

Optimizing Multi-Period Fleet Utilization and Transition in Municipal Solid Waste Management*

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Abstract

Rapid urbanization is increasing the volume of municipal solid waste, demanding efficient and environmentally compliant waste management systems. In response to stricter regulations, such as those introduced by the European Green Deal, municipalities must reduce emissions and transition to cleaner vehicle technologies. This paper presents a novel Mixed-Integer Programming (MIP) model for the Multi-Period Utilization and Fleet Transition Optimization Problem (MPUFTO), aiming to minimize the total discounted costs of purchasing and retrofitting municipal vehicles over a planning horizon. The model ensures compliance with emission limits, adapts to growing service demand, and supports the strategic planning of vehicle procurement and modernization. A flexible model structure allows for pollutant-specific constraints and budget limitations. Two use cases based on real-world data from the Kraków metropolitan area validate the model's applicability and decision-support potential for sustainable municipal fleet transition planning.

Keywords: Strategic Decision-Making, Municipal Logistics, Fleet Transition Problem, Mixed Integer Programming, Solid Waste Collection Fleet, Strategic Fleet Management

Introduction

The relentless pace of urbanization in large metropolitan areas, exemplified by continued demographic shifts even as suburbanization occurs, escalates demands on municipal services, particularly waste management (World Bank, 2021). Local governments are thus compelled to develop increasingly efficient and environmentally compliant waste management systems. This demographic dynamic, coupled with evolving legislative requirements—such as stringent waste segregation mandates and growing environmental awareness (further amplified by events like the COVID-19 pandemic, which underscored the need for resilient and adaptive systems (Urbańska et al., 2023)—necessitates strategic fleet development. With projected increases in waste volumes and tightening vocational vehicle emission standards, municipalities face complex strategic decisions related to fleet renewal and compliance. These decisions involve balancing the replacement of existing vehicles with new, compliant ones, acquiring additional cars, and potentially retrofitting current fleets to meet increasingly rigorous regulatory standards, such as not exceeding the total CO₂ emissions targets set by initiatives like "Fit for 55." The challenge is further compounded by the need to integrate diverse new technologies, as evidenced by studies assessing life cycle GHG emissions of various truck types, where even seemingly greener options like battery electric vehicles require careful consideration of battery capacity versus emissions impact (Redick, 2022; Ewert et al., 2021; Raini and Hamzah, 2024; Vonolfen et al., 2011; Taghipour and Salari, 2015).

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Determining the optimal multi-period fleet development plan within a given planning horizon is non-trivial, requiring robust analytical tools to support and justify decisions. This paper addresses this critical need by formulating and exploring the following research questions:

Main Research Question (MRQ): How can mathematical models effectively support multi-period municipal fleet modernization planning by minimizing costs while ensuring compliance with environmental standards and growing service demand?

Detailed Research Question 1 (DRQ01): How can Mixed-Integer Programming effectively support decision-making in fleet modernization, considering the inherent complexity of the model and the required computation time?

Detailed Research Question 2 (DRQ02): How can mathematical models supporting multi-period vehicle fleet modernization planning be practically applied within a municipal solid waste management system?

This paper's main contribution is the introduction of a novel mixed-integer programming (MIP) model for the Multi-Period Utilization and Fleet Transition Optimization Problem (MPUFTOP). This research provides a comprehensive and practical framework for strategically planning the modernization of municipal heavy-duty vehicle fleets over a defined time horizon. Our model uniquely integrates several critical aspects of decision-making: optimizing vehicle purchasing, determining retrofitting schedules, and incorporating technological shifts, all while ensuring compliance with stringent environmental emission limits and accommodating rising service demands.

The developed MIP model aims to minimize the total discounted costs of vehicle purchasing and retrofitting. For each planning period, the model determines the optimal number and type of vehicles to purchase, as well as the number of existing vehicles to modernize and the standards to which they will be upgraded, ensuring that overall emission targets are met by the end of the planning horizon. The practical applicability and potential of this exact optimization model for long-term strategic planning are rigorously showcased through a detailed use case tailored to a real-world municipal waste collection system, utilizing characteristics of the Kraków agglomeration in Poland.

Specifically, two distinct cases are examined over a seven-year planning horizon:

Case 1: Focuses on maintaining constant pollution emission levels despite increasing service demand, which necessitates strategic fleet expansion.

Case 2: Aims for a significant 30% reduction in pollution emissions over the planning horizon, achieved through the gradual replacement and modernization of the fleet.

The remainder of this paper is structured as follows. The next section positions the problem within the existing body of knowledge regarding decision support tools for multi-period technology transition problems in municipal solid waste management. The Multi-Period Utilization and Fleet Transition Optimization Problem (MPUFTOP) and its detailed mathematical model are introduced in the following section. The following section presents the computational experiments for the two defined cases, detailing the model's performance and the obtained solutions. The last section provides conclusions and suggests avenues for future research.

