Impact of Fleet Electrification and Charging Infrastructure on Free-Floating Car Sharing in Milan

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Abstract: The automotive industry's transition toward sustainability has prioritized Electric Vehicles (EVs) due to their potential to reduce pollution and improve energy efficiency. This evolution is particularly critical in urban contexts such as Milan, where free-floating car sharing services present unique challenges and opportunities for electrification. The integration of EVs into car sharing fleets demands careful consideration of battery autonomy, charging times, and the distribution of charging infrastructure to meet high vehicle utilization rates. This study evaluates the feasibility of transitioning Milan's internal combustion car-sharing fleet to an electric model, analyzing technical and operational challenges through a scenario-based simulation approach.

1 INTRODUCTION

Urbanization is rapidly reshaping global mobility. By 2050, an estimated 6.3 billion people will reside in urban areas, posing significant challenges for urban mobility systems (Moss, 2012). Transportation networks, essential for the movement of people and goods within and between cities, will need to evolve to address growing demand, congestion, and environmental concerns (Colombo et al., 2023). This context underscores the necessity of rethinking mobility strategies to achieve more efficient and sustainable urban transport systems. Traditional car sharing has gained prominence as an effective solution to reduce private car ownership, optimize vehicle utilization, and reduce the environmental impact of urban transportation (Hensher, 2018) (Weibin et al., 2018). Car sharing is experiencing rapid global growth, with user bases and fleets expanding significantly. For example, from 2022 to 2027, the number of car sharing users is expected to increase at a Compound Annual Growth Rate (CAGR) of 16. 9% (Cederqvist, 2023). However, reliance on Internal Combustion Engine (ICE) vehicles in many traditional car sharing services limits their overall environmental benefits. Although car sharing reduces the total number of vehicles on the road, ICE-powered fleets still contribute to urban air pollution and greenhouse gas emissions. To overcome these limitations, the industry is increasingly turning to Electric Car Sharing (ECS), which integrates the operational advantages of car sharing with the environmental benefits of battery electric vehicles (BEVs) (Perboli et al., 2018). Electric car sharing offers significant potential to amplify the environmental benefits of shared mobility by incorporating zero-emission vehicles into fleets. BEVs produce no tailpipe emissions, reducing air pollution and contributing to cleaner urban environments. In addition, they support the transition to more sustainable energy systems, particularly when charged using renewable energy sources. As a result, ECS has become a growing focus in the shared mobility sector, with an increasing number of operators adopting Electric Vehicles (EVs). In 2019, 66% of the global car sharing services included electric vehicles in their fleets, demonstrating the trend towards cleaner transportation solutions (Nicholas and Bernard, 2021). Despite its potential, the feasibility of ECS largely depends on the availability, efficiency, and distribution of charging infrastructure. Charging stations differ in speed, with some enabling fast charging within minutes, while others require several hours for a full charge. This variability can be challenging for EV

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users, who must plan charging around station availability while accounting for potential queuing times (Rauf et al., 2023).

The effectiveness of electric car-sharing depends on overcoming critical challenges such as charging point accessibility, system interoperability, and compatibility with vehicle usage patterns (Liao and Correia, 2021). Various studies have proposed models to simulate vehicle charging and assess its impact on the power grid (Hammerschmitt et al., 2024), as well as simulate energy consumption (Genikomsakis and Mitrentsis, 2017; Gerossier et al., 2019). However, for vehicles used in car-sharing, predicting routes and driving styles is difficult due to the fact that they can be rented by different individuals for a variety of purposes. This variability significantly impacts the charging needs.

This study aims to tackle a critical issue for the city of Milan, focusing on facilitating the widespread adoption and effectiveness of an all-electric car-sharing solution. It achieves this by analyzing real-world demand and evaluating various charging technologies, such as conventional charging stations, wireless charging systems, and battery swapping solutions. The study assesses whether transitioning the fleet to EVs can be sustainable and evaluates which charging methods are best suited to meet the system's needs.

