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Electric vehicles in the last mile of urban freight transportation: A sustainability assessment of postal deliveries in Rio de Janeiro-Brazil

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A R T I C L E I N F O

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A B S T R A C T

The growth of urban population and the rise of e-commerce activities increase the complexity of the last-mile of parcel deliveries and its impacts to the environment and quality of life. Despite the relevance, emerging countries have difficult to establish and implement alternatives to the conventional scope of fossil-based operations. This paper proposes a method to assess alternative strategies for the last-mile of parcel deliveries, in terms of social, environmental, and economic impacts and presents an application to assess the distribution strategy of a postal company located in the city of Rio de Janeiro, Brazil. Moreover, we developed a systematic literature review to develop realistic alternatives to the baseline scenario, which operates with diesel propelled light duty vehicles. Literature points to the reduction of the dimensions of vehicles, as well as to the migration of the propulsion source to electric energy, as sustainable alternatives for last mile deliveries in urban areas. For that reason, we opted to evaluate the use of electric vehicles of smaller dimensions, tricycle and LDV, in the last mile of parcel deliveries, assessing two alternative scenarios: one with the use of electric LDV type BEV; and the other with electric tricycles. Results indicated that the use electric tricycle is a more feasible alternative regarding the economic, environmental and social aspects, demanding no public incentives.

1. Introduction

According to United Nations' (UN) forecasts, by 2050 more than 70% of the world's population will live in urban areas (ONU, 2013). Along with this urban population growth, the demand for goods, and thus for freight transportation, within city borders also increases. In this context, just-in-time practices and the explosive growth of e-commerce generate significant volumes of personal deliveries (Crainic et al., 2004). Moreover, according to the results of a survey with 4700 respondents developed by (Joerss et al., 2016), customers worldwide desire fast and home deliveries, increasing even more the demand for parcel deliveries.

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The cost of global parcel delivery, excluding pickup, line-haul and sorting and including labor costs, amounts to 70 billion euros, and the last mile's share in this total often reaches or even exceeds 50 percent (Joerss et al., 2017). Therefore, the last-mile of parcel delivery is a key process step for postal systems, express mail, private courier companies and less than truckload shipping carriers, which are the companies that usually provide this type of service (Dennis, 2017). Therefore, due to its relevance, this paper aims to assess alternative strategies for the last-mile of parcel deliveries, considering not only costs and level of service as key performance indicators, but also the social, environmental, and economic impacts of this strategy are evaluated.

Under these circumstances, we analyzed a case study based on the distribution process of a public postal company located in the city of Rio de Janeiro, Brazil. The current distribution process is considered the base-line for our analysis, and alternative scenarios are proposed to develop a comparative assessment. Nonetheless, to guarantee realistic scenarios, we opted to apply a systematic literature review (SLR) to identify the main type of vehicle that could increase the sustainability in the last mile of urban freight distribution. A SLR attempts to obtain and portray a clear and objective conclusion about a particular sphere of knowledge (Tranfield et al., 2003; Cook, Mulrow and Haynes, 1997), and consequently it was chosen as part of the research.

In the following section, we present more details of the SLR, which points to the reduction of the dimensions of vehicles, as well as an increase of electric propulsion systems as sustainable alternatives to last-mile deliveries in urban areas. For that reason, we opted to evaluate the use of electric vehicles of smaller dimensions (tricycle and light duty vehicles – LDV), assessing two alternative scenarios for the traditional distribution strategy adopted by the postal company: one that uses a light-duty battery electric vehicle (LDBEV); and another that uses electric tricycles. In addition, Section 3 details the procedure developed to assess the economic, social and environmental aspects of the distribution process. Section 4 analyses the results, and Section 5 presents the conclusions and recommendations.

2. Literature review

For the development of the SLR we followed the methodology proposed by Thomé et al. (2016). Step 1 involved selecting the database, which included scientific journals of interest to the area in Web of Science, SCOPUS, EBSCO, Science Direct, DOAJ, Springer Link and Compendex.

Step 2 consisted in identifying keywords for search and resulted in the following structure: last mile and (urban freight or urban freight distribution or city logistics) and vehicles. This combination of the keywords was chosen to identify studies that propose different technologies for last-mile urban deliveries. The combination of terms: last mile and (urban freight or urban freight distribution or urban freight transportation or city logistics) enabled the identification of studies that deal with the last mile in urban freight transport or urban logistics. The objective of complementing these terms with the Boolean operator "and" plus the term "vehicles" is to restrict the search to papers that focus on the vehicles adopted in this type of strategy. The search request was applied in the research field, title, abstract and keywords, with the time span restriction of 2007 to 2016, with the purpose of identifying the trends observed world widely in the last decade. It was also restricted to papers published in English in indexed and peer-reviewed international journals, as recommended by (Nord and Nord, 1995; Ngai and Wat, 2002; Oliveira et al., 2016) to ensure the quality of the studies. As a result, 157 papers were identified.