Paper Positioning

Municipal fleet modernization is increasingly driven by the rising demand for waste collection services and the need to comply with stringent environmental regulations. Early research primarily emphasized operational efficiency of traditional diesel fleets (Kleindorfer et al., 2012; Pantuso et al., 2016; Dietz and Katz, 2001; New, 1975; Korcyl et al., 2020; Książek et al., 2021). However, evolving policies such as the European Union's "Fit for 55" and the European Green Deal have shifted the focus toward adopting zero-emission vehicles, reflecting climate goals and public health priorities (European Union, 2020, 2024; Aiello et al., 2024). The transportation sector's substantial greenhouse gas emissions further underline the urgency for fleet transitions (Ahani et al., 2023; Velazquez et al., 2016). Simultaneously, aging vehicle fleets incur increasing operational and maintenance costs, motivating the adoption of replacement strategies (Emiliano et al., 2020; Figliozzi et al., 2011). Advances in alternative vehicle technologies, such as electric, compressed natural gas (CNG), and hydrogen fuel cell, offer promising solutions but demand significant upfront investments and infrastructure planning (Bieda et al., 2023; Ahani et al., 2023). Legislative frameworks, especially in the EU, increasingly mandate electrification targets for municipal fleets, placing additional pressure on local governments to comply (Republic of Poland, 2018).

Municipal solid waste volumes continue to increase worldwide, driven by demographic shifts, economic development, and lifestyle changes (Adeleke et al., 2022; Dyson and Chang, 2005; Chen et al., 2020). For example, forecasts in Poland predict a steady rise in waste generation, with household waste particularly

increasing (Kulisz and Kujawska, 2020; Główny Urząd Statystyczny, 2024; Polska Agencja Prasowa, 2024; European Environment Agency, 2024a, 2024b). Localized studies, such as in the Kraków metropolitan area, have documented a 4.3–4.9% growth in waste from 2015 to 2023, interrupted only briefly by the COVID-19 pandemic (Urząd Miasta Krakowa, 2025; Urbańska et al., 2023). This growth necessitates proportional expansion and modernization of waste collection fleets. However, this expansion must be balanced with environmental goals to avoid offsetting benefits gained from improved waste management with increased vehicle emissions. Compliance with strict EU emissions targets and alternative fuel infrastructure regulations further complicates fleet composition decisions (European Union, 2014, 2019; Republic of Poland, 2018).

Recent literature increasingly addresses mathematical and operational models that support strategic fleet transitions by integrating cost, emissions, and operational constraints. Optimization approaches, notably Mixed-Integer Programming (MIP), have been widely used to balance economic and environmental objectives across multiple periods (Bieda et al., 2023). For example, Velazquez Abad et al. (2016) combined route simulation with evolutionary algorithms to select low-carbon technologies for heavy trucks, demonstrating emissions reductions with minimal cost increases. Other studies emphasize dynamic, data-driven replacement strategies responsive to fuel prices and vehicle usage patterns (Rubaiat, 2020). Emissions-aware integer programming models demonstrate significant reductions in pollution under budget constraints, reinforcing the value of integrating environmental goals into fleet renewal plans (Emiliano et al., 2020). Additionally, operational studies focusing on garbage truck driving cycles highlight how precise quantification of fuel consumption and emissions can improve fleet efficiency and environmental impact assessments (Hao et al., 2024).

Although life cycle assessments compare the emissions and costs of diesel, electric, hydrogen, and CNG vehicles (Redick, 2022; Perez et al., 2017), fewer models fully incorporate this diversity into multi-period fleet transition frameworks that reflect real-world municipal data and constraints. Studies of specific regions, such as Alberta (Redick et al., 2025) and Switzerland (Cabukoglu et al., 2019), highlight the infrastructure and energy demands necessary to adopt battery electric and fuel cell vehicles successfully. Local factors, such as geography, routing, and infrastructure availability, critically influence fleet performance and carbon footprint (Perez et al., 2017). The practical applicability of many models remains limited by the lack of comprehensive case studies focused specifically on municipal solid waste collection fleets, highlighting a significant research gap.

Despite advancements in modeling and technology evaluation, a notable gap remains: a scarcity of holistic, multi-period optimization frameworks that simultaneously address environmental compliance, cost minimization, evolving service demand, and operational realities unique to municipal waste collection. Notably lacking are approaches grounded in real-world municipal data that capture the interplay of fluctuating budgets, changing emission regulations, and technological diversification within a single integrated model. This study addresses these gaps by introducing the Multi-Period Utilization and Fleet Transition Optimization Problem (MPUFTOP). Our model integrates diverse vehicle technologies and operational constraints within a multi-period optimization framework specifically tailored to meet the needs. The approach is validated using detailed real-world data from the Kraków metropolitan area, offering a robust decision-support tool that effectively balances regulatory compliance, cost efficiency, and service demand growth. By bridging theoretical modeling with practical municipal challenges, MPUFTOP contributes a valuable framework for sustainable and economically viable fleet modernization.

The Multi-Period Utilization and Fleet Transition Optimization Problem

The Multi-Period Utilization and Fleet Transition Optimization Problem represents the problem of planning replacements and modernization of garbage trucks belonging to a fleet possessed by a company offering municipal solid waste collection services to meet the environmental requirements of the fleet composition. This study presents a multi-stage optimization problem based on the Fleet Transition Problem (Bieda et al., 2023). The problem involves planning the selection of municipal waste collection vehicles for replacement or retrofitting to meet environmental requirements and achieve zero emissions, while minimizing associated costs. The MPUFTOP models an idealized scenario in which decisions are made solely to minimize emissions. However, in real-world business contexts, decision-makers are typically constrained by budgetary limitations within each period of the planning horizon.