2 METHODOLOGIES

This section outlines the methodologies adopted to simulate the feasibility of transitioning a car sharing service from an ICE fleet to a BEV fleet, taking into account the compatibility with the autonomy of the BEV and the distribution and performance of the charging infrastructure.

2.1 Scope and Simulation Algorithm

The simulation aims to verify whether the car sharing demand observed with ICE vehicles can be effectively met using BEVs. The system must ensure that each BEV chosen by a user has sufficient energy to complete the rental. Modeling car sharing demand is particularly complex due to the interdependence between vehicle availability and the number of trips, especially in free-floating services where vehicles can be left in any parking space within the service area. This creates uncertainty regarding vehicle availability for subsequent users. To address this, the simulation focuses on representing vehicle availability at a local level and tracking individual trips with high spatial and temporal resolution. In addition to analyzing origin-destination flows, it also estimates energy consumption and kilometers traveled per rental. Since two rentals with the same start and end points may involve different routes, statistical models of mobility demand would be imprecise for calculating energy consumption. Therefore, a data-driven approach is employed, relying on existing usage data. Despite its limitations, this approach aligns with the goal of comparing BEV and charging infrastructure scenarios, rather than planning operational details of the car sharing service. Key simplifying assumptions include:

- Users must recharge BEVs only when the State of Charge (SOC) falls below a scenario-defined threshold, potentially requiring them to detour to the nearest charging station.
- No staff assistance for vehicle recharging is considered.
- The existing charging infrastructure in Milan is assumed to have uniform characteristics and compatibility with all BEVs in the scenarios.
- BEV range, charging times, and management are not assumed to impact the demand trends observed with ICE vehicles.

The simulation comprises the following steps:

1. Energy Consumption Calculation (E): The energy consumption for each trip was calculated based on the real consumption of the diesel car on that specific route, using Equation 1. In this equation, G represents the liters of gasoline used per trip, c_{gas} denotes the fuel consumption rate of an internal combustion engine (ICE) vehicle, expressed in liters per kilometer (L/km) and c_{el} represents the specific energy consumption of the selected EV.

$$E = \frac{G}{c_{gas}} \cdot c_{el} \quad [kWh] \tag{1}$$

2. SOC Calculation: The initial and final SOC for each trip are computed. If the SOC after a trip falls below the threshold, recharging is simulated. The SOC for the next rental depends on the energy recharged between rentals.
3. Charging Management: Charging is simulated to stop either when the SOC reaches 100% or a minimum of 20%. Charging during a trip assumes sufficient time to reach a charging station and continue the journey. The percentage of battery recharge (SOC_{rec}) over a time interval (Δt) depends on the power provided by the charging method (P) and the battery capacity of the selected vehicle (C_{batt}) as reported in Eq. 2.

$$SOC_{rec} = \frac{\Delta t \cdot P}{C_{batt}} \cdot 100 \quad (2)$$

Figure 1 visually represents the algorithmic flow for managing the SOC in an electric car sharing scenario.

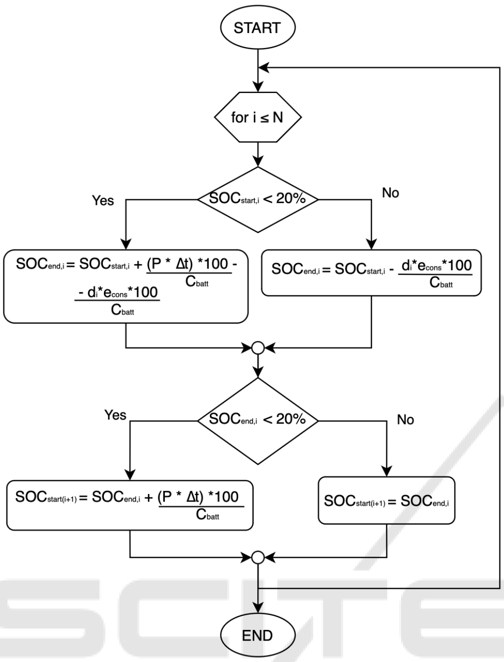

Figure 1: Recharging algorithm.

