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The Sustainable Parcel Delivery (SPD) Problem: Economic and Environmental Considerations for 3PLs

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ABSTRACT Sustainability in parcel delivery is a growing area of interest, especially for third-party logistics providers (3PLs). The recent increase of urban population is directly related to the increase request of goods in urban areas, and consequently to the growth of the urban freight transport and CO2 emissions. For these reasons, national and local institutions carried out regulations and incentives to reduce urban pollution and promote zero-emission vehicles. In particular, daily tickets to access to city centers is a common regulation applied to reduce freight transport. This paper presents a new SPD model that compares Eclectic Vehicles (EVs) and Fossil Fuel Vehicles (FFVs) considering economic savings and CO2 emissions, for parcel delivery from a single distribution center to a set of delivery point located inside and/or outside an urban area. Limitations as the daily ticket, the fuel cost, the battery duration are considered to provide 3PLs an innovative model to evaluate both the economic convenience and the environmental impact of its vehicles fleet. Through an explanatory study, economic considerations are carried out, related to the length of the route, the daily ticket cost, and the fuel cost to evaluate and to assess the different transportation options. It demonstrates that EVs are more convenient in terms of economic savings when the route (urban distances) and the daily ticket cost increase.

INDEX TERMS Electric vehicles, mixed fleet routing, economic saving, environmental saving, sustainable parcel delivery.

I. INTRODUCTION

Recently urban areas are getting more and more populated and according to the United Nations' (UN) forecasts, by 2050 more than 70% of the world's population will live in them [1]. Customers worldwide require always more home and fast deliveries; in fact, the explosive increase of the e-commerce market makes the volume of personal parcel delivery increase [2]. E-commerce for physical goods requires a significant demand for home delivery services, usually preferred by online consumers, and this contributes to the atomization of parcel delivery flow, causing particular problems in the urban areas in terms of urban freight transport [3]. Since urban population increase, the request for goods in urban areas increase too, and consequently the urban freight transport increase.

Freight transport contributes to increasing environmental and health problems. Road freight vehicles emit a greater portion of certain pollutants per kilometer traveled than other motor vehicles, with economic, environmental and social impacts [4]. As affirmed in [5] most relevant urban troubles are related to traffic congestion and urban environmental pollution. The rapid increase of demand for urban transportation has a negative impact on the environment [6]; [7] in their work refer to a recent study in EU which reports that in the 60% of European cities there are significant difficulties in terms of urban logistics management, 55% of vehicle emissions are caused by goods distribution and 40% of these goods are delivered in the city center. Moreover [8] affirms that urban freight vehicles cover about 6-18% of the total urban transport, but they are caused by 21% of CO_2 emissions.

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The European Union (EU) has announced new regulations and actions related to CO_2 emissions in the transport sector [9]. According to WEEA [10] the EU intends to decrease CO_2 emissions by 20% by 2020 and 40% by 2030. The need to reduce pollution and intensive urban freight traffic emerges as a priority for cities, through managing logistic processes more efficiently and reducing the use of high emission vehicles. Reference [11] presented a work based on the sustainability of delivery processes, taking into account environmental and social factors, for a "green logistics".

In this context, Electric Vehicles (EVs) are considered to replace standard freight vehicles in order to reduce urban environmental and health problems related to pollution. EVs present several advantages compared to Fossil-Fuel Vehicles (FFVs) as they do not have CO_2 emissions, they produce minimal noise, they can be powered from renewable energy sources and they are independent of fluctuating oil price [12], [13].

Third-Party Logistics providers 3PLs are increasing their interest in these technologies, looking to more sustainable design, planning, and execution of parcel delivery [14], [15]. In particular lots of routing, models have been implemented to study parcel delivery optimization with standard FFVs. EVs routing requires particular attention to different aspects, as the electric battery duration, the battery charge points, the vehicle speed, and the vehicle capacity. Reference [16] presents a survey about EVs and their application in freight transport; in particular, it discusses about the technological background of these vehicles (types and batteries), the market penetration (market shares, cost competitiveness, and incentives) and EVs transportation science (fleet size and mix, vehicle routing and optimal paths). From the survey, it emerges a good analysis of vehicle routing but a lack of fleet size and mix in literature. EVs' characteristics still present limitations and do not present high flexibility in assigning vehicles to deliveries routes [17]. The main challenges for EVs in urban freight transport are the high purchase cost, the long recharging time, the low capacity and the limited driving range [18]. On one hand, EVs are a solution for reducing urban pollution, but they need to be attractive for third-party logistics providers. Aiming to increase the use of EVs for urban freight transport, many national and local policies have been carried out, as fiscal incentives for encouraging their acquisition and limitations to the city center for internal combustion engine vehicles [19]. Three principal types of incentives are considered in [18]:

1. Purchase incentives on EVs: Direct incentives are given to reduce EVs price and increase their selling.
2. Zone fee: limited access to urban centers, defined as low-emission zones or congestion zones, where the entry for high-emission or heavy vehicles is restricted. Moreover, these zones are regulated by a daily ticket for these vehicles to reduce emissions and congestions.
3. Vehicle taxes reduction for EVs: Annual circulation taxes for these vehicles are lower than normal ones.

These initiatives are made to incentive the use of EVs for urban freight transport carry out from logistics companies and to reduce urban traffic in dedicated zones. In fact, in this way, two principal goals are achieved. On one hand, companies, looking to minimize total logistics costs, are motivated to adapt their vehicle fleet and routing plans. On the other hand, the increase in EVs use will reduce CO_2 emissions and air pollution.

Several studies about EVs routing have been carried out, focusing on criticalities as charge point locations, battery duration, and vehicle capacity, as discussed in the literature review section; some works refer also to routing problems with mixed vehicles fleets. However, a few consider the adoption of a mixed vehicle fleet and the presence of different economic incentives for EVs use (zone fee, vehicle taxes, etc.).

In this paper the parcel delivery problem is considered, focusing on the transportation of small items (e.g. packages) from a central distribution center located outside the city center to a set of delivery points located inside and/or outside it, using a mixed fleet of FFVs and EVs. Both economic aspects and incentives and sustainable aspects are considered in the routing model. The new SPD model can quantify, for the considered case study, whenever it is convenient to use EVs instead of conventional vehicles both by an economic and environmental point of view, quantifying saving parameters about the two aspects. The model calculates the distances traveled in urban and extra-urban areas and it considers the same incentives applied in [18] to reduce freight transport in urban areas, with a particular focus on the second one, that is the zone fee for urban access. This policy is already adopted by different municipalities in Europe, like Milan and London, which charge the commercial vehicle with 5.00 € and 11.50 £ per day, respectively. Different values of daily ticket cost, fuel cost and incentives (in terms of purchase EVs and vehicle taxes reduction) can be considered based on the country and the city of the route; for these reasons, these values are considered as input data in the model.

The model here presented will be useful for 3PLs to assign appropriate vehicles based on the route length, the daily ticket cost and the number of urban and extra-urban customers; it is inspired by [20] work, that presents a groupage transportation cost model that aims to estimate the cost-to-serve in routing problems. It considers a mixed fleet composed by EVs and FFVs, as defined in [18], in which 3PLs can assign to one route just one typology of vehicle. 3PLs providers offer outsourced logistics services, and often they have to respond and organize transportations in few times (24 hours), by estimating costs at minimum error [21]. Knowing the route (that is an input data in our model) and the other input parameters as fuel cost and daily ticket cost, they can easily evaluate the convenience of using EVs or FFVs.

The paper is divided into seven sections. Section 2 presents the literature review about parcel delivery problems and EVs; in section 3 the problem description is presented. Section 4 presents the SPD model while section 5 is dedicated to the analysis and discussion of it. Section 6 presents the application of the model to a real case study. Finally, managerial implications and further researches are presented in section 7.

II. LITERATURE REVIEW

In this section, we present relevant works about parcel delivery problems in the context of urban freight transport using EVs.