In step 3, we first excluded duplicated papers, reducing the total list to 137 studies. Afterwards, in step 4, at least three authors of the present article reviewed the papers' titles and abstracts. Those papers which content was related to last mile distribution and urban freight transportation but did not focus specifically on the type of vehicle adopted in such operation, were excluded. This is due to the fact that the goal of this SLR consisted in identifying trends in the type of vehicles adopted in last mile operations that could be applied in postal distribution in order to increase its sustainability. At the end of step 4, 46 papers were then selected for the full-text review carried in step 5. At least three authors read the full-paper and an interactive review process among these authors was conducted using the same exclusion criteria from step 4. In order to ensure the quality of the review process, we searched for high levels of agreement among the authors to select only papers that actually focused on the type of vehicle that could be adopted in last mile distribution. With such procedure, we guaranteed that papers that dealt with our main research topic were not excluded from the final list, which consisted of 26 papers.

2.1. Results of the systematic literature review

Table 1 connects vehicle's types and energy sources with the barriers, opportunities, and benefits (economic, environmental and social) related to their use. It also describes the data collection and assessment method adopted in each paper.

It can be observed that most of the papers were developed in Europe (77%). As a matter of fact, the geographical distribution of papers shows a marked predominance of publications originated from developed countries. Regarding the classifications of countries based on their level of development created by the International Monetary Fund (IMF), there are no publications from underdeveloped countries, and only two papers were from developing countries (Brazil and India). Moreover, most of the papers used field observations and data from literature reviews as inputs for the assessment.

Fig. 1 summarizes the results obtained in the SLR, presenting the distribution of papers according to the type of vehicle and the energy consumed.

From the total papers considered, 42% proposed bicycle/tricycle as alternatives for last mile urban deliveries, with regards to the energy used, 64% pointed to electric energy and 36% to human propulsion. On the other hand, LDVs, which are vehicles with a gross vehicle weight (GVW) less than 3.5 t, were considered in 58% of the studies, among which 73% of them indicated the use of electricity and 27% the use of other sources of energy (diesel, diesel/methane and diesel/biodiesel). It is noteworthy that

Table 1
Synthesis of the systematic literature review results.

Author	Country	Data collection method	Assessment method	Type of vehicle or equipment used	Source of energy	Barriers	Benefits/opportunities		
							Economics	Environmental	Social
Tozzi et al. (2013)	Italy	Field observations	Case study	LDV[a]	Diesel and Methane (dedicated)	–	–	–	–
Lebeau et al. (2013)	Spain	Literature review and Field observations	Simulation	LDV	Electric	Fleet acquisition costs; Capacity (weight and dimensions)	–	Reduction of CO2 emissions and atmospheric pollutants	–
Sadhu et al. (2014)	India	Literature review and Field observations	Case Study	Bicycle[b] Tricycle[b]	Human	Customers concerns	Energy consumption; Delivery time; Traffic congestion	Reduction of CO2 emissions and atmospheric pollutants	Job creation/ Health problems
Visser et al. (2014)	Netherlands	Literature review	Case study	LDV	Diesel and Biodiesel	–		Reduction of CO2 emissions and atmospheric pollutants	Quality of life
Gruber et al. (2014)	Germany	Field observations	Case study	Bicycle/Tricycle	Electric	Road and recharge infrastructure; Customers concerns	Operational cost; Energy consumption;	Reduction of CO2 emissions and atmospheric pollutants	–
Roumboutsos et al. (2014)	Greece	Literature review	Simulation	LDV	Electric	Operational cost; Recharge infrastructure	–	Reduction of CO2 emissions, atmospheric pollutants and noise	–
Foltyński (2014)	Italy	Literature review	Case study	Motorcycles[c] Trolleys[d]/Bicycle/ Tricycle and LDV	Electric	–	Traffic congestion	–	–
Oliveira et al. (2014)	Brazil	Literature review	Case study	Bicycle/Tricycle	Human	–	Delivery time	Reduction of CO2 emissions and atmospheric pollutants	–
Montwiłł (2014)	Italy	Literature review	Case study	LDV	Electric	–	–	–	–
Diziain et al. (2014)	Japan	Literature review	Case study	Bicycle/Tricycle	Electric	Cargo consolidation center; Road and recharge infrastructure	–	Reduction of CO2 emissions and atmospheric pollutants	–
Thompson and Hassall (2014)	Australia	Literature review	Case study	LDV	Diesel	–	–		–
Schliwa et al. (2015)	England	Field observations	Case study	Bicycle/Tricycle	Human	Customers concerns; Cargo consolidation center; Capacity (weight and dimensions)	Energy consumption; Delivery time	Reduction of CO2 emissions and atmospheric pollutants	Job creation
Alessandrini et al. (2015)	Italy	Survey	Delphi	LDV (Autonomous)	Electric	Recharge and telecommunication infrastructure	–	Reduction of CO2 emissions and atmospheric pollutants	–
Faccio and Gamberi (2015)	Italy	Field observations	Simulation	LDV	Electric	–	Operational cost	Reduction of CO2 emissions and atmospheric pollutants	Quality of life
Lebeau et al. (2015)	Belgium	Literature review and Field observations	Case study	LDV	Electric	Fleet acquisition costs	–	Reduction of CO2 emissions and atmospheric pollutants	–
Andaloro et al. (2015)	South Korea	Literature Review	Case study	LDV	Electric	Fleet acquisition costs; Capacity (weight and dimensions)	–	Reduction of CO2 emissions and atmospheric pollutants	–

