour abandonment of internal combustion engines due to the smaller number of mid- and heavy-duty vehicles required. This had a positive impact on NO_x emissions.

To enhance the readability of the results and improve understanding of the role of MiFLM with more general changes in mobility in Zrenjanin, Table 6 and Fig. 3 show the absolute values in each scenario normalised to the value in scenario 0 N, according to Equations (1)–(8). The benefits of MiFLM are visible comparing each scenario H with the respective L and N (e.g., 2H compared to 2L and 2 N). However, comparison of each scenario 3 with the respective scenario 2, 1, or 0 (e.g., 3L compared to 2L, 1L, and 0L) clarified the impact of other factors with the assumption of a constant MiFLM level. The impacts of MiFLM were limited, but clear. Even in scenario 0, passenger–freight integration contributed to energy efficiency by reducing overall consumption by 2.8 % due to the reduction in distances, although energy use by PT and freight vehicles increased. In more advanced scenarios, three delivery and bus fleets were substituted with cleaner vehicles. Thus, the impacts of MiFLM-related traffic, measured by PIs 2.1, 3.1, and 4.1, had greater relative importance than the respective general indicators. High MiFLM uptake (scenario 3H) ensured pollutant reductions between 3.1 % and 4.8 % compared with scenario 3 N, and energy use decreased by 4.9 %. These results suggest that MiFLM schemes are far more effective when fleet innovation is combined with passenger–freight integration.

5. Discussion of results

In different scenarios of future mobility policy and technological development, MiFLM has a positive impact on overall energy use and emissions (measured by indicators I_2, $I_{2.1}$, I_3, $I_{3.1}$, I_4, and $I_{4.1}$). This is also due to the reductions in vkm throughout the road network, one of the main points favouring passenger–freight integration schemes (Bruzzone et al., 2021a). However, previous studies have focused on MiFLM assessment considering that exogenous factors (vehicle technology, policy approach to mobility, infrastructural assets, and offered level of service) remain unchanged (Savelsbergh and Van Woensel, 2016). Combination of different levels of MiFLM uptake and changes in technology and production factors reveal that MiFLM is still beneficial; however, future mobility strategies could pursue more ambitious targets by renewing vehicle fleets and fostering a modal shift, as described in our scenario analysis. For instance, MiFLM in scenario 0 reduces overall local pollutant emissions by approximately 1,400 g/day, from 149,815 g in scenario 0 N to 148,439 g in scenario 0H (-0.9 %). Yet, the base scenario 1 (1 N), with no mixed passenger–freight service, reduces daily local pollutant emissions by an additional 15 % to 125,841 g, indicating a footprint of a different magnitude.

Thus, in more general terms, our scenarios describe conditions in which significant environmental and energy benefits are achieved as a result of technological development (visible comparing scenarios 0 N with 1 N, 2 N, and 3 N, or 0L with 1L, 2L, and 3L). However, the contribution of MiFLM alone seems marginal (1 N compared to 1H or 3 N compared to 3H). In contrast to the results of other studies (Jansen, 2014; Fatnassi et al., 2015; Arvisson et al., 2016; Bruzzone et al., 2021a) and the theoretical potential highlighted for MiFLM (Trentini and Mahléné, 2010; Ghilas et al., 2013; Ghilas et al., 2016; Savelsbergh and Van Woensel, 2016), its role seems more limited with an extended time horizon, including other transport solutions, and incorporating fleet innovation and structural changes into the transport infrastructure.

In interpreting the results, we must remember that assumptions were made in the analysis, as described in Sections 4.1 and 4.2. The relatively small case study and simplicity of its road and PT network allow for easy determination of coefficients. Use of more complex simulation tools is recommended to generalise the method to more challenging scales. Additional constraints, such as normative and practical limits to the conversion of buses for mixed passenger-freight transport, should also be considered, as well as transport capacity limits. Similarly, it would be needed to include the value of passenger travel time and the implications of additional transfers for parcels and freight units. These can constitute a significant limit to innovation in FLM management (Zamparini and Reggiani, 2016) and affect determination of future transport demand (Libardo and Nocera, 2008). Methodologically, our scenario analysis is based on local planning documents, with future aspects of mobility systems computed using the Roadmap Tool. Although it is a suitable tool for small and mid-sized European cities, the tool is designed for policymakers and authorities; thus, it focuses on simplicity and multifocality rather than analytical precision.

6. Conclusions and policy implications

Mixed passenger–freight first-last mile (MiFLM) transport has been proposed as a promising solution to the negative impacts of passenger transport and logistics in both urban and rural areas that improves the overall efficiency and financial sustainability of transport operations. In this study, we shed light on the long-term energy and environmental impacts of MiFLM transport on buses in a medium-sized city in Europe. When the analysis period was extended from a short time to a longer period, the ability of MiFLM to achieve energy benefits was limited. This is evident when the results are compared with technological advancement. For example, the reduction in energy consumption in 2H (strong role of PT, with a modal split of 33.6 % compared to 29.8 % for private cars, and almost half of the fleet powered by alternative sources) was 46 %, 1 % greater than in 2 N (same exogenous conditions but no passenger–freight integration). Some environmental benefits were also observed, depending on the driving distance and energy consumption. In summary, our results suggest that the energy performance of mobility is significantly improved by transition to more sustainable fuels, supported by a policy-driven modal shift toward active modes, rather than by MiFLM. In terms of energy consumption and reduction of pollutant emissions, this solution can be an important side-measure with positive effects on other externalities (such as congestion).

However, the results should be considered in a broader perspective. Other drivers of passenger–freight integration in the long-term, such as its social value and its ability to reduce conflicts between road and urban users, remain valid (Bruzzone et al., 2021a). Furthermore, MiFLM seems particularly promising in the medium- and short-term, when changes to the vehicular fleet are less prominent. However, this contrasts with the need for initial investment (consolidation facilities, appropriate storage, and coordination software) and deep normative reforms to overcome the traditional legal approach of logistics and passenger transport as separate entities.

Promising future developments in this research may involve extension of the set of PIs to better describe the operational, environmental, and energy performances of MiFLM. Inclusion of a comprehensive sensitivity analysis may reduce limitations due to the approximation inherent in scenario analysis. In addition, use of other modelling tools to complement or replace HBEFA should provide more accurate and up-to-date results, especially with respect to cutting-edge solutions such as hydrogen fuel-cell vehicles. However, this evaluative approach adds a new perspective to the discourse on first-last-mile freight integration. This topic has the fundamental potential to be an active part of the solution for the transition to sustainability if properly promoted and framed within other energy, transport, and spatial planning policies.

CRediT authorship contribution statement

Francesco Bruzzone: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Federico Cavallaro:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Silvio Nocera:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2023.100958.

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