First of all, it is needed to define the aim of a sustainable transport strategy that is to answer, as far as possible, how society intends to provide the means of opportunity to meet economic, environmental and social needs efficiently and equitably, while minimizing avoidable or unnecessary adverse impacts and their associated costs, over relevant space and time scales [22]. Freight transport is essential to the modern economy, but to preserve future environment actions are required. Reference [4] in their work individuated two typologies of groups that might change the urban freight system: (i) changes implemented by governing bodies, i.e. policies and measures that force companies to change their actions and become more environmentally and socially efficient; (ii) and company-driven changes, i.e. companies that implement measures that will reduce the impact of their freight operations because they will achieve some internal benefit from this. The most used action against the increase of urban traffic is the *time-window strategy*, which is a time-access regulation to the city center to improve social sustainability issues [23]. Another action taken by governments is the *daily ticket strategy*, that regulates the access to city centers with a fee that discourages the entrance. EVs are not involved in these strategies since they do not produce CO_2 emissions either noise.

EVs have been deeply studied as a solution for sustainable freight transport from the 3PLs point of view. Reference [24] studied the use of electric commercial vehicles and provided a critique of their key technical specifications, identifying the main operating conditions that influence their effectiveness. Reference [25] presented a project to develop a not commercial vehicle in which the challenge was to reach the lowest ratio between the total weight and load capacity (in particular euro-pallet places). Reference [26] presented a study about the use of electric fleets for urban logistics, considering various typology of EVs used in Europe. Finally [27] focused on the potential CO_2 reduction by transferring urban freight from diesel to electric vehicles, considering two main constraints as electric vehicle range and the impact on congestion linked to change diesel heavy-duty vehicles to much smaller electric vehicles.

Despite its increasing importance, few works are focused on parcel delivery problems with a mixed fleet, composed of traditional and eclectic vehicles. The Vehicle Routing Problem (VPR) is an NP-hard optimization problem that aims to determine a set of delivery routes from a depot to a set of customers at the minimum costs, subject to side constraints [28]. Usually, the primary objective is to minimize the total number of vehicles used and then to minimize the total distance traveled [29]. The Electric Vehicles Routing Problem (E-VRP) aims to design EV routes to serve a set of customers by taking into account constraints as the vehicle load capacity, customer time windows, the driving range, the working hours, etc. Reference [30] presented an interesting survey about the different E-VRP objective functions, as the minimization of total costs, or the traveled distance, or the energy consumption, etc.

First works considered general recharging vehicles or alternative fuel vehicles fleets, and aims to minimize the total number of vehicles and to minimize the total traveling costs [31] or total traveled distance [32] or only to minimize total costs, i.e. fixed costs, time and emissions [33]. Recently works also propose approaches that simultaneously minimize the aggregate operating costs and reduce carbon dioxide emission [34], [35].

First E-VRPs that considered homogeneous fleets of EVs aim to reduce the energy consumption of vehicles [36]–[38]; [39], [40] instead, considered as first the minimization of the total number of vehicles and the minimization of the traveled distance. Reference [41] presented a similar E-VRP model, but in addition they consider also the recharging and waiting time minimization. Reference [42] proposed as objective function the minimization of total traveling costs, considering routing and planning costs, while [43] introduced a multi-objective function that minimizes the battery charging and power loss costs and the network capacity releasing.

All previews works consider homogeneous fleets, composed of EVs or alternative fuel vehicles. Reference [44] proposed instead a model for VRP that considers a mixed fleet of FFVs and EVs, aiming to minimize the total traveled distance. Other works instead, considers as a primary objective the minimization of the total number of vehicles, in relation to other objectives as the minimization of traveling and charging costs [45], the minimization of traveling costs [46] or traveled distance, fuel costs and battery replacement costs [47]. Finally [48] proposed in their work a multi-objective function considering recharging, routing and activation costs.

According to the literature review explained before, there is a lack of studies providing E-VRP models with mixed fleets that evaluate both economic and environmental benefits able to consider the following four factors at the same time:

1. the presence of a mixed fleet of vehicles for last-mile delivery (as EVs and traditional ones)
2. a set of different governmental incentives
3. the presence of freight transportation limitations in urban areas due to sustainability-oriented strategies.
4. the manufacturing of EVs is much more pollutant than FFVs one due to the lithium battery emissions generated during its fabrication and during its disposal.

In [18], the authors present a framework that considers three government incentives as the zone fee, the purchase incentive, and the annual taxes reduction; considering these factors it is implemented an economic framework to evaluate the convenience of an eclectic vehicles fleet considering three different scenarios (one for each incentive).

Our work, instead, aims to fill up this gap by considering all the incentives together in the same scenario, by carrying out an original model based on a mixed fleet of FFVs and EVs that aims to carry out when EVs are convenient both economically and environmentally (as both costs and CO_2 emissions are calculated to define the parcel delivery configuration). For doing this the model is applied to a real case study.

III. PROBLEM DESCRIPTION

A. PROBLEM SETTINGS AND ASSUMPTIONS

The parcel delivery problem considered in this research deals with the transportation of small items (e.g. packages) from a central distribution center located outside the city center to a set of delivery points located inside and/or outside the urban area (Figure 1). 3PLs that work with mixed fleets (i.e. FFVs and EVs) need to decide whether to use an EV or an FFV for a determinate route. FFVs have more autonomy in terms of distance traveled, but fuel costs are higher; moreover they are limited in the city centers by the time windows and the daily ticket costs. On the other hand EVs have free access to city centers, without any time restrictions or fees, but are less autonomous in terms of distance traveled and more expensive (considering both purchase costs and maintenance costs).

The route is an input parameter of the problem, as a preliminary vehicle routing defines which delivery points have to be visited by the vehicle starting from the distribution center and in which order.

B. PURPOSE OF THE MODEL

This study aims to propose an evaluative model for the Sustainable Parcel Delivery (SPD) to quantitatively assess which conditions make EVs economically and environmentally more convenient than FFVs. Giving a certain route, it calculates the routing costs and the CO2 emissions of the two alternatives. It considers purchase and maintenance costs, fuel costs, operator costs and fixed costs as the daily ticket, all based on vehicle performances. In this way, the 3PLS is in the condition of assign a certain typology of the vehicle to a defined route.

IV. SPD MODEL

The SPD model aims to carry out costs and CO_2 emissions for a certain route that starts and ends from a distribution center, to serve a set of customers, passing through urban and extra-urban areas; the model compares the same route with FFVs and EVs.

To define the cost of a determinate route r the model considers four costs as (i) the fixed annual costs (purchase yearly amortization, maintenance yearly costs, and battery costs, for EVs only), (ii) the fuel consumption costs (gasoline or kWh depending on the vehicle), (iii) the operator costs and (iv) the daily ticket cost (only for FFVs). The total delivery cost for one route r can be defined as:

$$C_{rh}^{delivery} = C_{rh}^{fix} + C_{rh}^{fuel} + C_{rh}^{oper} + C_{rh}^{tick} \ [€] \tag{1}$$

where for h = 1 it is considered an FFV and for h = 2 an EV. The annual fixed cost is calculated as:

$$C_{rh}^{fix} = \left(C_h^{purch} + Z_h^{elect} C^{batt} + C_h^{main}\right)/m \ [€] \tag{2}$$