(continued on next page)

Table 1 (*continued*)

Author	Country	Data collection method	Assessment method	Type of vehicle or equipment used	Source of energy	Barriers	Benefits/opportunities		
							Economics	Environmental	Social
Dampier and Marinov (2015)	England	Literature review and Field observations	Case study	Bicycle/Tricycle	Human	Cargo consolidation center	Delivery time; Traffic congestion	Reduction of CO2 emissions and atmospheric pollutants	–
Schau et al. (2015)	Germany	Public policy	Simulation	LDV	Electric	Cargo consolidation center; Road and recharge infrastructure; Capacity (weight and dimensions); vehicles charging time	–	Reduction of CO2 emissions and atmospheric pollutants	–
Margaritis et al. (2016)	Greece	Literature Review	Case study	LDV	Electric	–	–	–	–
Navarro et al. (2015)	Italy	Field observations	Case study	Bicycle/Tricycle	Electric	Cargo consolidation center; Road and recharge infrastructure; Capacity (weight and dimensions)	–	Reduction of CO2 emissions, atmospheric pollutants and noise	–
Rizet et al. (2015)	France	Literature Review	Simulation	LDV	Electric	Recharge infrastructure (electric)	Traffic congestion	Reduction of CO2 emissions and atmospheric pollutants	–
Gruber and Kihm (2016)	Germany	Field observations	Case study	Bicycle/Tricycle	Electric	–	–	–	–
Heitz and Beziat (2016)	France	Field observations	Case study	Bicycle/Tricycle	Electric	Cargo consolidation center;	Operational cost	Reduction of CO2 emissions and atmospheric pollutants	–
Anderluh et al. (2016)	Austria	Literature Review	Simulation	Bicycle/Tricycle	Electric	–	Traffic congestion	Reduction of CO2 emissions, atmospheric pollutants and noise	–
Taniguchi et al. (2014)	Japan	Literature Review	Case study	LDV	Diesel	Cargo consolidation center	–	Reduction of CO2 emissions, atmospheric pollutants and noise	–
Schier et al. (2016)	Germany	Field observations	Case study	Bicycle/Tricycle	Electric	–	–	Reduction of CO2 emissions and atmospheric pollutants	Quality of life

[a] Vehicles for the shipment of goods and having a maximum total gross weight (TGW) not exceeding 3.5 t.
[b] A bicycle specially designed for shipping loads.
[c] Two-wheel vehicles without a sidecar (category L3e) or with a sidecar (category L4e), fitted with an engine having a cylinder capacity of more than 50 cm^3 with a maximum design speed of more than 45 km/h.
[d] Small vehicles with two or four wheels that can be used to transport large or heavy loads.

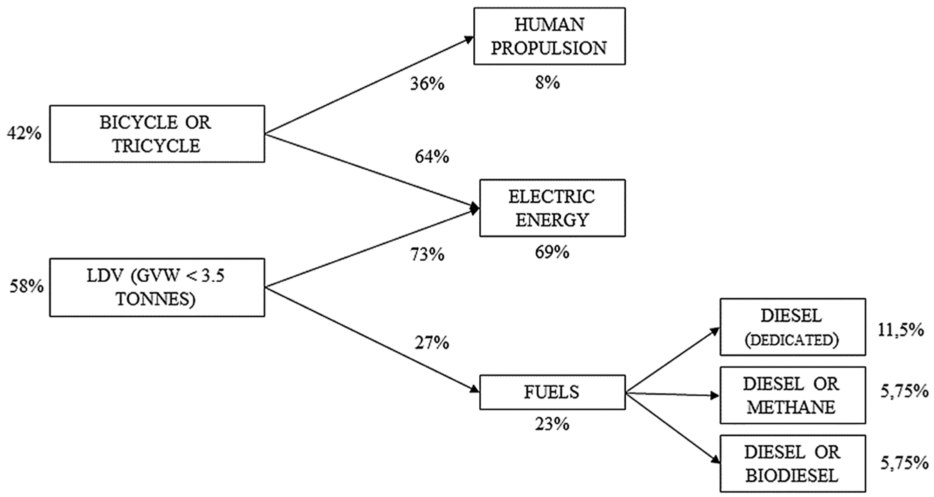

Fig. 1. Type of vehicle and energy consumption.

(Alessandrini et al., 2015) considered the use of an unmanned LDV powered by electricity. Moreover, (Foltyński, 2014) suggested the use of bicycles, tricycles and motorcycles together with LDV (all electric), as alternatives for last mile delivery.

According to (Schoemaker et al., 2006), the number of LDV in Europe has increased by 15% between 1990 and 2003, while the number of vehicles with a GW over 3.5 t has increased by 6.6% during the same period. This demonstrates that, corroborating to the alternatives pointed by the SLR, there is a tendency to increase the use of LDV in the urban freight transport. In addition, according to (Dablanc, 2009) urban freight transport is inefficient in most cities, including those in developed countries, with low population density rates. For example, in London the occupancy rate of this type of vehicle varied between 40% and 60% in 2006 (Schoemaker et al., 2006). Consequently, the use of vehicles with smaller dimensions for last mile deliveries would contribute to a more efficient operation. Moreover, factors such as traffic congestion and specific geographic characteristics of cities (ground surface relief, presence of a historical center, and population density) generated impedances that led to the gradual use of even smaller vehicles like tricycles, bicycles and motorcycles, as suggested by 42% of the papers identified in this SLR.