Mixed-Integer Model for the Multi-Period Utilization and Fleet Transition Optimization Problem

A mixed-integer linear program was formulated to address the Multi-Period Utilization and Fleet Transition Optimization Problem. The notation used in the formulas of the MIP model for the Multi-Period Utilization and

Fleet Transition Optimization Problem is presented in Table 1. Employing Formulas (1)–(15), we present a multi-period fleet transition planning problem with an unlimited budget, but with the goal of minimizing total costs.

$$\min f = \sum_{t \in T} \left(\sum_{r \in R} \sum_{l \in R} c_{rl} f_{rlt} + \sum_{r \in R} C_r u_{rt} \right) q^t \quad (1)$$

$$f_{rr0} = I_r, \quad r \in R \quad (2)$$

$$f_{rl0} = I_r, \quad r \in R, l \in R, r \neq l \quad (3)$$

$$\sum_{r \in R} u_{r0} = 0 \quad (4)$$

$$\sum_{r \in R} y_{rt} = d_t, \quad t \in T \quad (5)$$

$$\sum_{r \in R} e_{rp} y_{rt} \leq b_{pt}, \quad p \in P, t \in T \quad (6)$$

$$x_{rt} = \sum_{\substack{l \in R, \\ r \neq l}} f_{rlt} + f_{rrt} + u_{rt}, \quad r \in R, t \in T \quad (7)$$

$$f_{rrt} \geq u_{rt-1}, \quad r \in R, t \in T, t > 0 \quad (8)$$

$$\sum_{l \in R} f_{rlt} = \sum_{l \in R} f_{rlt-1} + u_{rt-1}, \quad r \in R, t \in T, t > 0 \quad (9)$$

$$x_{rt} = \sum_{\substack{l \in R, \\ r \neq l}} f_{rlt} + f_{rrt} + u_{rt}, \quad r \in R, t \in T, t > 0 \quad (10)$$

$$y_{rt} \geq 0, \quad r \in R, t \in T \quad (11)$$

$$x_{rt} \geq 0, \text{ integer}, \quad r \in R, t \in T \quad (12)$$

$$u_{rt} \geq 0, \text{ integer}, \quad r \in R, t \in T \quad (13)$$

$$f_{rrt} \geq 0, \text{ integer}, \quad r \in R, t \in T \quad (14)$$

$$f_{rlt} \geq 0, \text{ integer}, \quad r \in R, l \in R, t \in T \quad (15)$$

Table 1: Notation used for the MPUFTOP

Indices	
T	the set of planning periods (i.e., planning horizon)
R	the set of the types of fueling available
P	the set of pollutant types emitted by vehicles, representing distinct harmful substances released into the environment
Parameters	
d_t	demand for waste collection service in period t , expressed as the total number of kilometers required to complete all collection routes
b_{pt}	maximum allowable emission of pollutant type p in period t
c_{rl}	the cost of replacing technology r by technology l
C_r	the cost of purchasing a vehicle equipped with technology r
e_{pr}	emission of pollutant type p generated by a vehicle equipped with technology r per kilometer
I_r	the initial number of possessed vehicles equipped with technology r
S_r	maximum allowable annual kilometrage for a vehicle of type r

L_r	maximum feasible expenditure allowed in period t
q	discount rate
Decision variables	
f_{rrt}	(integer non-negative) number of vehicles equipped with technology r possessed by the company at the end of period t
f_{rt}	(integer non-negative) number of vehicles in which technology r was replaced with technology l in period t (for $r \neq l$)
x_{rt}	(integer non-negative) number of vehicles equipped with technology r possessed by the company in period t
u_{rt}	(integer non-negative) number of vehicles equipped with technology r purchased in period t
y_{rt}	(continuous non-negative) distance traveled by a vehicle of type r in period t

The Mixed-Integer Programming (MIP) model (1)-(10) is used to optimally plan the modernization of the vehicle fleet over the planning horizon T , considering vehicle purchase costs, technology shifts, and harmful emissions. The objective is to minimize the total discounted investment costs while satisfying environmental regulations related to pollutant emissions. The objective function (1) aims at minimizing the total cost of modernizing the existing vehicles (i.e., shifting them from fuel type r to l) and purchasing new ones. Constraint (2) forces taking into account the initial composition of the fleet possessed by the solid waste collection company, i.e., the number of vehicles equipped with each fueling technology (I_r) before the modernization and replacement project. The availability of trucks with a total range that enables them to drive the required total kilometrage (d_t) in each period t is ensured by constraint (5). Constraint (6) ensures that the allowable emission limit (b_{pt}) is maintained for each period t , so the total volume of harmful substances emitted into the environment is limited. Constraints (6)–(9) manage the internal consistency of the fleet transition: they ensure that the number of vehicles in each period accounts for new purchases and scheduled technology replacements, and that the assignment of newly purchased cars to future periods is appropriately done. Constraint (10) ensures that the total driving distance of vehicle r in period t does not exceed the annual kilometrage limits of the cars in use, thus preserving feasibility concerning operational capabilities. Constraints (11)–(15) ensure the integrity of the model.

