SUSTAINABLE PATHS: STRATEGIES FOR EFFICIENT ROUTES IN REDUCING FUEL CONSUMPTION AND POLLUTANT EMISSIONS IN SÃO PAULO

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***Abstract*—This study focuses on optimizing bus routes to reduce fuel consumption and emissions in São Paulo, using the Green Vehicle Routing Problem (GVRP) strategy. Three routes were analyzed, considering different vehicles and emission levels. Results indicate that the shortest route reduces CO_2 emissions by 24%, while the fastest route decreases travel time by 60%. The replacement of Euro III vehicles with Euro VI stands out in pollutant reduction. The analysis weighs operational efficiency, passenger comfort, and sustainability, pointing to optimization opportunities in vehicle management and the adoption of more sustainable technologies in urban transportation.**

***Index Terms*—urban mobility, route optimization, Green Vehicle Routing Problem (GVRP), emission reduction, public transportation.**

I. INTRODUCTION

The rapid urbanization of major centers is a prominent feature of modern times in Brazil. In particular, São Paulo, as the largest South American metropolis, daily faces the challenges of managing its dense population and ensuring the efficient operation of this megalopolis. Urban planning encompasses everything from food supply to public health strategies, and mobility becomes a critical component in this context, given the city's vast territorial dispersion and the surrounding metropolitan area, composed of 39 municipalities [1].

The dynamics of urban mobility in São Paulo not only deal with the large movement of its population but also confront the challenge of mitigating the environmental impacts resulting from this activity. The increase in vehicle volume and congestion on urban roads contribute to increased pollutant emissions, making it imperative to develop strategies that minimize these negative effects. In this context, the concept of the Green Vehicle Routing Problem (GVRP), initially addressed by [2], emerges as a promising approach. The GVRP aims to optimize vehicle routes, considering not only economic efficiency but also fuel consumption reduction and, consequently, pollutant emission reduction, aligning with contemporary environmental concerns [3]–[8].

This study proposes an in-depth investigation into sustainable mobility strategies in São Paulo, focusing on reducing fuel consumption and pollutant emissions. The intention is to analyze the GVRP as a viable approach to enhance the efficiency of public transportation, considering the peculiarities of the largest city in Brazil. The work will explore relevant studies, apply specific methodologies to the local reality, and ultimately seek to contribute to the implementation of solutions that reconcile operational efficiency, passenger comfort, and environmental sustainability.

II. REFERENCES IN THE APPLICATION OF GVRP

As mentioned earlier, sustainable route planning using the Green Vehicle Routing Problem (GVRP) has been a subject of study over the past decade. Existing literature offers various approaches that seek to address the reduction of pollutant emissions and economic optimization in transportation operations. To contextualize the relevance of these approaches in our specific study on urban mobility in São Paulo, we examine research that contributes to understanding the GVRP in different contexts.

The work of [9] explores the application of GVRP in smart cities, aiming to reconcile economic efficiency, environmental quality, and social justice. The proposal seeks to adjust commercial and personal vehicle routes based on traffic information, directing driver decisions to improve road and traffic efficiency. Although the application is in a city with different dynamics, the considerations about efficiency and local adaptation provide a good starting point for the analysis presented here.

In response to environmental distress, characterized by factors such as carbon emissions and extensive traffic restrictions in distribution logistics, efforts have been made to enhance distribution efficiency, reduce costs, and mitigate the impact of these restrictions. [10] Addresses increasingly stringent traffic limitations, establishing a multi-objective optimization model that encompasses minimum distributions and minimum carbon emissions. The article states the challenges of limited battery and cargo capacity, formulates a Green Vehicle Routing Problem with Soft Time Windows (GVRPTW) involving heterogeneous fleets. Delving it into detailed considerations of three key factors: restricted areas, vehicle travel times, and carbon tax prices. Proposing an Improved Ant Colony Optimization algorithm (IACO) to solve the NP-hard model.

In a parallel vein, another pertinent study conducted by [11], integrates electric vehicles into the Green Vehicle Routing Problem, evaluating the operational costs of a mixed fleet comprising both diesel and electric vehicles. While this investigation does not directly align with our conventional bus-focused approach, reflections on operational costs and the integration of new technologies resonate with the broader context of sustainable mobility.

In the context of the Green Vehicle Routing Problem (GVRP), the essential contribution of [12] and [13] is underscored, providing a pivotal understanding of classifying GVRP concerning different types of motorization, diverse objectives, and methodological approaches. A comprehensive literature review and meticulous comparison between exact, heuristic and metaheuristic methodologies are presented, establishing a robust foundation for comprehending the current state of research in the field. The studies extends the foundation, detailing the intricacies of GVRP, specifically targeting the reduction of greenhouse gas emissions through the incorporation of Alternative Fuel Vehicles (AFVs) or the utilization of existing conventional fossil fuel vehicles within fleets. Consideration is given to environmental sustainability within transportation and logistics, addressing critical aspects such as charging, pick-up, delivery and energy consumption.