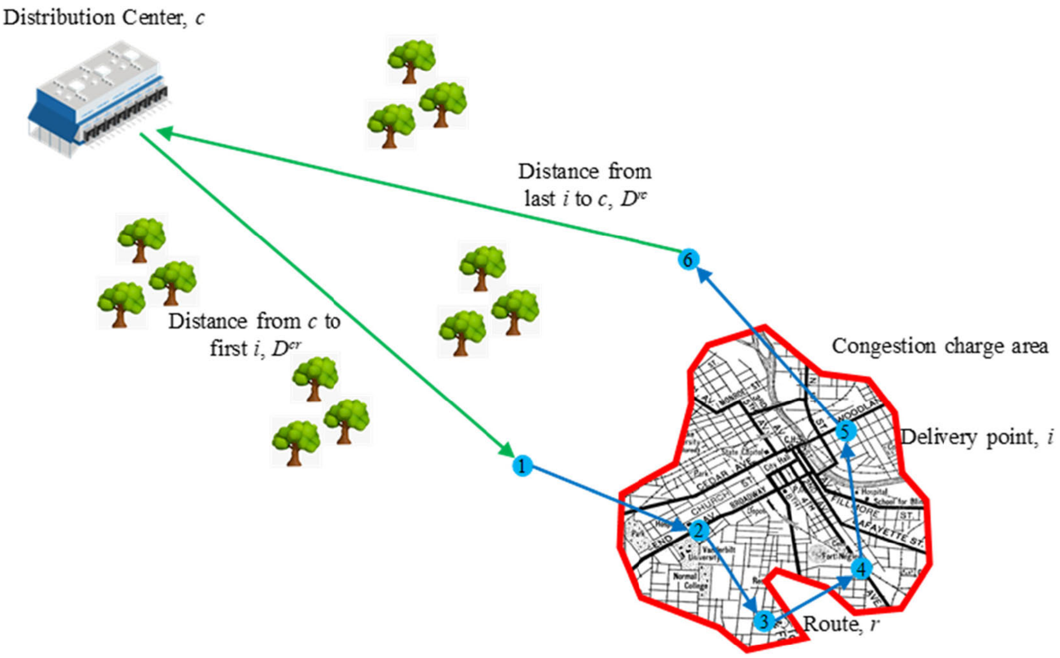

FIGURE 1. Schema of the sustainable parcel delivery problem under analysis.

where vehicle and battery, as well as the maintenance cost per route, depends on the total number of routes m traveled by the vehicle during a working year.

The fuel consumption costs for route r is defined as:

$$C_{rh}^{fuel} = (D_r^{exurb} F_h^{exurb} + D_r^{urb} F_h^{urb}) C_h^{fuel} \; [€] \tag{3}$$

where:

$$D_r^{exurb} = X^c \left(D^{cr} + D^{rc}\right) + X^r r \; [\text{km}] \tag{4}$$

$$D_r^{urb} = \left(1 - X^c\right) \left(D^{cr} + D^{rc}\right) + \left(1 - X^r\right) r \; [\text{km}] \tag{5}$$

The extra-urban D_r^{exurb} and urban D_r^{urb} covered the distance to connect the distribution center to the route and to travel within the route are separately evaluated to assess the vehicle fuel consumption considering its performance inside and outside the city center. Then it is defined as the operator cost for route r as:

$$C_{rh}^{oper} = \left[\frac{D_r^{exurb}}{S^{exurb}} + \frac{D_r^{urb}}{S^{urb}} + T^{load} + T^{unload}\right] C^{oper} \; [€] \tag{6}$$

where $\mathrm{T}^{\mathrm{load}}$ and $\mathrm{T}^{\mathrm{unload}}$ are evaluated with the functions:

$$f\left[\underset{i}{\mathrm{avg}}(J_i), \underset{ji}{\mathrm{avg}}(V_{ji}), \underset{ji}{\mathrm{avg}}(W_{ji})\right] [\text{h}]$$

Finally, the daily ticket cost for route r is defined as:

$$C_{rh}^{tick} = \left(1 - Z_h^{elect}\right) Y^{cong} C^{tick} \; [€] \tag{7}$$

where it is defined:

$$Z_h^{elect} = \begin{cases} 1, & \text{if vehicle } h \text{ is electric} \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

$$Y^{cong} = \begin{cases} 1, & \text{if at least 1 customer is} \\ & \text{inside the urban center} \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

Table 1 reports the parameters and notations used.

Once Equation (1) is defined for both FFV and EV solution, it is possible to calculate the saving as:

$$C_r^{sav} = \frac{C_{r,gasol}^{delivery} - C_{r,electr}^{delivery}}{C_{r,gasol}^{delivery}} [\%] \tag{10}$$

This index (10) evaluates the relative economic saving achievable by the EV compared to the traditional FFV to perform the same parcel delivery route distinguished by identical features. Since the operator cost is equal for both vehicles and it is not related to environmental savigs (as the others), it is not considered in the C_r^{sav} calculation. Anyway, it is important to determinate the real route cost.

Similarly, it is possible to evaluate the parcel delivery environmental impact for any route r of interest distinguished by the aforementioned features in terms of greenhouse gas emitted (kg CO_2 eq.) to serve all the delivery points belonging to the route. To evaluate this parameter the model considers not only the emissions related to the route but also the ones related to the manufacturing of the vehicles. The total delivery emissions for one route r can be defined as:

$$E_{rh}^{delivery} = E_{rh}^{manuf} + E_{rh}^{fuel} [\text{kg CO}_2\text{eq}] \tag{11}$$

The emissions for vehicles' manufacturing is defined as:

$$E_{rh}^{manuf} = \left(E_h^{purch} + Z_h^{elect} E^{batt} + E_h^{main}\right) / m \tag{12}$$

where the vehicle and battery manufacturing emissions as well as the maintenance environmental impact per route depend on the total number of routes m traveled by the vehicle during a working year. The emissions related to fuel consumption, instead, are defined as:

$$E_{rh}^{fuel} = (D_r^{exurb} F_h^{exurb} + D_r^{urb} F_h^{urb}) E_h^{fuel} \tag{13}$$

where the extra-urban D_r^{exurb} and urban D_r^{urb} covered the distance to connect the distribution center to the route and to travel within the route are separately evaluated to assess the vehicle pollutions considering its environmental performance inside and outside the city center. Finally, the relative environmental saving achievable by the EV compared to the traditional FFV to perform the same parcel delivery route distinguished by identical features is assessed through (14).

$$E_r^{sav} = \frac{E_{r,gasol}^{delivery} - E_{r,electr}^{delivery}}{E_{r,gasol}^{delivery}} [\%] \tag{14}$$

A. PARCEL DELIVERY MODEL CONSTRAINTS

The model is developed considering the following four constraints:

1) The vehicle is driven by one operator which also performs the loading activities at the distribution center and the packages drop-off at the delivery points which belong to the route.
2) The FFVs and EVs are comparable in terms of technical performances, e.g. distinguished by identical values for the following parameters: $\mathrm{S}^{\mathrm{urb}}$, $\mathrm{S}^{\mathrm{exurb}}$, $\mathrm{T}^{\mathrm{load}}$, $\mathrm{T}^{\mathrm{unload}}$, $\mathrm{C_V}$, $\mathrm{C_W}$.
3) The vehicle load capacity in volume and weight is compatible to carry all the parcels to be transported to every delivery point belonging to the route, e.g. fulfilling both the following constraints:

$$\sum_{i=1}^{n} \sum_{j=1}^{J_i} V_{ji} \mathrm{Cv}$$

$$\sum_{i=1}^{n} \sum_{j=1}^{J_i} W_{ji} \leq Cw$$

4) The distance to connect the distribution center to the route and to travel within the route has to be compatible with the battery/tank capacity of the vehicle, e.g. the vehicle can complete the entire route and to deliver all the assigned parcels without any required refueling.
5) The route is an input data for the model. Many exact algorithms and heuristics are reported in [28].

TABLE 1. Parameters and variables used in the model.