Computational Study

The experience of the Municipal Sanitation Company (MPO) in Krakow, Poland, adapting its fleet to the requirements of the Electromobility and Alternative Fuels Act, provides a practical foundation for developing a generalized, scalable optimization framework for fleet modernization. In response to the Act, a dedicated team within MPO was established in 2018 to identify necessary adaptations, evaluate opportunities for replacing aging diesel vehicles with electric or natural gas-powered alternatives (CNG, LNG), and assess market availability of suitable vocational vehicles (Miejskie Przedsiębiorstwo Oczyszczania w Krakowie Sp. z o.o., 2021a; Road Authority of the City of Kraków, 2023; Miejskie Przedsiębiorstwo Oczyszczania Sp. z o.o. w Krakowie, 2021b; Kraków, 2023). The company also undertook infrastructure upgrades, including enhancements to the power grid at its operating bases and the installation of electric vehicle charging stations, to support the integration of electric vehicles into its fleet. To ensure operational independence and cost-effectiveness, MPO invested in its own CNG refueling station, addressing logistical and economic inefficiencies caused by reliance on a distant third-party facility (City of Kraków, 2021; NBI, 2020; Miejskie Przedsiębiorstwo Oczyszczania Sp. z o.o. w Krakowie, 2021b). By 2023, the company will have operated 53 electric or CNG-powered vehicles, including 45 that conformed to the legal thresholds set by the Electromobility and Alternative Fuels Act. The legislation mandates a minimum share of 10% clean vehicles in public service fleets as of 2022, increasing to 30% by 2025. Although an amendment in 2021 exempted seasonal road maintenance tasks from the Act, MPO proactively achieved a 30% compliance rate within its fleet used for public services. Beyond compliance, MPO's fleet management challenges, from vehicle wear, expanding service scope, and varying operational requirements, underscore the need for a structured, long-term fleet renewal strategy. Drawing inspiration from this case, the paper formulates a multi-period fleet transition planning model applicable to any organization managing vocational vehicles. The model incorporates regulatory compliance, operational needs, and budgetary constraints, supporting informed decision-making in planning, replacing, and expanding vehicle fleets. This approach can serve as a strategic tool for municipalities and service providers seeking to modernize their fleets while balancing environmental, legal, and financial objectives (INTHERWASTE Project Partnership, 2019).

Results and Discussion

The experiment considers six vehicles currently used or potentially implementable in municipal solid waste collection: Euro 6, Euro 6 CNG, Euro 7, Euro 7 CNG, Electric, and Hydrogen-powered vehicles. All vehicle types

comply with relevant environmental regulations and are considered eligible options within the optimization model. The ecological impact of each vehicle type is expressed through the emissions of selected pollutants, including PM_{2.5}, PM₁₀, NO_x, NMVOC, TSP, SO₂, and CO₂, as shown in Table 2. These values serve as inputs to the model's emission constraints, enabling the assessment of the environmental footprint of each fleet composition.

Table 2: Volume of pollutant emissions [g/km]

Vehicles	PM _{2.5}	PM ₁₀	NO _x	NMVOC	TSP	SO ₂	CO ₂
Euro 6	0.070	0.128	1.396	0.081	0.185	--	1441.319
Euro 7	0.065	0.123	0.327	0.061	0.180	--	1441.319
Euro 6 CNG	0.061	0.116	0.497	0.252	0.168	--	1257.204
Euro 7 CNG	0.059	0.114	0.423	0.252	0.166	--	1257.204
Electric	--	--	0.694	--	0.159	0.643	1057.445
Hydrogen	--	--	2.564	--	0.226	2.374	3904.413

The computational experiment is designed to verify the applicability of the proposed mixed-integer programming model by simulating a realistic fleet modernization scenario based on data loosely inspired by waste collection operations in Kraków (see Table 3 and Table 4). The purpose is to assess the model's capacity to support strategic planning under various environmental and economic constraints. The basic operational parameters are presented in Table 3, including the initial demand for waste collection (in tonnes), the expected annual growth in service demand, vehicle loading capacity, and the average number of daily trips. These values estimate the required transport effort in kilometers covered in each planning period. Table 4 outlines the projected demand for waste collection over eight planning periods, along with the corresponding number of vehicles needed to fulfill that demand. These forecasts are used to generate service-level constraints in the optimization model, ensuring that the fleet can meet demand at each stage of the planning horizon.

Table 3: Essential parameters

Parameter	Value
Initial demand for the solid waste collection service	403698.52 tonnes
Forecasted year-on-year demand growth rate	4.34 %
Vehicle capacity	10 tonnes
Average number of rides per day	3.42

Table 4: Demand for solid waste collection service

Period	0	1	2	3	4	5	6	7
Solid waste [tonnes]	403698	421219	439499	458574	478476	499242	520909	543516
Number of vehicles	50	52	54	56	59	61	64	67

Vehicle acquisition costs are listed in Table 5, while Table 6 specifies the cost of technology replacement, including both upgrades within conventional fuel classes and transitions toward zero-emission vehicles. Downgrading vehicles to lower environmental standards is prohibited. Furthermore, each newly purchased or upgraded vehicle is assumed to remain operational for at least one period (i.e., one year).