It outlines how vehicle energy levels are calculated and adjusted throughout a rental process, as well as during transitions between rentals. The starting point of the algorithm calculates the SOC at the beginning of a rental, then based on the kilometers driven and vehicle consumption rate, the energy used during the rental is determined. The final SOC is updated by subtracting the consumed energy from the initial SOC. If the SOC falls below a specified threshold, the algorithm incorporates a recharging event, either mid-rental or at the end of the trip. When a recharge occurs, the SOC is adjusted to reflect the additional energy gained, constrained by battery capacity. If the final SOC of one rental is sufficient for the next user, the car is made available; otherwise, it is assumed to undergo recharging.

2.2 Performance Metrics

The algorithm is applied to various scenarios, each using a single type of BEV and charging infrastructure. The performance of each scenario is assessed using several key metrics that provide insight into the operational feasibility and efficiency of transitioning to a BEV-based car sharing system.

One important metric is the number of unfeasible rentals. These represent instances where a rental cannot be completed because the vehicle's battery charge, or SOC, is insufficient to meet the energy demands of the trip. Such cases highlight the limitations of BEV autonomy under specific conditions or charging infrastructure availability. Another critical measure is charging during rentals. This metric reflects how often users would need to interrupt their trips to recharge the vehicle mid-journey. It provides an indication of the practicality of the BEV fleet, especially in scenarios with longer rental distances or sparse charging infrastructure. Similarly, charging at rental end is evaluated, referring to the number of rentals that require a recharge at the conclusion of the trip due to the SOC falling below the minimum threshold. This metric captures the impact of low battery levels on subsequent vehicle availability for the next user. The analysis also considers the average distance to charging points, which represents the typical detour a user would need to make to reach the nearest charging station when recharging is necessary. A longer detour can increase inconvenience for users and potentially deter them from adopting the service. Finally, the number of feasible rentals is examined. This metric indicates how many rentals can be completed without the need for mid-trip recharging or disruptions due to SOC limitations. A higher proportion of feasible rentals suggests better alignment between BEV capabilities, user demand, and the charging infrastructure.

These metrics collectively provide a comprehensive evaluation of the system's performance, helping to identify strengths, weaknesses, and areas for improvement in different scenarios.

3 CASE STUDY

The dataset was compiled from car-sharing records, focusing on ICE vehicles. Vehicle availability was tracked at regular intervals, capturing essential details such as location, timestamp, and fuel level. Although the data does not allow for full route reconstruction, it provides valuable insights into mobility patterns by identifying trip start and end points, duration, and fuel consumption. This information serves as a basis for analyzing vehicle utilization and operational efficiency. Trip duration was inferred by examining the time elapsed between consecutive stops for each vehicle. However, only key trip attributes—such as departure and arrival locations, travel time, and fuel level variations—are available, while the exact routes taken remain unknown. The subsequent analysis focuses on the spatial distribution of stops, vehicle availability trends, trip and stop durations, refueling patterns, and fuel consumption.

Table 1 outlines the vehicle categories considered in this study, organized by battery capacity and energy consumption. It includes several types of small vehicles, emphasizing their versatility and appropriateness for urban settings.

Table 1: Vehicles characteristics.

Category	C_{batt} [kWh]	e_{cons} [kWh/km]
Small A	17.6	0.175
Small B	42	0.146
Small C	10.3	0.075
Medium	57.5	0.143
Large	90	0.208

The analysis considers three main charging methods, with varying power capacities, commonly used in Milan for both quick and fast charging. The location of all the charging infrastructure has been assessed based on the existing positions of public chargers, as shown in Figure 2 (Electromaps, 2024).