Regarding vehicles' energy consumption, it was verified that 69% of the papers deals with vehicles powered by electricity. Fuels like methane, biodiesel, diesel (23%), and human propulsion (8%) were other sources of energy considered. This result shows the potential use of electric vehicles in urban freight transport, especially in the last mile distribution, since electrification is widely considered as a viable strategy for reducing the oil dependency and environmental impacts of road transportation (Weiss et al., 2015), in particular to reduce greenhouse gas (GHG) emissions, especially CO_2, the main cause of global warming (Fernandes et al., 2015; Rezvani et al., 2015; Weiss et al., 2015).

From the results of the SLR, it is evidenced the existence of a trend towards more sustainable alternatives for the last mile of urban deliveries, with a shift on the vehicles' source of energy from fossil fuels to electric energy and the reduction of vehicle' sizes, specifically in the adoption of bicycles, tricycles and LDV (Table 1). These results justify the importance of an approach, that considers the «triple bottom-line» of environmental, economic and social equity sustainability (Richardson, 2005), to assess alternatives for the last-mile of urban deliveries, such as presented in Section 3.

3. Method

Going beyond the traditional approach, this paper proposes a method that seeks to reconcile the economic, environmental and social aspects when assessing alternatives for last-mile postal deliveries. This section describes the strategies, the delivery area, the data collection and analysis tools.

3.1. Strategies description

The analysis is restricted to the neighborhoods of Leme and Copacabana, in Rio de Janeiro, Brazil. These neighborhoods cover a small flat area (4.1 km^2), squeezed among a mountain, a lagoon and the beach, with a high population density (36,000 inhab/km^2), high levels of traffic congestion and lack of parking areas for loading and unloading operations. These aspects provide a complex delivery scenario, which is in accordance with the SLR results. Moreover, the postal distribution is preceded by a series of internal activities, such as receiving, sorting and posting orders, which sums up to a large part of the postman's work schedule, followed by the delivery activity. Nonetheless, the focus of this assessment is on the delivery activity itself, evaluating three strategies such as follows.

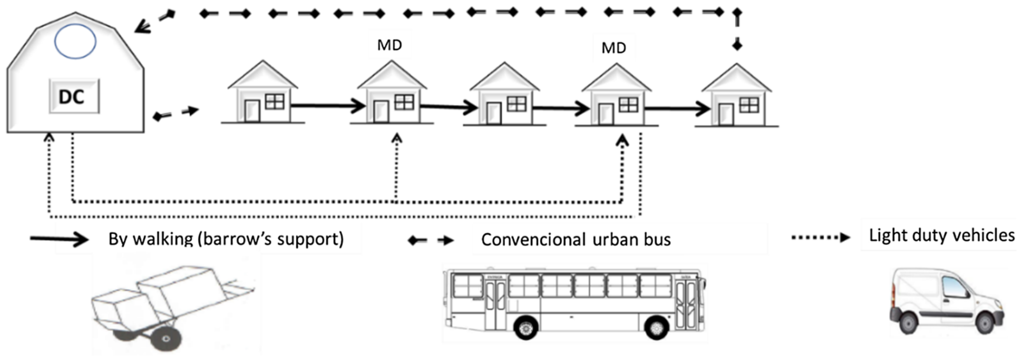

Fig. 2. Traditional intermodal distribution (TID).

3.1.1. Traditional Intermodal Distribution (TID)

When leaving the distribution center (DC), the postman follows the stablished route by walking (if the destination is near the DC) or by bus until the delivery area. The deliveries are made with the help of a trolley and a mailbag. The weight limit of the bag, established by a collective agreement, is 10 kg for men and 8 kg for women. Once the postman delivers an average of 50 kg per route, he is supported by a fossil-fueled LDV to carry the surplus weight to pre-defined points, the mobile depots (MD). Anytime the postman delivers the content of his mailbag, he reloads the mailbag in the MD, when a new delivery begins. At the end of the route, the postman returns to the DC using a conventional urban bus, as shown in Fig. 2.

3.1.2. Alternative Intermodal Distribution (AID)

The AID and TID strategies are performed by walking with support of a trolley and a mailbag. The postman takes a conventional bus to the destination, however with is the support of an electric LDV type BEV (battery electric vehicle) to carry the surplus weight to the MD. This alternative distribution aims to assess the socioeconomic and environmental aspects of the adoption of an electric LDV instead of a fossil-fueled one.

3.1.3. Distribution by Electric Tricycles (DET)

In the DET strategy, the postman performs the deliveries using an electric tricycle throughout the entire route. In this case, weight limit is the capacity of the tricycle (50 kg), instead of the weight limit imposed by the collective agreement. This strategy does not require the support of an LDV and the use of MD. The postman moves from the DC to the first delivery point using only the electric tricycle. Upon reaching the delivery area, he parks the tricycle and delivers by foot, as shown in Fig. 3. In order to evaluate this strategy, we tested the use of electric tricycles in the test-rig area for two weeks.