Variables & parameters	Description	Unit
r	route total length, e.g. distance from the first to the last delivery point that belongs to the route	km
n	number of delivery points belonging to the route	-
m	number of route performed in a working year	-
D^{cr}	distance from the distribution center to the first delivery point of the route r	km
D^{rc}	distance from the last delivery point of the route to the distribution center of route r	km
X^{c}	percentage of the distance between the distribution center and the route (and viceversa) to be traveled using extra-urban roads of the considered route r	%
$1- X^{c}$	percentage of the distance between the distribution center and the route (and viceversa) to be traveled using urban roads of the considered route r	%
X^{r}	percentage of the route length to be traveled using extra-urban roads of the considered route r	%
$1- X^{r}$	percentage of the route length to be traveled using urban roads of the considered route r	%
i	1,…,n delivery points	-
j	$1, \dots, J_i$ parcels to be delivered	-
V_{ji}	parcel volume	dm^3
W_{ji}	parcel weight	kg
S^{urb}	vehicle average speed in urban roads	Km/h
S^{exurb}	vehicle average speed in extra-urban roads	Km/h
T^{load}	vehicle loading time	h
T^{unload}	vehicle unloading time	h
C_V	vehicle load capacity, as volume	dm^3
C_w	vehicle load capacity, as weight	kg
h	h= 1 for FFV and h=2 for EV	-
F_h^{urb}	vehicle h gasoline/electricity consumption in urban roads	l/km or kWh /km
F_h^{exurb}	vehicle h gasoline /electricity consumption in extra-urban roads	l/km or kWh /km
C_h^{purch}	vehicle h yearly amortization based on the vehicle rental or purchase cost, expected lifetime and yearly covered mileage	€/year
C^{batt}	battery yearly amortization based on the battery rental or purchase cost, expected lifetime and yearly covered mileage, for the electric vehicle only	€/year
C_h^{main}	vehicle h yearly maintenance cost, battery excluded	€/year
C^{oper}	operator hourly cost, considering the different activities he has to perform, e.g. driving, van loading, parcel drop off, etc.	€/h
C_h^{fuel}	vehicle h gasoline/electricity cost. It is strongly affected by the country considered	€/km or €/ kWh
C^{tick}	daily ticket cost to enter with the vehicle in the congestion charge area, to be paid by the non-electric vehicle only	€
E_h^{purch}	vehicle h yearly greenhouse gas emissions based on the environmental impact of the vehicle manufacturing and disposal, its expected lifetime as well as yearly covered mileage	kg CO_2 eq/year
E^{batt}	battery yearly greenhouse gas emissions based on the environmental impact of the battery manufacturing and disposal, its expected lifetime as well as yearly covered mileage, for the electric vehicle only	kg CO_2 eq/year
E_h^{main}	vehicle h maintenance environmental impact determined by the greenhouse gas emitted to manufacture the components for its maintenance, battery excluded	kg CO_2 eq/year
E_h^{fuel}	vehicle h gasoline/electricity emissions. It is strongly affected by the country considered	kg CO_2 eq/l or kg CO_2 eq/kWh

TABLE 2. Technical, economic and environmental input data for the considered case study.

Variable	Value	Unit
r	[5;10]	km
n	22	-
m	264	-
D^{cr}	[2,5;60]	km
D^{rc}	[2,5;60]	km
X^{c}	100%	%
$1- X^{c}$	0%	%
X^{r}	0%	%
$1- X^{r}$	100%	%
i	22	-
j	1	-
$\sum Vji$	4	m^3
$\sum Wji$	500	kg
S^{urb}	30	Km/h
S^{exurb}	60	Km/h
T^{load}	15	min
T^{unload}	2.5*i*j	min/parcel
C_V	4.5	m^3
C_w	600	kg
F_1^{urb}	0.052	l/km
F_2^{urb}	0.183	kWh /km
F_1^{exurb}	0.044	l/km
F_2^{exurb}	0.236	kWh /km
C_1^{purch}	3,382	€/year
C_2^{purch}	4,094	€/year

C^{batt}	1,827	€/year
C_1^{main}	101	€/year
C_2^{main}	122	€/year
C^{oper}	20	€/h
C_1^{fuel}	1.62	€/km
C_2^{fuel}	0.21	€/ kWh
C^{tick}	[0;10]	€
E_1^{purch}	288.9	kg CO_2 eq/year
E_2^{purch}	297.5	kg CO_2 eq/year
E^{batt}	79.2	kg CO_2 eq/year
E_1^{main}	8.66	kg CO_2 eq/year
E_2^{main}	8.92	kg CO_2 eq/year
E_1^{fuel}	2.78	kg CO_2 eq/l
E_2^{fuel}	0.61	kg CO_2 eq/kWh
Expected economic lifetime [49]	5	years
Purchase cost FFV [49]	20,900	€
Purchase cost EV [49]	25,300	€
Residual value at the end of the lifetime [49]	30%	%
The opportunity cost of capital [49]	3%	%
Expected environmental lifetime [49]	10	years
Vehicle manufacturing emissions FFV [49]	2,889	kg CO_2 eq
Vehicle manufacturing emissions EV [49]	2,975	kg CO_2 eq
Battery manufacturing emissions [49]	792	kg CO_2 eq

V. ANALYSIS OF THE MODEL AND DISCUSSION

A. INPUT DATA FOR THE ANALYSIS

A detailed analysis is performed to determine whose characteristics of the parcel delivery problem make the considered EVs comparable to the traditional FFVs both from an economic and an environmental perspective, e.g. C_r^{sav} and E_r^{sav} equal to zero, respectively. To perform this analysis, $C_{rh}^{delivery}$ and $E_{rh}^{delivery}$ equations are evaluated varying the value of the most relevant parameters of the parcel delivery model, namely:

1) $r \in [5; 100]$ (km)
2) $(Dcr + Drc) \in [5; 120]$ (km)
3) $C^{tick} \in [0; 10]$ (€)

The analysis is based on real data taken from a case study and standard practice. Table 2 summarize data used to construct and to analyze the model. It is considered a standard commercial vehicle for medium distance parcel delivery manufactured with two fuelling options, namely traditional Fossil Fuel vehicle (FFV) and Electric Vehicle (EV) equipped with an adequate battery for electricity storage. Thus, these vehicles are identical for every technical feature, fuelling excluded. The vehicle technical, economic and environmental performances are presented in Table 2. The vehicles considered in the analysis have the same model, i.e. Renault Kangoo Express Maxi, with Gasoline engine dCi 110 EDC for the FFV and full electric engine 5 AQ 44 kW for the EV. The geographical location where the delivery is executed is of major importance since it determines the gasoline and electricity cost as well as environmental emissions (defined by the energy source mix leveraged to produce electricity in that country); for the analysis we consider Italy as country where is performed the route, to evaluate fuel costs and emissions. The presented input data propose a situation where 2 routes performed per day by a vehicle operating 22 days per month to ensure just one charge of battery during night hours and full operations during the entire day duration, e.g. no charge required during parcel delivery. The deliveries are performed entering the congestion charge area through a path distinguished by only extra-urban roads between the distribution center and the route (and vice versa) and just urban roads for the route. Concerning the vehicle economic performances, the expected economic life of both the vehicles is considered equal to 5 years, with a residual value equal to 30% of the purchasing cost, whereas the maintenance yearly cost is equal to 3% of the initial investment. Focusing on the vehicle environmental performances, the input data represents the greenhouse gas emissions measured in $kgCO_2eq$ generated by the manufacturing, operations and disposal phases of the vehicle lifecycle.

Furthermore, it is of major importance to underline that for the proposed dataset and under the current assumptions, FFVs are less pollutant than EVs for extra-urban traveling. However, this feature is significantly affected by the country considered, since it mostly depends on the energy source mix leveraged to produce electricity. Finally, a further feature of the considered case study which is relevant to be mentioned is that under the current assumptions EVs use considerably more electric power per km traveled for extra-urban paths than in urban settings.

B. DISCUSSION AND IMPLICATIONS

This section presents and discusses the results obtained leveraging the developed SPD model for the input data of the analysis. In particular, $C_{rh}^{delivery}$ and $E_{rh}^{delivery}$ have been determined for different scenarios of the performed parcel delivery. Different combinations of the route total length r, the distance from and to the distribution center and the route (Dcr + Drc) as well as the daily ticket cost to enter into the congestion charge area $\boldsymbol{C^{tick}}$ have been tested to assess under which circumstances and to which extent the EV outperforms the FFV one, both from an economic and environmental perspective, respectively $\boldsymbol{C_r^{sav}} > \mathbf{0}$ and $\boldsymbol{E_r^{sav}} > \mathbf{0}$.