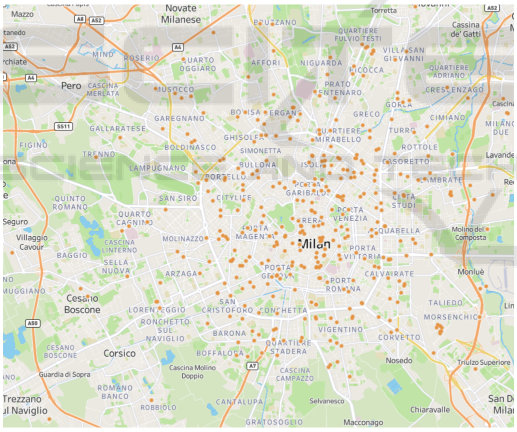

Figure 2: Actual distribution of charging station in Milan.

A total of 143 charging stations have been added in the last six months, and 304 in the last 12 months. This data provides valuable insight into the rapid pace at which charging stations are being installed across the city. There are currently 2,643 connectors, with the majority being of type 2. The following charging infrastructures has been analyzed:

- Conductive Charging: This method involves fixed charging points at specific locations throughout all scenarios. The power capacities for these points are 7 kW, 22 kW, and 110 kW, catering to different charging speed needs.
- Wireless Charging: This technology allows for a more convenient charging process, as it doesn't require physical connection to the vehicle. It is assumed that the wireless system will be available for vehicles with a SOC below 40%. The power levels considered for wireless charging are 3 kW, 7 kW, and 11 kW.
- Battery Swap: This method resembles traditional refueling, where the vehicle's battery is exchanged for a fully charged one in just a few minutes. For vehicles in category Big, it is assumed that the infrastructure consists of automated Battery Swapping Stations, enabling a quick and seamless transition. In contrast, for vehicles in category Small C, the process requires operator intervention to perform the battery swap.

3.1 Analysis of the Results

Figure 3 provides a comprehensive summary of the simulation results across all scenarios, with data averaged on a daily basis. Each row corresponds to a scenario derived from a combination of a specific BEV model and charging infrastructure, while the columns contain key performance indicators used to evaluate the scenario.

The study revealed significant variability in the feasibility and efficiency of electric carsharing trips based on the combination of charging methods and BEV models. Across all scenarios, the percentage of feasible trips—those completed without requiring user behavior changes—ranged from 55% to 92%. Scenarios utilizing Battery Swap and high-power conductive charging (110kW) performed the best, with feasible trip percentages exceeding 90% in most cases. Conversely, Inductive charging at 3kW showed the poorest performance, with feasible trips dropping to as low as 55% for smaller battery vehicles, like the ForTwo. A key priority for improving carsharing systems is the reduction of unfeasible trips, as shown in Figure 4, which ranks the 32 scenarios based on the Unfeasible Rentals metric. In all the cases the percentage reminas below the 16% across all scenarios with values dropping to less than 1% in favorable scenarios (e.g., Battery Swap and 110kW conductive charging). Battery Swap and Conductive 110kW consistently rank as the top-performing methods, recording unfeasible trip rates of approximately 1%, regardless of the vehicle type. However, in subsequent scenarios, vehicles like the XEV YOYO and the Tesla Model 3 emerge as strong performers. When paired with Conductive 22kW, Inductive 11kW, or Inductive 7kW charging, these models maintain unfeasible trip rates of around 3%, showcasing their adaptability to mid-tier charging solutions.