3.2. Data collection

Data collection occurred from Tuesday to Thursday, for two months. During this period, we monitored the same postman for ten working days: five of which he performed the TID strategy to accomplish his deliveries, and the other he performed the DET strategy. On average, the postman carried deliveries to 60 different points per working day. Therefore, the data can be grouped into five categories: (i) time: round trip and delivery; (ii) distance: round trip and delivery; (iii) average speed: round trip and delivery; (iv)

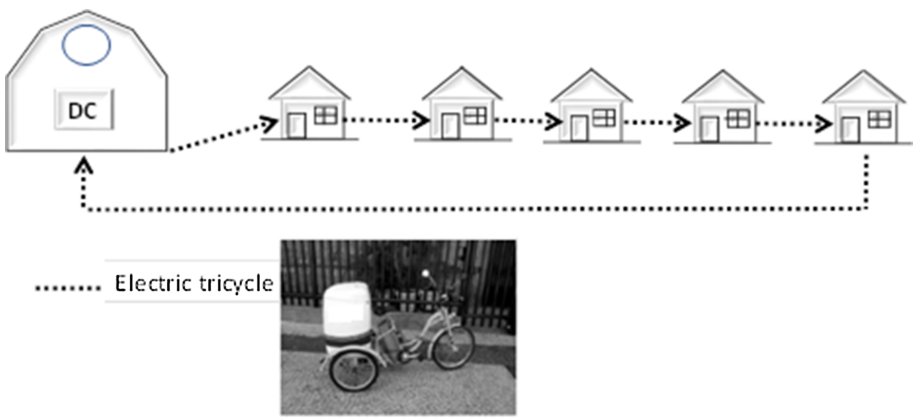

Fig. 3. Distribution with support of electric tricycle (DET).

Table 2
Descriptive statistics for TID and DET strategies.

	TID		DET	
	Mean	Standard deviation	Mean	Standard deviation
Total time (h)	02:02:21	00:16:40	01:34:45	00:14:24
Total distance (km)	13.31	1.58	10.74	0.58
Speed (km/h)	6.55	0.36	6.89	0.70
Average Heart Rate (bpm)	103.27	8.67	100.18	2.89

number of customers served, and (v) postman's heart rate. We used the Forerunner 405 Garmin device to measure the heart rate.

Table 2 shows the descriptive statistics for the assessed variables for each distribution strategy. In addition, we also estimated the fuel consumption and its respective cost for both strategies. Regarding the AID strategy, we used the same data from the TID strategy, changing the technical features of the conventional vehicle for those from the electric LDV, since this is the only difference between the two strategies. Data was tabulated, and the samples normality was verified by the Shapiro-Wilk test (Bussab and Morettin, 1987). The p-value was superior to .05 (significance level adopted) in all data analyzed, varying from 0.0902 to 0.9314. Hence, we assumed that data can be approximated by a normal distribution.

3.3. Assessment

In this section, we present the proposed protocol for assessing the economic, social and environmental facets of the three strategies.

3.3.1. Economic assessment

The comparison of each delivery strategy, regarding economic aspects, was based on the level of service and the total urban freight transportation cost. Level of service was measured based on the number of customers served, according to Eq. (1).

$$LS = \frac{\sum cs}{\sum td} \tag{1}$$

wherein

LS = Level of service;
cs = Number of customers served;
td = Total delivery time.

On the other hand, the total urban freight transportation cost was calculated according to Eqs. (2) and (3) (NTC, 2014).

$$TC_{TID} = (cm/h * tct) + (bf * n) + (cv/h * vct) + (cv/km * tdv) \tag{2}$$

wherein

TC_{TID} = Total cost of TID;
cm/h = Cost of postman per hour;
tct = Total round-trip time;
bf = Bus fare;
n = Number of bus trips;
cv/h = Cost of LDV driver per hour;
vct = LDV round trip time;
cv/km = Cost of the LDV per km;
tdv = Total distance traveled by the LDV (km).

$$TC_{DET} = (cm/h * tct) + (ct/km * tdt) \tag{3}$$

wherein

TC_{DET} = Total cost of DET;
cm/h = Cost of postman per hour;
tct = Total round trip;
ct/km = Cost of the tricycle per km;
tdt = Total distance traveled by the tricycle (km).

Costs related to vehicle depreciation, maintenance, taxes, compulsory insurance, fuel and electric energy were considered when calculating the costs per km of the tricycle and LDVs (fossil fueled and electric), as indicated in the NTC manual for calculating costs and describing price formation of freight transportation, which is used as a reference for several studies in Brazil (NTC, 2014). A market survey was conducted with suppliers of different materials and equipment to collect input costs.