Concerning the economic perspective, Figure 2 presents the relative economic saving of EV adoption compared to FFV one $\boldsymbol{C_r^{sav}}$ evaluated for multiple delivery scenarios varying the route length r between 5 and 100 km and the distance from and to the distribution center and the route $(D^{cr} + D^{rc})$ between 5 and 120 km. Focusing the analysis on Italy, the price of the congestion charge ticket $\boldsymbol{C^{tick}}$ is considered equal to 5 €, as a reference value for multiple and relevant Italian urban areas, e.g. Milan. As proposed by Figure 2a, for every delivery configuration, e.g. all the combinations of r and $(D^{cr} + D^{rc})$, the EV is more convenient than the FFV with an economic saving which ranges from a minimum of 5% to a maximum of 25%. Considering Figure 2b, the slope of $\boldsymbol{C_r^{sav}}$ is not constant. The increment of $\boldsymbol{C_r^{sav}}$ is greater increasing the distance traveled during the routing (r) than the one required to reach the distribution center $(D^{cr} + D^{rc})$. Indeed, the economic saving of the EV adoption is much greater if the prominent portion of the total distance is traveled using the urban road. Indeed, in these circumstances, the kilometric cost of an EV is significantly lower than the one of the FFV (e.g. urban travel cost 0.037 €/km electric – 0.083 €/km gasoline vehicles; extra-urban travel cost 0.047 €/km electric – 0.071 €/km gasoline vehicles).

C^{tick} equals to 5 € considered in the former analysis results in an EV economic convenience for any delivery configuration form the traveled distance perspective. Thus, a former investigation is performed to evaluate C_r^{sav} for a different level of incentive to sustainable parcel delivery, namely 0, 3 and 7 € as ticket price per day. Figure 3 presents C_r^{sav} surfaces as a function of r and $(D^{rc} + D^{cr})$ for those C^{tick} values, increasing from bottom to the top. Furthermore, the black plane identifies the boundary which makes the EV more (above the plane) or lower (under the plane) convenient compared to the FFV alternative. A very high incentive to the

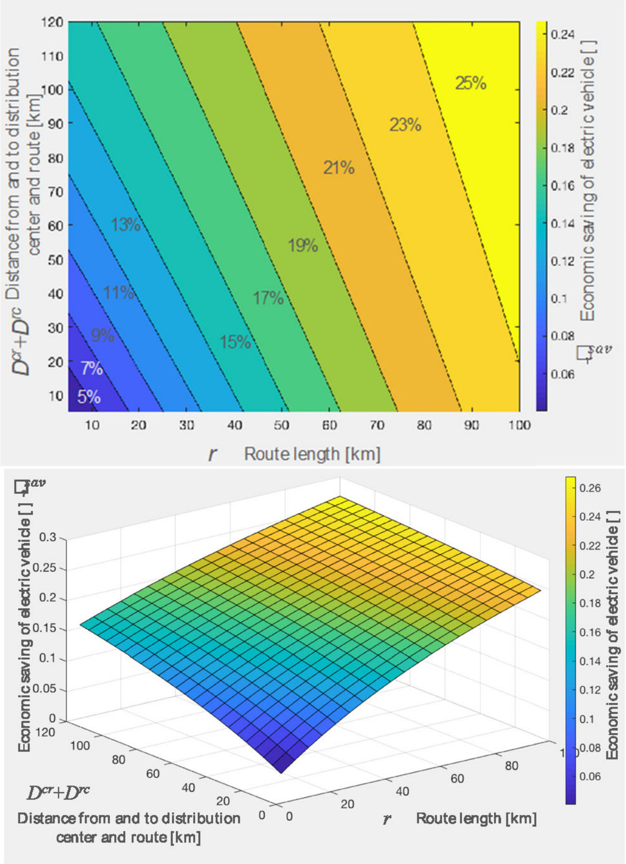

FIGURE 2. Economic saving of electric vehicle as a function of the route length and the distance from and to the distribution center and the route (evaluated for $C^{tick} = 5€$), 2D (a) and 3D (b) views.

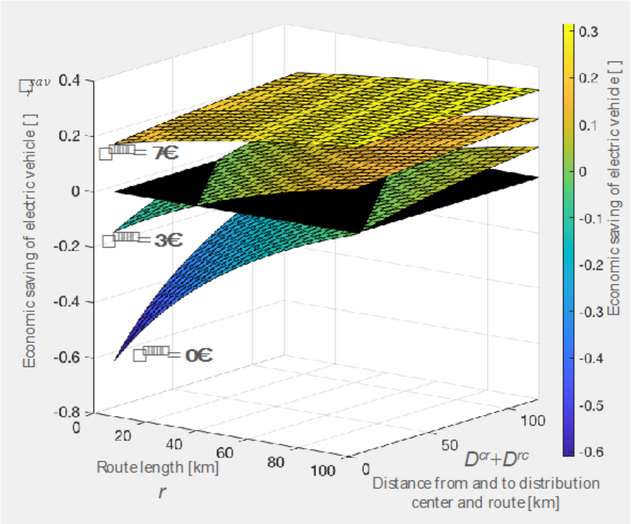

FIGURE 3. Economic saving of electric vehicle as a function of the route length and the distance from and to the distribution center and the route, evaluated for $C^{tick} = 0; 3; 7$ €(surfaces from bottom to top of the figure; black plane identifies $C_r^{sav} = 0$).

adoption of electrical vehicle $C^{tick} = 7€$ makes this delivery option much more convenient compared to more pollutant alternatives, from 17.8% to 24.6%. However, this economic saving is not affected by the traveled distance and its distribution between r and $(D^{rc} + D^{cr})$. Lowering $C^{tick} = 3€$ the EV is not convenient for short traveled distance, e.g. $r < 31\ km$ and $(D^{rc} + D^{cr}) < 47km$. Indeed, under these circumstances, the additional fixed cost required to purchase the EV and to rent its battery is not overcome by the benefit of a lower kilometric cost due to a cheaper fueling option. Finally, of major interest is the assessment of the economic feasibility of electrical parcel delivery with no incentives, e.g. $C^{tick} = 0€$. For most of the delivery configuration, the FFV is much cheaper (even to -64%). However, the electric distribution is still profitable if the total traveled distance is greater than 119 km, e.g. $(r + D^{rc} + D^{cr}) > 119km$. Furthermore, this positive trend is much higher if the portion of the total distance traveled using urban road increases (for increasing r values). Indeed, in the long run, the saving achievable by the electric vehicle due to a cheaper fuel overcome the additional initial investment due to more expensive vehicle purchase and it makes this option more convenient than the gasoline one even without any incentive.

A further relevant assessment deals with the determination of $\boldsymbol{C^{tick}}$ which makes the electrical vehicle comparable to the gasoline one in terms of the economic performance for the $\boldsymbol{C^{tick}}$ price considering the extension and shape of their congestion charge area (which determines $\boldsymbol{r}$ average value) considered parcel delivery, i.e. $\boldsymbol{C_r^{sav} = 0}$. This information could be fruitfully adopted by the policymakers to define the and the geographical distribution of the distribution center of the logistic service providers which operate in their area (which determines $\boldsymbol{\left(D^{rc} + D^{cr}\right)}$ average value).

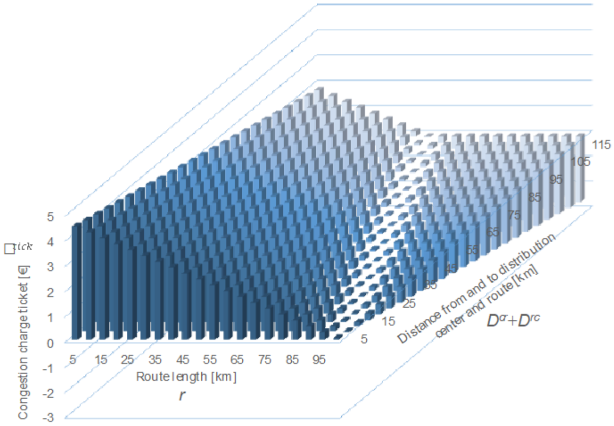

FIGURE 4. Congestion charge ticket value C^{tick} which makes the electric vehicle comparable to the gasoline-fueled one from an economic perspective $C_r^{sav} = 0$, as a function of the route length and the distance from and to the distribution center and the route.