While reviewing existing GVRP variations and specializations, a predominant focus on operational-level routing decisions in prior publications is identified, with a noticeable gap in addressing broader supply chain issues. The prevalent use of metaheuristic methods in the literature is significat, raising awareness of the underexplored potential of emerging machine learning methods, reinforcement learning, distributed systems, internet of vehicles (IoV), and novel fuel technologies as a proposition for future GVRP research.

These studies, while not directly aligned with the specific reality of São Paulo, provide concepts, methodologies, and approaches that are applicable and can inspire adaptations for our context. In the next section, we will present the methodological structure adopted to investigate the application of GVRP in the city of São Paulo.

III. Data and Methodology

To support the analysis and proposals, data from the General Transit Feed Specification (GTFS) were used, a standardized format for exchanging information about schedules and routes in public transportation systems. GTFS enabled the mapping of bus lines in the city of São Paulo, identifying relevant routes for the study.

The proposals for improving urban bus routes aim to adapt the current condition to the proposed scenario. Using São Paulo as a case study, it is necessary to consider the age of the fleet, the type of available vehicle, and the overall mode of transportation to ensure a successful alternative. As a premise, the study considers one of the 1,347 operating lines in the city [14], detailing elements such as the type and year of the vehicle, emission level, the number of passengers traveling on the line, and the distance of the route, for comparison with current operations.

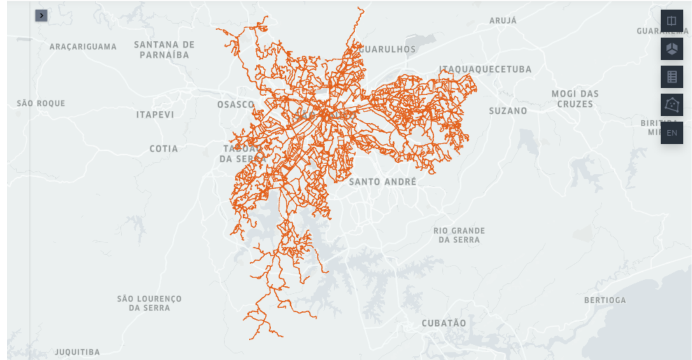

Fig. 1. Distribuition routes of São Paulo

The use of GTFS data allows the mapping of municipal lines, focusing on distribution routes that connect peripheral regions to the center, as illustrated in Figure 1. This allows observing relevant commuting routes. The line's layout and stopping points are treated as a graph, enabling the application of minimum path algorithms, such as Dijkstra. The adjustment of weight on edges can be done considering distance optimization or time optimization, depending on the preference for roads with higher average speed. Figure 2 presents the format of the proposed routes, using the OSMNX library [15] to generate two alternatives to the current route.

After addressing the logistical perspective of the problem, it was necessary to consider material aspects, including the vehicles available in the city. Fuel consumption comparisons were made based on data available at [16], originating from the emissions report of the European Environment Agency [17]. These comparisons allow estimating the environmental impact by analyzing three available routes. The study uses the current vehicle, Basic Bus, and the standard emission level in the city, Euro V or Proconve P7. Table I presents the comparison between routes using the same vehicle.

Considering the passenger comfort perspective, route proposals consider not only the time/size of the route but also the total occupancy of the vehicle. To meet this need, the passenger load for the month of August 2023 was used to

TABLE I
Environmental impact per route

Indicator	Current	Shortest route	Fastest route
CO (g)	59.34	45.07	57.74
CO_2 (Kg)	22.17	16.84	21.57
NOx (g)	189.67	144.05	184.55
Diesel Consumption (L)	12.26	9.31	11.93
Travel Time (min)	114	88	43

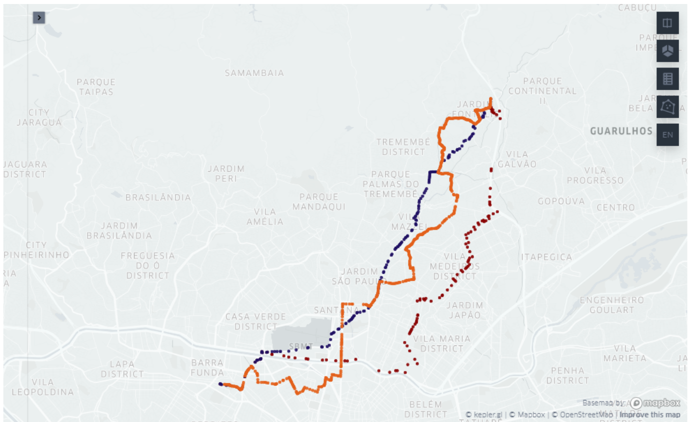

Fig. 2. Detail of 179X-10 route. Orange: Original, Blue: Shortest route and Red: Fastest route