3.3.2. Environmental assessment

Regarding the end-use energy consumption, DET is considered a zero-emission strategy, and thus the assessment is based on how much this strategy ceases to emit, comparing with the TID and AID strategies. Along these lines, we analyzed the emissions of carbon monoxide (CO), nitrous oxide (N_2O), nitrogen oxides (NO_x), aldehydes (RCHO), non-methane hydrocarbons (NMHC), methane (CH_4), particulate matter (PM) and carbon dioxide (CO_2). According to Eq. (4), a bottom-up approach was used to estimate GHG and air pollutants emissions.

$$E = (efv * tdv) + [(efb * tdp)/(IPKo * tdp)] \tag{4}$$

Thus

E = Emission of air pollutants in the TID strategy (g);
efv = Emission factor of the LDV for each pollutant (g/km);
efb = Emission factor of the bus for each pollutant (g/km);
tdp = Total distance traveled by the postman on the bus (km);
tdv = Total distance traveled by the LDV (km);
IPKo = Index of passenger per kilometer (bus) (pass/km).

For calculating end-use pollutant emissions, we multiplied the emission factors (MMA, 2013) by the average fuel consumption of each fossil-fueled vehicle used in the TID strategy (Table 3). It is noteworthy that buses are powered by diesel S10 B7 in Brazil, a blend containing 7% by volume of biodiesel and 93% by volume of low Sulphur (10 ppm) petroleum diesel oil. In addition, the LDV is supplied with an ethanol-gasoline blend consisted of 73% of automotive petroleum gasoline and 27% of anhydrous ethanol.

In order to estimate the life-cycle GHG emissions, CH_4 and N_2O emissions were converted into CO_2e emissions, considering the global warming potential (GWP) values of 21 for CH_4 and 310 for N_2O (IPCC, 2014). Nonetheless, up to this point, we only considered end-use energy consumption. For a more in-depth assessment, we also adopted the factors stated by the Brazilian Ministry of Mines and Energy to estimate CO_2e emissions through a tier 2 approach (IPCC, 2006). We opted to use such emission factors because they better represent the Brazilian energy generation scenario, such as presented on Table 4. It is important to reinforce that such emissions factors present different values than those adopted in Europe, China and the United States.

The data related to public transport were provided by the Rio de Janeiro bus companies league, which organizes a database since 1984. These data allowed the calculation of the IPK (1.67) and energy efficiency (2.59 km/l) of the conventional bus. In turn, the energy efficiency of the LDV (4.56 km/l) was obtained from the data collected during the operation.

3.3.3. Social assessment

According to Campos et al. (2009), the main impacts that can be associated with urban transportation systems considering the social context are: health, equality and justness of opportunities. For this reason, we considered the effort made by the postman during the deliveries as a social indicator, since it has direct impact on worker health. It was evaluated by monitoring the heart rate (HR), which the maximum value is estimated according to the postman's age, using the adjusted age-predicted maximal heart rate (APMHR) proposed by Arena et al. (2016) (Eq. (5)).

$$MHR = 209.3 - 0.72 * (a) \tag{5}$$

wherein

MHR = Maximum Heart Rate (beats per minute);
a = age (years old).

It should be noted the existence of a standard error presented in all equations that estimates maximum HR, since it is a physiological variable, difficult to determine due to the complexity of cardiac variables in general, as well as the relationship between maximum HR and age (Froelicher et al., 1998).

The frequency of beats per minute was divided into five percentage ranges related to the postman's maximum HR, which are: (1)

Table 3
Pollutants emission factors.

Vehicle's year/model	Vehicle type	Fuel	CO[a]	NO_x[a]	RCHO[a]	NMHC[a]	MP[a]
2013	LDV	Ethanol-gasoline	0.25	0.0030	0.0017	0.014	0.0011
Euro V	Buses	Diesel	0.44	2.103	–	0.033	0.0200

[a]g/km; [b]kg/l, the values presented were obtained by the weighted average of the proportion of fuels in the mixture.

Table 4
Emission factors for tier 2 analysis.

Fuel	Anhydrous ethanol	Hydrous ethanol	Biodiesel	Gasoline	Diesel	Electricity (tCO_2e/MWh)
Emission factor (CO_2e/MJ)	20.5	20.7	22.1	87.4	86.5	0.12

Very low (HR < 57%); (2) Low (57 ≤ HR < 64%); (3) Moderate (64 ≤ HR < 77%); (4) High (77 ≤ HR < 96%) and (5) Maximum (96 ≤ HR ≤ 100%) (Garber et al., 2011). The analysis was based on the percentage of time that the measured frequency remains in each effort range during the accomplishment of the activity.

It is important to point out that, when cycling with surrounding traffic, postmen will be more exposed to poor air quality, which may generate pulmonary or cardiac diseases over time. Therefore, we made sure that postmen used a mask during the operation in order to avoid such exposure.

4. Results and discussion

Table 5 presents the items considered in the composition of the deliveries' total costs (TID, AID and DET). Thus, based on the economic assessment method presented in Section 3.3.1, we calculated the fixed and variable costs of each strategy, as presented in Table 6.

Comparing with the TID strategy, we identified a cost saving of 27.9% by adopting the DET strategy. On the other hand, the costs increased 6.16% when adopting the AID strategy. This result was expected due to the higher acquisition value of an electric LDV.