Charging Method	BEV	Unfeasible trip	Charging during trip	Feasible trip	Charging at trip end	Average distance to reach a CP [m]
Battery Swap	Large	0,83%	2,36%	91,79%	5,03%	540
	Small C	0,83%	8,26%	81,82%	9,10%	531
Conductive 7kW	Small B	5,52%	5,37%	75,37%	13,75%	514
	Large	7,59%	3,63%	75,66%	13,12%	507
	Small A	7,66%	13,99%	59,78%	18,56%	509
	Medium	5,31%	3,83%	79,49%	11,37%	515
	Small C	4,09%	9,31%	74,00%	12,61%	523
Conductive 22kW	Small B	2,79%	4,60%	84,15%	8,46%	534
	Large	2,84%	3,20%	85,75%	8,20%	523
	Small A	3,76%	11,62%	72,60%	12,01%	516
	Medium	2,47%	3,34%	87,12%	7,06%	534
	Small C	2,37%	8,43%	79,62%	9,57%	528
Conductive 110kW	Small B	1,41%	3,76%	88,12%	6,72%	535
	Large	1,49%	2,49%	90,63%	5,39%	529
	Small A	1,45%	11,25%	76,32%	10,97%	526
	Medium	1,36%	2,69%	90,69%	5,26%	535
	Small C	1,11%	8,35%	81,24%	9,30%	523
Inductive 3kW	Small B	9,98%	4,51%	77,97%	7,54%	517
	Large	12,82%	3,03%	77,14%	7,02%	507
	Small A	15,62%	12,81%	55,09%	16,49%	505
	Medium	8,80%	3,15%	82,62%	5,42%	523
	Small C	5,93%	8,45%	78,61%	7,02%	550
Inductive 7kW	Small B	4,41%	4,01%	87,72%	3,86%	547
	Large	5,50%	2,63%	88,33%	3,54%	541
	Small A	6,23%	11,02%	74,21%	8,54%	552
	Medium	4,10%	2,66%	90,19%	3,05%	547
	Small C	3,54%	7,43%	84,35%	4,68%	552
Inductive 11kW	Small B	3,19%	3,62%	90,03%	3,17%	559
	Large	3,78%	2,42%	91,05%	2,74%	552
	Small A	4,75%	10,10%	78,43%	6,71%	547
	Medium	2,86%	2,48%	92,00%	2,65%	553
	Small C	2,94%	7,15%	85,87%	4,05%	556

Figure 3: KPI analysis for each vehicle.

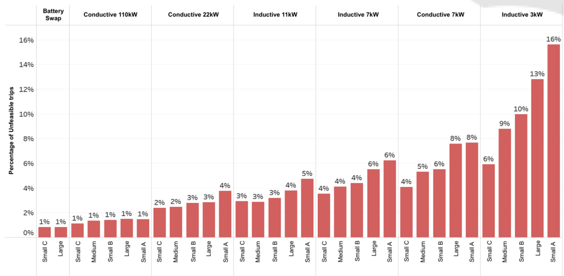

Figure 4: Unfeasible trips scenario comparison.

While BSS and Conductive 110kW charging are clearly superior in terms of performance, their implementation poses significant challenges. These include high costs, extensive infrastructure requirements, and compatibility issues, especially with existing electric vehicle models and networks. To maximize their potential, careful planning, targeted investments, and a phased deployment strategy will be critical. Mid-tier solutions like Conductive 22kW and Inductive 11kW provide a compelling compromise, especially for vehicles with moderate to large batteries such as the Tesla Model 3. These options strike a balance between performance and practicality, delivering relatively low unfeasible trip rates while being more affordable and easier to deploy at scale. This reinforces the need for a tiered approach to charging infrastructure, where high-power solutions are reserved for high-demand locations, and mid-power solutions are implemented more broadly to ensure accessibility and efficiency. Lastly, it is important to highlight that the average distance between end-of-rental points requiring charging and the nearest charging station remains relatively stable across both the days analyzed and the simulated charging scenarios. These distances are well within the 500-meter threshold that users are typically willing to walk to access a vehicle (Herrmann et al., 2014).