As proposed by Figure 4, whatever the distribution configuration is, $\boldsymbol{C^{tick} = 4.68€}$ ensures the electric vehicle to be the most profitable option for the considered parcel delivery. Increasing the traveled distance, cheaper $\boldsymbol{C^{tick}}$ is enough to suggest the adoption of an EV. Ticket cost reduction is higher with $\boldsymbol{r}$ increment compared to longer $\boldsymbol{\left(D^{rc} + D^{cr}\right)}$. Thus, for those delivery configurations distinguished by longer route traveled in an urban area, the incentive value which lets electrical distribution be competitive drops with a dramatically steep slope. Finally, for a total traveled distance $\boldsymbol{\left(r + D^{rc} + D^{cr}\right)}$ greater than 120 km, $\boldsymbol{C^{tick}}$ is negative. Under these circumstances electrical delivery is more convenient than the traditional one, thus it does not requires an incentive.

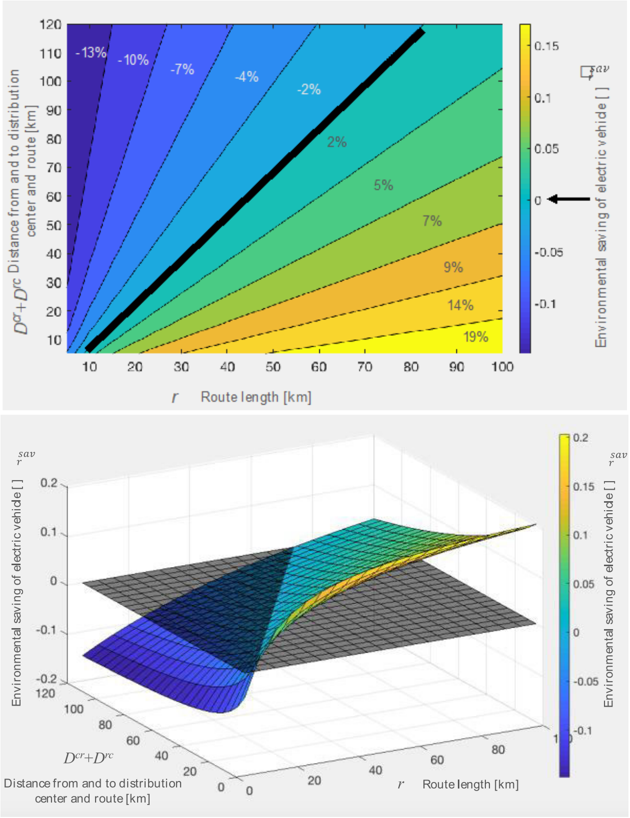

FIGURE 5. Environmental saving of electric vehicle as a function of the route length and the distance from and to the distribution center and the route, 2D (a) and 3D (b) views. Black line and plane distinguish between electric vehicle saving or loss.

To conclude the Discussion Section, it is of major importance to assess the environmental aspect of SPD. Aim of this final analysis is the evaluation of the pollution emissions saving achievable by delivering goods using EV compared to traditional one fueled by gasoline measured in terms of greenhouse gases emissions (kg $\mathbf{CO_2}$ eq.). Figure 5 presents the relative environmental saving of electric vehicle adoption $\boldsymbol{E_r^{sav}}$ evaluated for multiple delivery scenarios varying the route length r between 5 and 100 km and the distance from and to the distribution center and the route $(D^{cr} + D^{rc})$ between 5 and 120 km. The congestion charge ticket is obviously not considered in this scenario since it does not have any impact from an emission perspective. Figure 5a presents $\boldsymbol{E_r^{sav}}$ as a function of r and $(D^{cr} + D^{rc})$. The greater the portion of the delivery distance traveled using the urban road is, the greater $\boldsymbol{E_r^{sav}}$ is. Furthermore, the black line depicted on this figure enables us to quantitatively determine the equation which could be used to define if an electric vehicle is more ecological than a traditional one for parcel delivery. This electric vehicle sustainability is achieved uniquely for those deliveries whose traveled distances satisfy the following Eq. 15:

$$\left(D^{rc}+D^{cr}\right) < 1.428 * r - 4.821 \tag{15}$$

The manufacturing of EVs is much more pollutant than a traditional one due to the lithium battery emissions generated during its fabrication and during its disposal. This limit is overcome by the lower kg $\mathbf{CO_2}$ eq. emitted during the vehicle usage due to traveling activities which makes electricity a much more sustainable fuel option compared to gasoline, but only for urban transit (e.g. urban travel emissions 0.109 kg $\mathbf{CO_2}$ eq./km electric – 0.144 kg $\mathbf{CO_2}$ eq./km gasoline vehicles; extra-urban travel emissions 0.140 kg $\mathbf{CO_2}$ eq./km electric – 0.122 kg $\mathbf{CO_2}$ eq./km gasoline vehicles).

Finally, Figure 5b is of major help to further analyze this relevant pattern. $\boldsymbol{E_r^{sav}}$ the slope is not constant. On the contrary, it is much more positively affected by an increment in the urban distance traveled rather than by the identical increase of the extra-urban one, due to the afore described background. The black plane distinguishes those delivery distances, both $\left(\boldsymbol{D^{rc}}+\boldsymbol{D^{cr}}\right)$ and r, which makes electrical delivery more sustainable than traditional one from an environmental perspective.

VI. CASE STUDY

In this section, it is presented the application of the model to a real case study. The company is situated in Northern Italy and serves various cities. It is considered the parcel delivery problem to one specific city, located 15km from the distribution center. It is applied a standard route, of about 60 km, all inside the city center; to calculate this route the algorithm of Baldacci, Christofides and Mingozzi is used [50]. Moreover it is considered that a standard route has 1 parcel for customer delivery point (i.e. 22 parcels in total). Table 3 summarizes the input data for the case study.

TABLE 3. Input data for the case study.

Variable	Value	Unit
i	22	-
j	1	-
$\mathbf{D^{cr+}\ D^{rc}}$	30	km
r	60	km
$\mathbf{C^{tick}}$	5	€

Applying the SPD model, the delivery cost and the delivery emissions are calculated for both vehicles, FFV and EV. Table 4 summarizes results. Considering economical saving, it is more convenient the EV solution with 15.24 € per route (without considering the operator costs), with a saving of 19%. In particular the fixed costs are higher for the EV solution (+73.5%), but fuel costs are lower (−47%) and there is no daily ticket cost. Considering the environmental saving, it is more convenient the EV solution too, even if with a lower saving (9%). That's because the impact of EVs and battery constructions are much more incisive than FFV one.

TABLE 4. Results of the case study.

	FFV	**EV**
$\boldsymbol{C_{rh}^{delivery}}$	**18.79 €**	**15.24 €**
C_{rh}^{fix}	6.60 €	11.45 €
C_{rh}^{fuel}	7.19 €	3.79 €
C_{rh}^{oper}	(70.00 €)	(70.00 €)
C_{rh}^{tick}	5.00 €	-
$\boldsymbol{E_{rh}^{delivery}}$	**12.25 kg $\mathbf{CO_2}$ eq**	**11.04 kg $\mathbf{CO_2}$ eq**
E_{rh}^{manuf}	1.13 kg CO_2 eq	1.46 kg CO_2 eq
E_{rh}^{fuel}	11.12 kg CO_2 eq	9.577 kg CO_2 eq
$\boldsymbol{C_r^{sav}}$	**18.9%**	
$\boldsymbol{E_r^{sav}}$	**9.00%**	

VII. CONCLUSION AND MANAGERIAL IMPLICATION

The paper develops an original model called SPD model to evaluate the economic and environmental savings in a parcel delivery problem using a mixed fleet of EVs and FFVs for third-party logistics providers. The focus is on the transportation of small items (e.g. packages) from a central distribution center located outside the city center to a set of delivery point located inside and/or outside it; the access of FFVs to the city center is regulated with a congestion charge, e.g. a daily ticket which has to be paid to get a one-day travel allowance in this area. The E-VRP is not considered in this research but is taken as an input for the model, as the aim is to carry out the conditions for economic and environmental savings in using EVs for SPD problem. The model is applied to a specific case study of parcel delivery performed in Italy by a commercial vehicles with both traditional internal combustion engine as well as full electric fueling options varying three relevant parameters as the route length, the distance from and to the distribution center and the daily ticket cost. Furthermore, the model relies on different input parameters as the route, the delivery points, and the vehicle technical, economic and environmental performances. As the society aims is to reduce urban freight transport to improve social welfare, national and local policies are considered as fiscal incentives, zone fees, and vehicle taxes reduction from the 3PL providers' point of view. This work is 3PLs oriented as it aims to quantify economic and environmental savings for these subjects.