According to the authors' surveys, an electric LDV is 138% more expensive than a conventional one. Thus, due to its smaller costs of fuel, lubricants and tires, a reduction of 52.5% in the electric LDV acquisition price is necessary to equalize the costs of TID and AID strategies. Nonetheless, according to (Delft, 2013), this difference tends to fall by approximately 17.5% in 2020 and 37.2% by 2030. On the other hand, one might expect greater reductions than that estimated by (Delft, 2013) due to the program Mobilize Your City Local Governments in Developing Countries Take High Road to Low-Carbon developed by the United Nations Framework Convention on Climate Change (UNFCCC, 2015) which aims to support developing countries (Africa, South Asia, South America, and the Middle East), starting in 2020, for the development and implementation of urban sustainability programs and the city of Rio de Janeiro is one of the potential municipalities to receive support. Another program that may influence the final value of the BEV is the partnership between Brazil and Germany, which have signed a technical cooperation agreement to improve the development of electric vehicles (GO4SEM, 2015).

Concerning the level of service, we observed a 26% increase in the productivity, when comparing the DET strategy with TID/AID strategies. It was verified that the DET strategy, besides taking less time, was able to carry out a greater number of deliveries: 39 deliveries per hour in comparison to 31 deliveries per hour by the TID/AID strategies.

Regarding the environmental assessment, Table 7 shows the monthly emissions of the TID and AID strategies. TID life-cycle GHG emissions were 23.72 kg. Since the DET strategy only uses an electric tricycle, it can be considered as a zero-emission strategy in an end-use analysis. Nonetheless, in a life-cycle approach, the emission of CO_2e would be equivalent to 0.35 kg due to the electricity consumption of the tricycle. So, by using this strategy, monthly reductions are equivalent to 23.37 kg.

The emission of CO_2e in the AID strategy would be equivalent to 17.89 kg per month, 17.5 kg due to the bus operation and 0.39 kg due to the electricity consumption of the electric LDV. Therefore, in such assessment, the reduction in CO_2e would be equivalent to 5.91 kg.

In relation to the social aspect, Table 8 shows the comparison between the HR collected during the execution of the TID and DET strategies. We emphasize that the results obtained during the execution of the TID and AID strategies would be the same, since there are no differences in the activities between both. Furthermore, we ran the tests in a 34-year-old employee, weighing 82 kg.

The heart rate level 4 (high) is reached only during the TID and AID strategies (0.02% of the time). Likewise, the lower heart rate levels are evidenced during the DET strategy, since in both classes (3-moderate and 2-low) there is a smaller participation of this strategy (−95% and −43% respectively), while at level 1 (very low) the share of the DET is 27% higher. The HR level 5 (maximum)

Table 5
Items considered in the composition of total costs by strategy.

Description of the variables	Unit	TID	AID	DET
Number of working days in a month	Unit	26	26	26
Average kilometers traveled	km	5.01[b]	5.01[b]	10.74[a]
Daily trips	Unit	2	2	1
Average number of bus passes	Unit	2.40	2.40	–
Bus ticket value	US$	1.32	1.32	–

[a] In the DET strategy, one postman leaves the DC in the electric tricycle, performs the deliveries and then returns to the DC, in a total distance traveled of 10.74 km.

[b] In the TID and AID strategies, after delivering the content of this mailbag, the postman goes to pre-defined points to meet the LDV, where he reloads his mailbag and then a new delivery begins (which is done by walking). In these strategies, each LDV travels 5.01 km from the DC to the MD.

Table 6
Fixed and variable costs by strategy.

Fixed costs (month)	Unit	TID	DET	AID
Capital expenditure (CAPEX)	US$	207.68	35.38	712.76
Driver's salary + charges	US$	1161.28	–	1161.28
Postman's salary + charges (during deliveries)	US$	259.96	202.43	259.96
Mechanical salary	US$	187.51	19.53	82.60
Vehicle licensing	US$	53.11	–	46.71
Motor hull insurance	US$	71.72	–	170.33
Optional civil liability insurance	US$	41.81	–	41.81
Total (fixed)	US$	1983.07	257.34	2475.44
Variable costs	Unit	TID	DET	AID
Maintenance parts	US$/km	0.3128	0.0869	0.1678
Fuel	US$/km	0.3237	0.0044	0.0204
Lubricants	US$/km	0.0067	–	0.0001
Battery Replacement	US$/km	–	0.0166	–
Washing	US$/km	0.1259	0.0631	0.0545
Tire	US$/km	0.0144	0.0409	0.0144
Total (variable)	US$/km	0.7835	0.2119	0.2572
Total daily cost of the deliveries	5.1.4. US$/day	5.1.5. 16.88	5.1.6. 12.17	5.1.7. 17.92

Table 7
Emissions of pollutants of TID and AID strategies.

Strategy	CO[a]	NOx[a]	RCHO[a]	NMHC[a]	PM[a]	N_2O[a]	CH_4[a]	CO_2[b]
TID	10.11	32.78	0.02	0.70	0.33	0.81	1.27	23.72
AID	6.85	32.74	0.00	0.51	0.31	0.47	0.93	17.89
Monthly reductions (TID-AID)	*3.26*	*0.04*	*0.02*	*0.19*	*0.02*	*0.34*	*0.34*	*5.91*
Monthly reductions (TID-DET)	*10.11*	*32.78*	*0.02*	*0.70*	*0.33*	*0.81*	*1.27*	*23.37*

[a] End-use emissions, calculated in g.
[b] Life-cycle emissions, calculated in kg.