Table 5: Purchase prices of vehicles [PLN]

Vehicles	Euro 6	Euro 7	Euro 6 CNG	Euro 7 CNG	Electric	Hydrogen
Price	756890	768572	899079	910761	1379703	1796947

Table 6: Vehicle replacement cost [PLN]

	Euro 6	Euro 7	Euro 6 CNG	Euro 7 CNG	Electric	Hydrogen
Euro 6	--	768572	16000	20000	1379703	1796947
Euro 7	--	--	--	20000	1379703	1796947
Euro 6 CNG	--	--	--	--	1379703	1796947
Euro 7 CNG	--	--	--	--	1379703	1796947
Electric	--	--	--	--	--	--
Hydrogen	--	--	--	--	--	--

Computational experiments were conducted to find the optimal purchase and retrofit plan in the defined planning horizon using the newly developed MIP model for the MPUFTOP. Two planning scenarios were considered: one in which the only changing factor is the increasing linear demand for solid waste collection services (Case 1), and another where demand increases but emissions are allowed to decrease from period to period (Case 2). The MIP models were implemented in AMPL and solved using the GLPK embedded solver. Computations were run using a standard computer, as the models are intended for use in typical company environments with available computational power. A laptop with a two-core Intel Core i7-4710HQ CPU @ 2.50 GHz and 16 GB of RAM was used for these computations. The computational study evaluates the model's performance under two distinct strategic planning scenarios, both of which reflect common real-world challenges faced by municipal waste collection operators as they navigate environmental regulations, budgetary constraints, and increasing service demands. These two scenarios demonstrate the flexibility and robustness of the proposed model, enabling stakeholders to evaluate trade-offs among environmental performance, service reliability, and financial feasibility. Summary results for both cases are presented in Tables 7–11 and illustrated in Figures 1–4.

Table 7: Fleet replacement schedule – number of vehicles

Period	Action	Case 1				Case 2				
		Euro 6	Euro 6 CNG	Euro 7 CNG	Elect- ric	Total	Euro 6	Euro 6 CNG	Elect- ric	Total
0	Purchased	--	--	--	--	--	--	--	--	
	Sold	--	--	--	--	--	--	--	--	
	Modified	--	--	--	--	--	--	--	--	
	Owned at the end	16	2	--	--	18	16	2	--	18
1	Purchased	--	--	--	--	--	--	--	--	
	Sold	--	--	--	--	--	--	--	--	
	Modified	--	--	--	--	--	-3	3	--	--
	Owned at the end	16	2	--	--	18	13	5	--	18
2	Purchased	--	--	--	--	--	--	1	--	
	Sold	--	--	--	--	--	--	--	--	
	Modified	-2	1	1	--	--	--	--	--	
	Owned at the end	14	3	1	--	18	12	5	2	19
3	Purchased	--	--	--	--	--	--	--	--	
	Sold	--	--	--	--	--	--	--	--	
	Modified	-4	4	--	--	--	-2	2	--	--
	Owned at the end	10	7	1	--	18	10	7	2	19
4	Purchased	--	--	--	1	--	--	--	--	
	Sold	--	--	--	--	--	--	--	--	
	Modified	--	--	--	--	--	-2	2	--	--
	Owned at the end	10	7	1	1	19	10	7	2	19
5	Purchased	--	--	--	--	--	--	2	--	
	Sold	--	--	--	--	--	--	2	--	
	Modified	-5	--	5	--	--	--	--	--	
	Owned at the end	5	7	6	1	19	10	5	4	19
6	Purchased	--	--	--	1	--	--	1	--	
	Sold	1	--	--	--	--	1	--	--	
	Modified	--	--	--	--	--	--	--	--	
	Owned at the end	4	7	6	2	19	9	5	5	19
7	Purchased	--	--	--	--	--	--	--	--	
	Sold	--	--	--	--	--	--	--	--	
	Modified	--	--	--	--	--	--	--	--	
	Owned at the end	4	7	6	2	19	9	5	5	19