The explanatory study quantifies, for the specific case study considered, the possible economic and environmental savings using EVs in sustainable parcel delivery. Due to recent growth of importance of sustainability in the transports field, from technologies to pollution regulations, this work carries out a SPD model useful for 3PLs to evaluate and quantify the convenience of EVs also from a sustainable point of view.

The following main conclusions can be summarized:

(a) As the route length (urban roads) increases, the greater is the economic saving (in %) provided by using EVs, from 5% to 25%. Moreover, these results are stronger related to the distance from/to the Distribution center ($D^{cr} + D^{rc}$), as the economic saving of the EV adoption is much greater if the prominent portion of the total distance is traveled using urban roads. In particular if r is >70km, the economic saving in using EVs is almost the 20%, while if $(D^{cr} + D^{rc}) > 50$km the economic saving in using EVs is almost the 10%.

(b) Considering the daily ticket for urban access, as it increases the more economic saving is achieved using EVs. The explanatory study considers different daily tickets costs, quantifying the economic saving with a maximum of 24.6% in the highest case (7€/day); otherwise, in the lowest case (0€/day, i.e. no daily ticket) the FFVs results in the more convenient with a maximum saving of 64% against EVs solution. In general, the more the daily ticket is high, the more it is convenient to use the EVs. Secondly, the EVs could be not economically convenient if the daily ticket is cheap and the urban route is short. In the considered case study, the sum of all distances (r + D^{cr} + D^{rc}) should be almost 120km to make EVs more convenient without the daily ticket.

(c) Instead, considering environmental savings, results show that the greater the portion of the delivery distance traveled using the urban road is, the greater they are. Anyway, it is necessary to consider the manufacturing of EVs that is much more pollutant than a traditional one; this limit is overcome by the lower kg CO_2 eq. emitted during vehicle usage due to traveling activities which makes electricity a much more sustainable fuel option compared to gasoline, but only for urban transit. For the considered case study, if the route r is greater than 80km, there is always environmental saving using EVs; otherwise, it depends on $D^{cr} + D^{rc}$ as the greater it is, the lower are benefits.

(d) Considering the case study, it is evident the different influence that each cost and emission has on the total saving. Fixed costs, in general, are higher for EVs than FFVs; this is in accord with government policies that aim to incentive EV purchases with facilitations. The fuel costs, instead, is much lower for EVs, as expected. On the other hand, emissions for producing both vehicles are higher, but more the EV's one due to battery production; the emissions due to the route are lower for the EV, as expected. Further considerations might be carried out changing vehicles models and country, to individuate the better combination of factors affecting the two savings.

(e) Finally, the model carries out useful graphs and results to evaluate EVs utilization in the Parcel Delivery problem in urban and extra-urban areas for 3PLs. The model has been analyzed starting from data of an Italian case study, i.e. data as fuel costs, daily tickets, the standard number of working days, distance from city centers, etc. are from an Italian database. Further researches might be carried out in other different countries, to study the different effects of these input data on economic and environmental savings. Another important input data is the optimal route, carry out with a general model that aims to minimize the total traveling distance; future researches will be about the study of the effects on economical and environmental savings of different VRP and E-VPR applied to carry out the optimal route. Different routing objectives might influence (or not) the economical and environmental savings. Moreover, the influence of the external weather on EVs performance might be considers for further researches, as Italian warm climate is different from Northern countries climates, as Sweden or Norway.

REFERENCES

[1] R. A. de Mello Bandeira, G. V. Goes, D. N. S. Gonçalves, M. D. A. D'Agosto, and C. M. D. Oliveira, "Electric vehicles in the last mile of urban freight transportation: A sustainability assessment of postal deliveries in Rio de Janeiro-Brazil," *Transp. Res. D, Transp. Environ.*, vol. 67, pp. 491–502, Feb. 2019.

[2] T. G. Crainic, N. Ricciardi, and G. Storchi, "Advanced freight transportation systems for congested urban areas," *Transp. Res. C, Emerg. Technol.*, vol. 12, no. 2, pp. 119–137, Apr. 2004.

[3] E. Morganti, S. Seidel, C. Blanquart, L. Dablanc, and B. Lenz, "The impact of e-commerce on final deliveries: Alternative parcel delivery services in France and Germany," *Transp. Res. Procedia*, vol. 4, pp. 178–190, 2014.

[4] S. Anderson, J. Allen, and M. Browne, "Urban logistics—How can it meet policy makers' sustainability objectives?" *J. Transp. Geogr.*, vol. 13, no. 1, pp. 71–81, Mar. 2005.

[5] Y. Wei, C. Huang, P. Lam, Y. Sha, and Y. Feng, "Using urban-carrying capacity as a benchmark for sustainable urban development: An empirical study of Beijing," *Sustainability*, vol. 7, no. 3, pp. 3244–3268, 2015.

[6] D. Battini, I. Zennaro, R. Aldrighetti, and F. Sgarbossa, "Centralized healthcare supply networks for efficient and sustainable drug management: An Italian case study," *Int. J. Integr. Supplychain Manage.*, to be published.

[7] J. Wang, L. Chi, X. Hu, and H. Zhou, "Urban traffic congestion pricing model with the consideration of carbon emissions cost," *Sustainability*, vol. 6, no. 2, pp. 676–691, 2014.

[8] F. Russo and A. Comi, "City characteristics and urban goods movements: A way to environmental transportation system in a sustainable city," *Procedia-Social Behav. Sci.*, vol. 39, pp. 61–73, Jan. 2012.

[9] European Commission. (2009). *Effort Sharing: Member States Emission Targets*. https://ec.europa.eu/clima/policies/effort_en

[10] WEEA. (2015). *Greenhouse Gas Data—Emissions Share By Sector in EU28*. [Online]. Available: http://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer.

[11] A. Sbihi and R. W. Eglese, "Combinatorial optimization and green logistics," *Ann. Oper. Res.*, vol. 175, no. 1, pp. 159–175, Mar. 2010.

[12] B. A. Davis and M. A. Figliozzi, "A methodology to evaluate the competitiveness of electric delivery trucks," *Transp. Res. E, Logistics Transp. Rev.*, vol. 49, no. 1, pp. 8–23, Jan. 2013.

[13] M. Schiffer, S. Stütz, and G. Walther, "AreECVs breaking even?: Competitiveness of electric commercial vehicles in retail logistics," RWTH Aachen Univ., Aachen, Germany, Tech. Rep. G-2017-47, 2017.

[14] D. Battini, M. Calzavara, I. Isolan, F. Sgarbossa, and F. Zangaro, "Sustainability in material purchasing: A multi-objective economic order quantity model under carbon trading," *Sustainability*, vol. 10, no. 12, p. 4438, 2018.

[15] R. Aldrighetti, I. Zennaro, S. Finco, and D. Battini, "Healthcare supply chain simulation with disruption considerations: A case study from northern italy," *Global J. Flexible Syst. Manage.*, vol. 20, no. S1, pp. 81–102, Dec. 2019.

[16] S. Pelletier, O. Jabali, and G. Laporte, "50th anniversary invited article—Goods distribution with electric vehicles: Review and research perspectives," *Transp. Sci.*, vol. 50, no. 1, pp. 3–22, Feb. 2016.

[17] M. Lewis, C. Hearn, X. Feng, J. Hanlin, J. Levin, J. Ambrosio, P. Guggenheim, and C. Walker, "Design and modeling for hydrogen fuel cell conversion of parcel delivery trucks," in *Proc. IEEE Transp. Electrific. Conf. Expo (ITEC)*, Jun. 2017, pp. 674–678.