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4 CONCLUSIONS

This study analyzed the feasibility of transitioning Milan's free-floating car-sharing fleet from ICEVs to BEVs. Through a scenario-based simulation, it considered the interplay between vehicle energy autonomy, charging infrastructure distribution, and user demand.

The results demonstrate that the integration of BEVs into car-sharing services is achievable, provided that charging infrastructure is strategically planned. Battery swapping and high-power conductive charging (110 kW) emerged as the most effective solutions for ensuring high operational performance, with feasible rental percentages exceeding 90%. However, these solutions also face significant implementation challenges, including infrastructure costs and compatibility issues.

Mid-tier options, such as 22 kW conductive and 11 kW inductive charging, present a balanced compromise, offering acceptable performance with lower costs and scalability. Moreover, the study underscores the importance of maintaining short distances between rental endpoints requiring charging and the nearest charging stations, ensuring alignment with user convenience thresholds.

Ultimately, the findings highlight the need for a tiered and phased deployment strategy for charging infrastructure to support the successful electrification of car-sharing fleets. This approach can maximize environmental benefits while ensuring operational feasibility, positioning Milan as a model city for sustainable urban mobility.

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REFERENCES

Cederqvist, M. (2023). The carsharing telematics market. Technical report, Berg Insight AB.

Colombo, C. G., Borghetti, F., Longo, M., and Foiadelli, F. (2023). Electrification of motorway network: A methodological approach to define location of charging infrastructure for ev. *Sustainability*, 15(23).

Electromaps (2024). *https://www.electromaps.com/it*.

Genikomsakis, K. N. and Mitrentsis, G. (2017). A computationally efficient simulation model for estimating energy consumption of electric vehicles in the context of route planning applications. *Transportation Research Part D: Transport and Environment*, 50:98–118.

Gerossier, A., Girard, R., and Kariniotakis, G. (2019). Modeling and forecasting electric vehicle consumption profiles. *Energies*, 12(7).

Hammerschmitt, B. K., Unsihuay-Vila, C., Sausen, J. P., Capeletti, M. B., Aoki, A. R., Teixeira, M. D., Barriquello, C. H., and Abaide, A. d. R. (2024). Adaptive charging simulation model for different electric vehicles and mobility patterns. *Energies*, 17(16).

Hensher, D. A. (2018). Tackling road congestion – what might it look like in the future under a collaborative and connected mobility model? *Transport Policy*, 66:A1–A8.

Herrmann, S., Schulte, F., and Voß, S. (2014). Increasing acceptance of free-floating car sharing systems using smart relocation strategies: A survey based study of car2go hamburg. In González-Ramírez, R. G., Schulte, F., Voß, S., and Ceroni Díaz, J. A., editors, *Computational Logistics*, pages 151–162, Cham. Springer International Publishing.

Liao, F. and Correia, G. (2021). Electric carsharing and micromobility: A literature review on their usage pattern, demand, and potential impacts. *International Journal of Sustainable Transportation*, 16(3):269–286.

Moss, M. L. (2012). Urban mobility in the 21st century. Technical report, NYU Rudin Center for Transportation Policy.

Nicholas, M. and Bernard, M. R. (2021). Success factors for electric carsharing. Technical report, INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION.

Perboli, G., Ferrero, F., Musso, S., and Vesco, A. (2018). Business models and tariff simulation in car-sharing services. *Transportation Research Part A: Policy and Practice*, 115:32–48.

Rauf, H., Zehra Zaidi, S. S., Naveed, H., Mehmood, D., Jabeen, F., and Malik, A. W. (2023). Urbanevsim: Open-source electric vehicle mobility and charging simulation platform. In *2023 International Conference on Frontiers of Information Technology (FIT)*, pages 79–84.

Weibin, Z., Yuhang, S., Yong, Q., Qianmu, L., and Minglei, S. (2018). Traveler behavior analysis based on car2go sharing operation data. In *nternational Conference on Transportation and Development 2018: Planning, Sustainability, and Infrastructure Systems*.