Table 8
HR ranges measured.

HR ranges[a]		Bpm[b]	Average TID (%)	SD[c] TID	Average DET (%)	SD DET	Variation % DET × TID
1	< 57%	0–106	68.48	28.58	86.88	9.11	27%
2	57 ≤ HR < 64%	106–117	22.14	14.48	12.66	8.93	−43%
3	64 ≤ HR < 77%	117–141	9.37	16.24	0.46	0.51	−95%
4	77 ≤ HR < 96%	141–176	0.02	0.03	0.00	0.00	–
5	96 ≤ HR ≤ 100%	176–184	0.00	0.00	0.00	0.00	–

[a] Average heart rate.
[b] Beats per minute.
[c] Standard deviation.

was not observed in any strategy. Data show that, during the TID and AID strategies, there was a higher HR variation, reaching 77% of the postman's maximum heart rate, while during the DET strategy the HR observed was constant (between levels 1, 2 and 3).

Results obtained indicate that the adoption of DET strategy or AID strategy in the postal distribution of Rio de Janeiro city, is aligned with the necessity to reduce the negative externalities produced by the freight transport activities, mainly related to the large consumption of fossil fuels, as pointed out by Rothengatter et al. (2003). However, due to the higher acquisition value of the electric LDV in the AID strategy, financial barriers were observed. This situation shows the necessity of public incentives for the production of electric vehicles, as pointed out by Peres et al. (2012), to increase their economic viability. Nevertheless, if compared to DET strategy, the adoption of such public incentives would not be justified, since the results indicated a cost reduction and the improvement of level of service by adopting the DET strategy.

DET strategy also showed advantages from the social point of view, since the employee's HR was constantly low (between levels 1, 2 and 3), during a time interval 27% higher than TID and AID strategies. This result is in line with (Hinde and Dixon, 2005), which points out the contribution of the use of electric tricycles in the maintenance of people's health, insofar as it makes possible the physical exercise.

Table 9 summarizes the gains by adopting the DET and AID strategies in comparison to the baseline. As a result, we verified that the adoption of electric tricycles in a postal distribution strategy is justifiable, considering economic, social and environmental

Table 9
Comparative assessment between DET and AID strategies to TID.

Aspect	Indicator (% variation)		DET	AID
Economic	daily cost of the deliveries		−28,0%	6,1%
Environmental	Tier 2 approach	CO_2e	−98,5%	−25%
	End-use approach	CO_2e	–	−28%
Social	< 57		27,0%	0%
	$57 \leq FC < 64$		−43,0%	0%
	$64 \leq FC < 77$		−95,0%	0%

aspects. Besides, the adoption of electric tricycles in this postal distribution demands no public incentives. Even considering the acquisition of electric tricycles by the company, the economic analysis still showed a reduction of the total cost, comparing the DET with the TID strategies.

5. Conclusion

The SLR conducted in this paper indicates a trend towards more sustainable alternatives to the last mile of urban deliveries, with a shift on the vehicles' source of energy and the reduction of vehicles' sizes, alongside the adoption of bicycles, tricycles and LDV.

Along these lines, we proposed an assessment procedure, which goes beyond the traditional approach that bounds the consideration to cost and level of service to assess sustainable alternatives for last mile urban deliveries. The method seeks to reconcile the economic, environmental and social aspects in the choice of alternatives for last-mile deliveries, which is the innovative contribution of this research.

Moreover, we addressed the sustainability gains associated with the use of electric vehicles in the last mile of a postal delivery service in the city of Rio de Janeiro, Brazil. We verified monthly reductions per route in the emission of air pollutants and GHG by replacing a fossil-fueled LDV used in the traditional strategy by an electric LDV (AID strategy) or electric tricycles (TED strategy), considering end-use and life-cycle emissions. Despite these environmental benefits, the total AID strategy's delivery-cost per route increased 6.16% in comparison to the TID strategy, due to the superior acquisition value of the electric LDV.

In the DET strategy, we verified a reduction of 27.9% in the total delivery-cost per route, besides a decrease in the emission of atmospheric pollutants and GHG. Nonetheless, it is important to reinforce that the postal company should consider a disposal and recycling program for the batteries used by the electric tricycles. The DET strategy also showed advantages from the social point of view, since the employee's heart rate was constantly low (between levels 1, 2 and 3), during a time interval 27% higher than TID and AID strategies. Concerning the level of service, we observed a 26% increase in the productivity, when comparing the DET strategy with TID and AID strategies. Therefore, the analysis showed that the electric tricycle alternative is feasible in the economic, environmental and social aspects, as well as in the maintenance of the level of service.

Finally, it was verified that using electric tricycles as an alternative for last mile postal distribution in the city of Rio de Janeiro was able to promote the economic, environmental and social aspects, maintaining the level of service. Moreover, the proposed modeling framework could also be adopted by futures studies to assess alternative policies, such as urban distribution centers, mobile depots, cycle paths, off-hour deliveries and others. Moreover, we suggest that a more detailed assessment of the social impacts, including the analysis of performance indicators related to accidents, taxes or income generated.

Declarations of interest

None.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2018.12.017.

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