TABLE II
POLLUTANT EMISSION PER VEHICLE SIZE AND TECHNOLOGY

Bus size	Pollutant	Vehicle technology	BAU
	CO (g)	Euro III	85.63
		Euro V	88.37
		Euro VI	8.61
	CO2 (Kg)	Euro III	25.27
Basic		Euro V	21.49
		Euro VI	22.16
	NOx (g)	Euro III	328.55
		Euro V	258.52
		Euro VI	15.64
	CO (g)	Euro III	63.03
		Euro V	66.96
		Euro VI	7.00
	CO2 (Kg)	Euro III	19.10
Midibus		Euro V	15.97
		Euro VI	16.51
	NOx (g)	Euro III	256.82
		Euro V	203.41
		Euro VI	14.91
	CO (g)	Euro III	85.63
		Euro V	88.37
		Euro VI	8.61
	CO2 (Kg)	Euro III	25.27
Padron		Euro V	21.49
		Euro VI	22.16
	NOx (g)	Euro III	328.55
		Euro V	258.52
		Euro VI	15.64

balance the number of passengers transported by this line. Thus, two other types of buses, Padron and Midiônibus, were studied.

This case study focuses on a single line, but in planning on a larger scale, it is crucial to consider the available fleet for allocation. In addition to the type of vehicle, the emission level is relevant for this analysis. Table II presents the comparison between routes considering different emission levels.

IV. Results and Discussion

After applying the Dijkstra shortest path algorithm, it was possible to obtain two additional routes—one with the shortest distance and another with the fastest travel time. This was achieved by considering the edges, in this case, the connections between bus stops, with relative weight in terms of distance or time in transit.

From the information in Table I, it is evident that the shortest route has the least environmental impact compared to the other two. It emits 24% less CO_2 than the original route, in addition to consuming approximately 3 liters less fuel. The fastest route has a substantially shorter travel time, as it travels on express roads with an average time of 43 minutes—roughly 60% less than the original route and half the time of the shortest route. However, it has fuel consumption and emission levels closer to the original route than the shortest route.

Taking a broader perspective, including multiple vehicles with different emission levels, alternatives emerge that better represent environmental impact, operator cost, and passenger cost criteria. Regarding the environment, vehicles compliant with Proconve-P8 or Euro VI standards significantly reduce CO and NO_x emissions compared to others. Also, considering load aspects of the vehicle is heavily indicated by the findings of [18]

Despite a slight increase in CO_2 levels, Euro VI vehicles emit only 10% of the carbon monoxide emitted by both Euro III and Euro V. In terms of hydrogen oxides, the reduction is even more significant, with Euro VI emitting only 5%, on average, of Euro III and 6% of Euro V.

Two factors are crucial in selecting the type of vehicle: capacity and consumption. As mentioned earlier, the studied line is operated by a Basic-type bus. According to [19], the average consumption of this type of vehicle with air conditioning is 0.53 L/km, carrying at least 70 passengers [20]. This study explores a slightly larger vehicle (Padron) and a smaller one (Midiônibus) as possible substitutes for operation. The former has a higher average consumption of 0.63 L/km but can carry 80 people, while the latter transports significantly fewer passengers—40 at a minimum—yet consumes less fuel at 0.47 L/km. Figure 3 shows that the lowest consumption occurs on the shortest route with the Midiônibus, but this vehicle carries 43% fewer people. In the combination of comfort and consumption, the most suitable option for this operation is the Padron vehicle, accommodating 10 more people while consuming the same amount of fuel as the Basic vehicle.

In general, the study presents the potential to alter the current operating conditions of the line, either by changing the route to reduce fuel consumption and environmental impact or by choosing a more comfortable vehicle to accommodate the passenger load. However, as city mobility planning is based on a holistic view of operations, aspects not addressed in this study, such as the number of available vehicles, passenger routes, operating hours, or even the initial cost of the vehicle, must be considered. Nevertheless, when analyzing line 179X-10, which travels from an external zone towards the city center, there are factors that can be adjusted to reduce fuel consumption, environmental emissions, and passenger travel time from the starting point to the final destination.

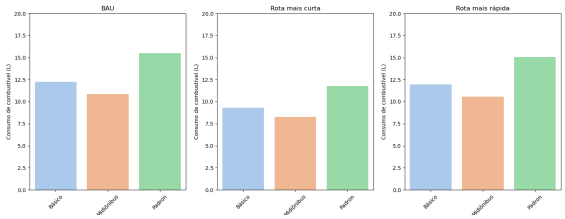

Fig. 3. Fuel consumption by vehicle type on the BAU, Shortest, and Fastest routes

V. Conclusions

This study has revealed that replacing Euro III vehicles with Euro VI models can immediately reduce pollutant emissions, highlighting the environmental impact of public transportation in São Paulo. Balancing operational efficiency and passenger comfort, vehicles such as Padron buses emerge as viable options. The analysis emphasizes the importance of carefully considering operational costs to ensure sustainable solutions. The study suggests possibilities for optimizing the current operation, indicating the need for further research on dynamic vehicle management and the integration of more sustainable technologies, such as hybrid or electric vehicles, in urban transportation. In addition, future projects could also evaluate vehicle distribution of Euro VI or electric vehicles in order to assess global fleet emission.

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