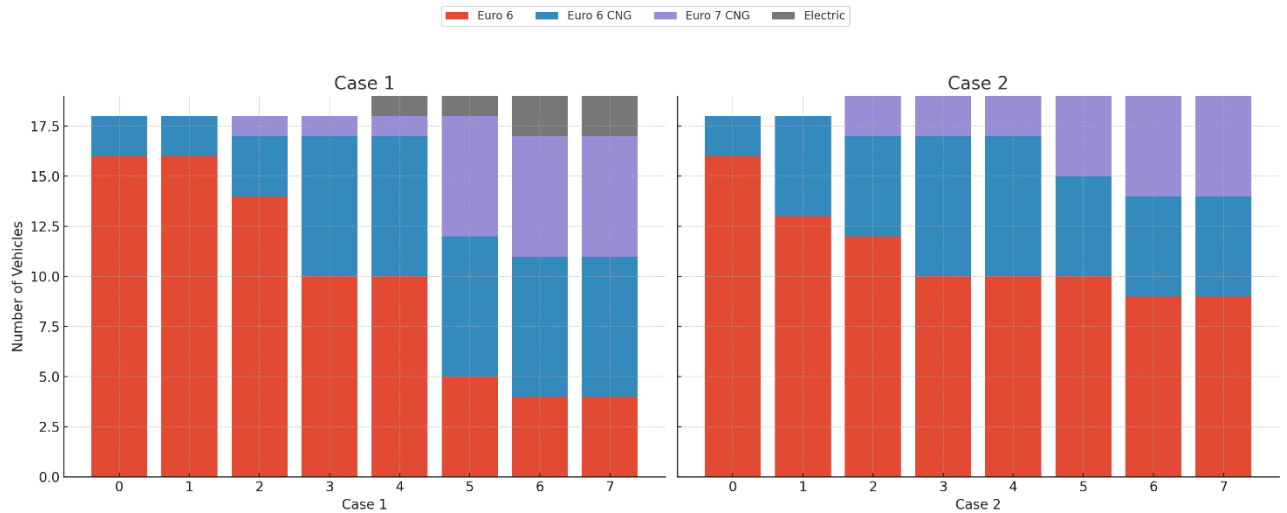


Fig 1. Fleet composition over time in Case 1 and Case 2

Table 8: Driven distance [km]

Period	Case 1					Case 2			
	Euro 6	Euro 6 CNG	Euro 7 CNG	Electric	Demand	Euro 6	Euro 6 CNG	Electric	Demand
0	--	--	--	--	--	--	--	--	--
1	126000	44000	--	--	170000	126000	44000	--	170000
2	133310	44000	--	--	177310	79803	97506	--	177310
3	96934	66000	22000	--	184934	113310	49624	22000	184934
4	16886	154000	22000	--	192886	136844	12042	44000	192886
5	17187	154000	22000	7992	201180	3921	15400	43258	201180
6	--	648621	132000	21991	218854	115702	15152	88000	218854
7	--	52264	132000	44000	228264	8264	110000	110000	228264
Total	390317	579126	330000	73984	1373428	583845	482325	307258	1373429

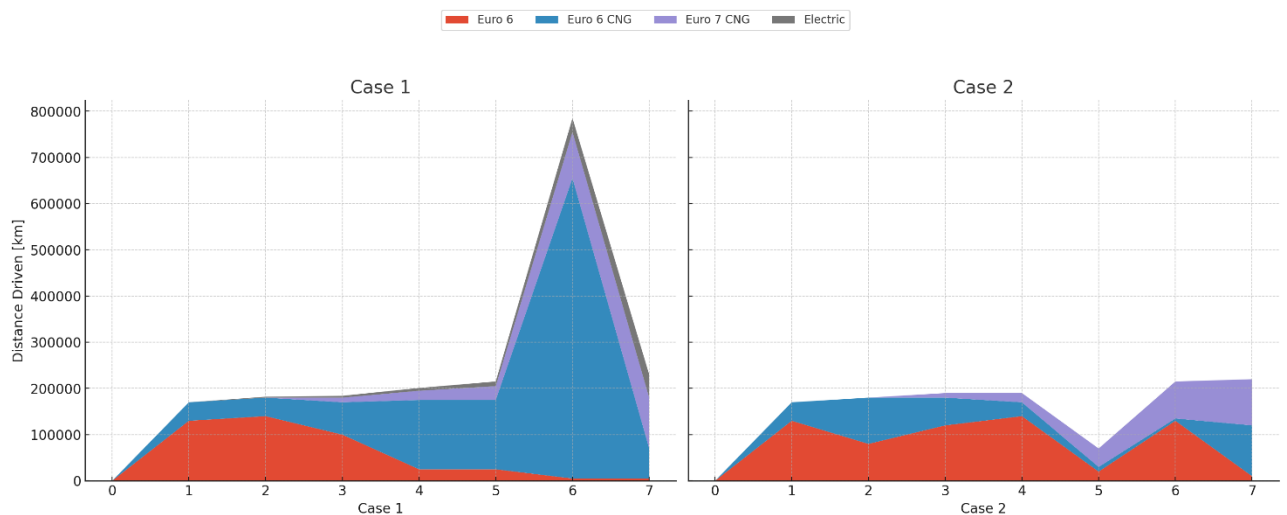


Fig 2. Distance driven by each vehicle type across Case 1 and Case 2 planning periods

Case 1 — Emission Stabilization with Increasing Demand: In Case 1, the main objective was to ensure that the total volume of emitted pollutants remains at the baseline level (i.e., does not increase compared to the current state), despite a projected rise in demand for waste collection services over the planning horizon of seven years. This scenario simulates the need for fleet expansion, triggered by population growth or increased service coverage, while maintaining a constant total emissions level. The fleet operator is subject to a limited investment budget

that must cover the purchase of additional vehicles and the potential modernization of existing units. The challenge lies in balancing the dual objectives of scaling capacity and adhering to environmental standards while staying within financial limits. The resulting fleet dynamics and emission levels are shown in Tables 7, 9, and 10, and visualized in Figures 1, 2, and 3.