[18] S. M. Mirhedayatian and S. Yan, "A framework to evaluate policy options for supporting electric vehicles in urban freight transport," *Transp. Res. D, Transp. Environ.*, vol. 58, pp. 22–38, Jan. 2018.

[19] T. T. Taefi, J. Kreutzfeldt, T. Held, and A. Fink, "Supporting the adoption of electric vehicles in urban road freight transport—A multi-criteria analysis of policy measures in Germany," *Transp. Res. A, Policy Pract.*, vol. 91, pp. 61–79, Sep. 2016.

[20] A. Azzi, D. Battini, and A. Persona, "Groupage transportation cost model," in *Proc. POMS 23rd Annu. Conf.*, Chicago, IL, USA, Apr. 2011, pp. 1–11.

[21] F. Sgarbossa, I. Zennaro, E. Florian, and A. Persona, "Impacts of weibull parameters estimation on preventive maintenance cost," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 508–513, 2018.

[22] *Defining a Sustainable Transport Sector*, UK Round Table Sustain. Develop., London, U.K., 1996.

[23] H. J. Quak and M. B. M. de Koster, "Urban distribution: The impacts of different governmental time-window schemes," Erasmus Res. Inst. Manage., Rotterdam, The Netherlands, ERIM Report ERS-2006-053-LIS, 2006.

[24] D. Margaritis, A. Anagnostopoulou, A. Tromaras, and M. Boile, "Electric commercial vehicles: Practical perspectives and future research directions," *Res. Transp. Bus. Manage.*, vol. 18, pp. 4–10, Mar. 2016.

[25] L. Andaloro, G. Napoli, F. Sergi, S. Micari, G. Agnello, and V. Antonucci, "Development of a new concept electric vehicle for last mile transportations," *World Electr. Vehicle J.*, vol. 7, no. 3, pp. 342–348, 2015.

[26] M. Foltyński, "Electric fleets in urban logistics," *Procedia-Social Behav. Sci.*, vol. 151, pp. 48–59, Oct. 2014.

[27] C. Rizet, C. Cruz, and M. Vromant, "The constraints of vehicle range and congestion for the use of electric vehicles for urban freight in France," *Transp. Res. Procedia*, vol. 12, pp. 500–507, Jan. 2016.

[28] G. Laporte, "Fifty years of vehicle routing," *Transp. Sci.*, vol. 43, no. 4, pp. 408–416, Nov. 2009.

[29] O. Bräysy and M. Gendreau, "Vehicle routing problem with time windows, part I: Route construction and local search algorithms," *Transp. Sci.*, vol. 39, no. 1, pp. 104–118, Feb. 2005.

[30] T. Erdelić and T. Carić, "A survey on the electric vehicle routing problem: Variants and solution approaches," *J. Adv. Transp.*, vol. 2019, pp. 1–48, May 2019.

[31] R. G. Conrad and M. Figliozzi, "The recharging vehicle routing problem," in *Proc. 61st Annu. Conf. Expoof Inst. Ind. Eng.*, May 2011, pp. 1–8.

[32] S. Erdoğan and E. Miller-Hooks, "A green vehicle routing problem," *Transp. Res. E, Logistics Transp. Rev.*, vol. 48, no. 1, pp. 100–114, 2012.

[33] A. Omidvar and R. Tavakkoli-Moghaddam, "Sustainable vehicle routing: Strategies for congestion management and refueling scheduling," in *Proc. IEEE Int. Energy Conf. (ENERGYCON)*, Florence, Italy, Sep. 2012, pp. 1089–1094.

[34] Y. Wang, X. Ma, Z. Li, Y. Liu, M. Xu, and Y. Wang, "Profit distribution in collaborative multiple centers vehicle routing problem," *J. Cleaner Prod.*, vol. 144, pp. 203–219, Feb. 2017.

[35] Y. Wang, S. Zhang, K. Assogba, J. Fan, M. Xu, and Y. Wang, "Economic and environmental evaluations in the two-echelon collaborative multiple centers vehicle routing optimization," *J. Cleaner Prod.*, vol. 197, pp. 443–461, Oct. 2018.

[36] J. Barco, A. Guerra, L. Muñoz, and N. Quijano, "Optimal routing and scheduling of charge for electric vehicles: A case study," *CoRR*, vol. 2017, pp. 1–16, Nov. 2013. [Online]. Available: https://arxiv.org/abs/1310.0145

[37] H. Preis, S. Frank, and K. Nachtigall, "Energy-optimized routing of electric vehicles in urban delivery systems," in *Operations Research Proceedings*, S. Helber, M. Breitner, and D. Rösch, Eds. Cham, Switzerland: Springer, 2014, pp. 583–588.

[38] S. Zhang, Y. Gajpal, S. S. Appadoo, and M. M. S. Abdulkader, "Electric vehicle routing problem with recharging stations for minimizing energy consumption," *Int. J. Prod. Econ.*, vol. 203, pp. 404–413, Sep. 2018.

[39] M. Schneider, A. Stenger, and D. Goeke, "The electric vehicle-routing problem with time windows and recharging stations," *Transp. Sci.*, vol. 48, no. 4, pp. 500–520, Nov. 2014.

[40] M. Keskin and B. Çatay, "Partial recharge strategies for the electric vehicle routing problem with time windows," *Transp. Res. C, Emerg. Technol.*, vol. 65, pp. 111–127, Apr. 2016.

[41] M. Bruglieri, F. Pezzella, O. Pisacane, and S. Suraci, "A matheuristic for the electric vehicle routing problem with time windows," 2015, *arXiv:1506.00211*. [Online]. Available: http://arxiv.org/abs/1506.00211

[42] M. Schiffer, S. Stütz, and G. Walther, "Are ECVs breaking even?—Competitiveness of electric commercial vehicles in mediumduty logistics networks," RWTH Aachen Univ., Aachen, Germany, Work. Paper OM-02/2016, 2016.

[43] S. S. Amiri, S. Jadid, and H. Saboori, "Multi-objective optimum charging management of electric vehicles through battery swapping stations," *Energy*, vol. 165, pp. 549–562, Dec. 2018.

[44] F. Gonçalves, S. R. Cardoso, S. Relvas, and A. P. F. D. Barbosa-Póvoa, "Optimization of a distribution network using electric vehicles: A VRP problem," in *Proc. Congresso Associação Portuguesa Investigação Operacional (IO)*, Coimbra, Portugal, Apr. 2011, pp. 18–20.

[45] O. Sassi, W. R. Cherif, and A. Oulamara, "Vehicle routing problem with mixed fleet of conventional and heterogenous electric vehicles and time dependent charging costs," Tech. Rep. hal-01083966, 2014. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01083966

[46] G. Hiermann, J. Puchinger, S. Ropke, and R. F. Hartl, "The electric fleet size and mix vehicle routing problem with time windows and recharging stations," *Eur. J. Oper. Res.*, vol. 252, no. 3, pp. 995–1018, Aug. 2016.

[47] D. Goeke and M. Schneider, "Routing a mixed fleet of electric and conventional vehicles," *Eur. J. Oper. Res.*, vol. 245, no. 1, pp. 81–99, Aug. 2015.

[48] G. Macrina, L. Di Puglia Pugliese, F. Guerriero, and G. Laporte, "The green mixed fleet vehicle routing problem with partial battery recharging and time windows," *Comput. Oper. Res.*, vol. 101, pp. 183–199, Jan. 2019.

[49] R. Hischier, B. Weidema, H.-J. Althaus, C. Bauer, G. Doka, R. Dones, R. Frischknecht, S. Hellweg, S. Humbert, N. Jungbluth, T. Köllner, Y. Loerincik, M. Margni, and T. Nemecek, "Implementation of life cycle impact assessment methods, v2.2," Swiss Centre Life Cycle Inventories, Dübendorf, Switzerland, Final Rep. Ecoinvent 3, 2010.

[50] R. Baldacci, N. Christofides, and A. Mingozzi, "An exact algorithm for the vehicle routing problem based on the set partitioning formulation with additional cuts," *Math. Program.*, vol. 115, no. 2, pp. 351–385, Oct. 2008.

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