Case 2 — Emission Reduction with Increasing Demand: In Case 2, the strategy shifts from emission stabilization to active reduction. The goal is to achieve at least a 30% reduction in total pollutant emissions over the same seven-year planning horizon. To reach this target, the model prioritizes the systematic modernization and replacement of vehicles with lower-emission or zero-emission alternatives, such as electric and hydrogen-powered trucks. Recognizing the higher costs typically associated with clean technologies, this case assumes access to additional external funding (e.g., subsidies, green transition grants, or public-private partnerships). Such supplementary financing enables a more ambitious environmental strategy within a constrained yet enhanced financial resources framework. This case highlights the planning needs of municipalities that align with ambitious climate goals or respond to policy mandates for emission reduction. Corresponding results are provided in Tables 7–11, and graphically illustrated in Figures 1–4.

Table 9: Emitted PM_{2.5} pollution [g]

Period	Case 1						Case 2				
	Euro 6	Euro 6 CNG	Euro 7 CNG	Electric	Total	Limit	Euro 6	Euro 6 CNG	Electric	Total	Limit
0	--	--	--	--	--	12249	--	--	--	--	--
1	8820	2684	--	--	11504	12249	8820	2684	--	11504	12249
2	9331	2684	--	--	12016	12249	5586	5947	--	11534	11603
3	6785	4026	1298	--	12109	12249	7931	3027	--	10959	10958
4	1182	9394	1298	--	11874	12249	9579	734	--	10314	10313
5	1203	9394	1298	--	11895	12249	274	9394	--	9669	9668
6	--	3956	7788	--	11745	12249	8099	924	--	9023	9023
7	--	3188	7788	--	10976	12249	578	6710	--	7288	8574

Table 10: Emitted PM₁₀ pollution [g]

Period	Case 1						Case 2				
	Euro 6	Euro 6 CNG	Euro 7 CNG	Electric	Total	Limit	Euro 6	Euro 6 CNG	Electric	Total	Limit
0	--	--	--	--	--	22572	--	--	--	--	--
1	16128	5104	--	--	21232	22572	16128	5104	--	21232	22572
2	17063	5104	--	--	22168	22572	10214	11310	--	21526	21525
3	12407	7656	2508	--	22572	22572	14503	5756	--	20260	20479
4	2161	17864	2508	--	22533	22572	17516	1396	--	18913	19432
5	2200	17864	2508	--	22572	22572	502	17864	--	18366	18386
6	--	7524	15048	--	22572	22572	14809	1757	--	16568	17340
7	--	6062	15048	--	21111	22572	1057	12760	--	13818	15800

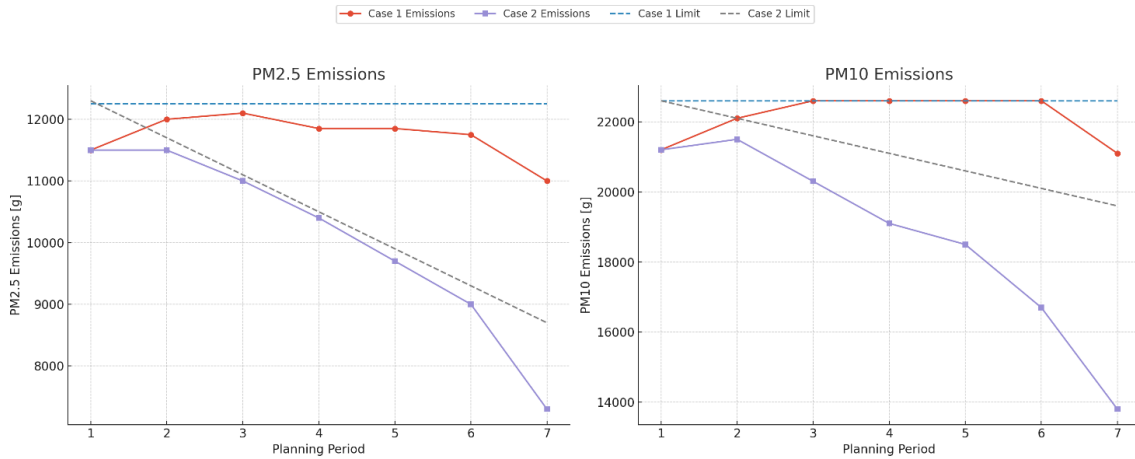


Fig 3. Emissions vs. regulatory limits for PM_{2.5} and PM₁₀ in Case 1 and Case 2

Table 11: Cost summary [PLN]

Period	Case 1		Case 2	
	Modification	Purchase	Modification	Purchase
0	--	--	--	--
1	--	--	48000	--
2	36000	--	--	1379703
3	64000	--	--	1379703
4	--	1379703	32000	--
5	100000	--	--	2759407
6	--	1379703	--	1379703
7	--	--	--	--
Subtotal	200000	2759406	80000	6898516
Total cost	2959406		6978516	

Modification Cost Purchase Cost

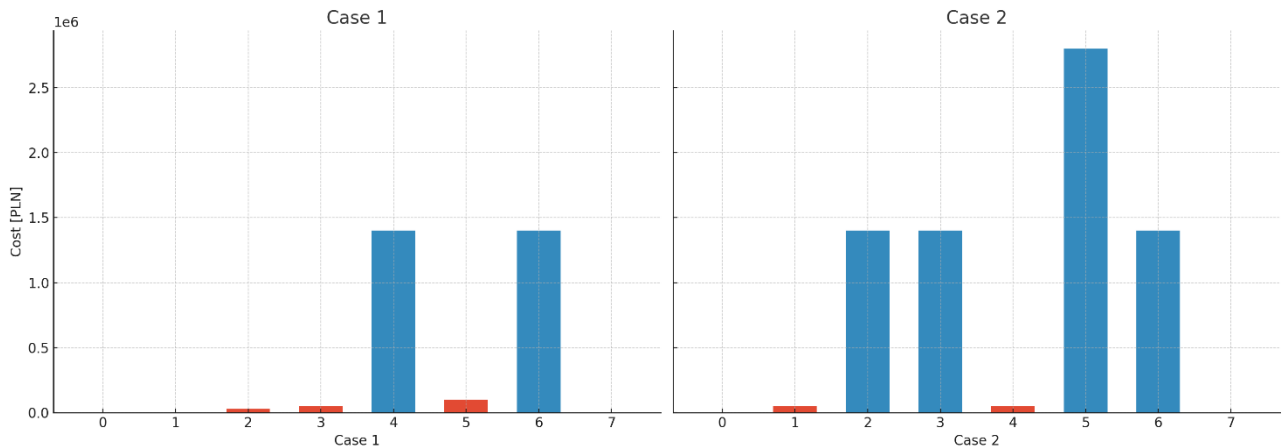


Fig 4. Cost breakdown of fleet modernization actions in Case 1 and Case 2

The results clearly show the trade-offs involved between the two planning strategies. In Case 1, the optimization model primarily focuses on cost-effective retrofitting of Euro 6 vehicles to CNG variants, thereby minimizing capital expenditures and achieving compliance through incremental changes. Only one electric vehicle is purchased over the planning horizon, indicating a conservative approach toward fleet renewal. Conversely, Case 2 demonstrates a more aggressive transition pathway, introducing multiple electric vehicles early on to meet the 30% emission reduction target. This shift results in higher upfront costs, as shown in Table 11, but leads to a more significant decline in both PM_{2.5} and PM₁₀ emissions (see Tables 9 and 10). Figures 1 and 2 further highlight

these differences. In Case 1, the fleet composition changes gradually with a firm reliance on CNG retrofits, while in Case 2, electric vehicles dominate by the end of the planning period. The annual distance driven by each vehicle type also reflects these patterns: electric cars are underutilized in Case 1 but take on a significant portion of the operational load in Case 2. Finally, Figure 4 shows that while Case 1 contains costs primarily through modifications, Case 2 incurs substantial expenditures due to electric vehicle purchases. The comparison illustrates how the MPUFTOP model enables flexible decision-making under diverse policy and budgetary scenarios, striking a balance between environmental ambitions and operational and financial constraints.

Conclusions

The study presents a Mixed-Integer Programming formulation that jointly optimizes purchasing and retrofitting decisions, reflecting the complexity of real-world waste collection fleet management. It responds to the main research question (MRQ) by minimizing discounted costs while ensuring compliance with emissions regulations. It also addresses DRQ01 by demonstrating computational feasibility for practical-sized cases, and DRQ02 through its application to a realistic use case from the Kraków metropolitan area. The model accommodates a wide range of vehicle technologies and intervention strategies, including acquisition, retrofitting, or operational reassignment, and has proven flexible in meeting various policy scenarios. The findings emphasize that emission reduction targets and service expansion objectives can lead to substantially different investment paths, underscoring the importance of context-aware planning. As a mixed-integer linear programming (MILP) formulation, MPUFTOP inherently belongs to the class of NP-hard problems due to its integer decision variables and multi-period structure. With further development, including uncertainty modeling and operational integration, MPUFTOP can be a robust foundation for sustainable fleet transition planning in urban environments. The model's complexity grows proportionally with the number of periods, vehicle technologies, and emissions types considered, as well as the granularity of the decision space. Despite this, the computational experiments revealed that the model is tractable for medium-scale municipal fleet instances. In the case study based on the Kraków metropolitan area, instances of Case 1 and Case 2 were solved using an open solver (e.g., GLPK) in under 10 seconds on a standard laptop with a two-core Intel Core i7-4710HQ CPU at 2.50 GHz and 16 GB of RAM. The total number of variables and constraints remained within a few thousand, even when extended to five planning periods and multiple vehicle technologies.

Based on the experimental results, the proposed MPUFTOP model presents a valuable tool for long-term strategic fleet planning. It provides a comprehensive optimization framework that supports informed investment decisions in a rapidly evolving regulatory and operational context. The model accommodates multi-period planning under emission constraints and increasing service demand, enabling municipalities to balance economic and environmental goals. Scalability analysis demonstrated that the model's performance remained stable when the number of vehicle types risen from 3 to 6 and the planning horizon expanded from 5 to 10 years. In most cases, solution times increased linearly with problem size, suggesting that MPUFTOP is suitable for practical deployment in municipal contexts with limited computational resources. Nevertheless, as the number of periods or vehicle categories grows, more advanced decomposition methods or heuristic approaches may be required for real-time or large-scale planning scenarios.

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