An economic comparison between zero-emission vehicles for urban deliveries from the logistics company perspective

Mario Binetti[1], Aleksandra Colovic*[1], Luigi P. Prencipe[1], Michele Ottomanelli[1]

[1] DICATECh, Polytechnic University of Bari, Italy

SHORT SUMMARY

Through the recent years, the sustainable eco-friendly vehicles have been demonstrated as an adequate solution for urban deliveries and restricted areas facing with traffic congestions and traffic zone limitation. Therefore, in this paper, we adopted a mathematical model, formulated as Electric Vehicle Routing Problem with Time Windows and Partial Recharging (EVRPTW-PR), which aims at selecting the best zero-emission vehicle for delivering goods in city logistics through a cost comparison. In this way, we compared two most emerging vehicles, i.e., e-cargo bikes and e-scooters, by minimizing the total costs related to the vehicles' investment salary costs, drivers' salary costs and energy costs. The comparison between these two types of vehicles encourages the adoption of zero-emission strategies for last-mile deliveries and helps the logistics companies to decide the type of vehicle that could fit with the environmental as well as economic aspect.

Keywords: e-cargo bikes, e-scooters, green logistics, electric vehicle routing problem

1. INTRODUCTION

An increase of environmental awareness in cities has been dealing with introducing novel technologies for urban freight deliveries. such as e-cargo bikes and e-scooters. Especially in cities, e-cargo bikes and e-scooters introduce many advantages such as environmental benefits and lower operating costs, higher flexibility and reduction of time needed for loading/unloading operations, parking flexibility, accessibility to historical and/or zones with traffic limitations, etc. Since these vehicles have the capacity limitations, they require better depot allocations (Zhang et al., 2018). Therefore, several factors need to be considered for estimating the possibilities of using cargo bikes and e-scooters, such as frequency, size and weight of orders, spatial factors, etc. Usually, these vehicles are intended for payload capacity up to 200 kg and for carrying out the packages no greater than 25 kg (Gruber at al., 2014). Another specification to be considered is the infrastructure conditions, especially for restricted traffic zones and historical areas, where traffic regulations are important factors when choosing the best route.

In this paper, we carried out the comparison between e-cargo bikes and e-scooters for last mile deliveries in urban areas. Specifically, we carried out the comparison by adopting Electric Vehicle Routing Problem with Time Windows and Partial Recharging (EVRPTW-PR) proposed by Keskin and Çatay, (2016). The objective function of the model aims at minimizing the total costs regarding the energy costs, initial vehicles' investment costs, and drivers' salary costs, while the constraints of the model are related to the capacity, time-windows and partial recharging. The scope of this paper is to highlight the usage of eco-sustainable vehicles (i.e., e-cargo bikes and e-scooters) and to evaluate the comparison between them in term of costs. Moreover, the results of the comparison could be perceived as an indication for the companies to evaluate the usage of suitable technology that will deal with emission as well as total travel and operation costs minimization.

The paper is summarized as follows. In Section 2 we provide the insight into the papers related to the proposed topic, while in Section 3 the mathematical formulation of the EVRPTW-PR for the specific problem is described. In Section 4 are reported the results of the numerical application on which we tested the model on the instanced of 10 and 15 customers. Finally, in the last section we provided the conclusion and further developments.

2. LITERATURE REVIEW

Through the recent years, e-cargo bikes and e-scooters have been introduced in various cities to meet the environmental protection goals. For example, according to case study in Berlin, the comparison of cargo bikes with commercial vehicles showed the reduction of emissions costs up to 22 % and delivery costs up to 28 %. Compared with diesel vehicles, this technology offers wide spectrum of possibilities for delivering shipments on smaller distances, especially on distances up to 5 km (Rudolph & Gruber, 2017). Another case study in Berlin carried out the comparison between cargo bikes and car messengers in view of traversed distance, the volume of shipments and delivery service (Gruber & Lenz, 2014). Total traversed distance on last mile deliveries considering zone restrictions, narrow streets and traffic regulation, accounted in 5.1 km for cargo bikes and 11.3 for car messengers. Moreover, the comparison of these two modes considering the total weight and volume carried by vehicle on last mile deliveries, showed that 42 % of shipments could be substantiable by cargo bikes. However, the market for cargo bikes hasn't been showing its full potential. The opportunities for cargo bike technology are manly determinized by the typology, commercial achievements, and targets of stakeholders (Rudolph & Gruber, 2017). On the other side, e-scooter has been barely investigated from freight transportation point of view. Most of the papers in the literature have been showing the effectiveness of e-scooters for people micromobility purposes (Fistola et al. 2022; Ricci & Bogenberger, 2021).
To the best of our knowledge, the comparison between eco-sustainable technologies, in particular e-cargo bikes and e-scooters, has been scarcely investigated in the literature with the exception of Nocerino et al. (2016). The authors made a comparison between traditional and e-fleet including e-scooters, e-cargo bikes and e-bikes alternatives for urban deliveries through a real case study application. Specifically, they observed by four pilots the effectiveness of e-fleet in terms of reduction of CO_2 emissions and energy savings in urban logistics. However, in this paper, we went further in evaluating the cost comparison between e-scooters and e-cargo bikes from logistics companies point of view by following modeling perspective.

3. PROBLEM DESCRIPTION

In this section, we describe the mathematical formulation of the EVRPTW-PR adopted by Keskin and Çatay, (2016). Here the problem is formulated considering the specific light EV and the logistics companies' perspective.
The goal of the EVRPTW-PR model is to evaluate which zero-emission vehicle (in this case e-scooter or e-cargo bike) would be the best option for the last-mile delivery.
The problem is formulated as a mixed-integer linear programming model and is defined on a directed graph $G = \left(V_{d,N+1}, A\right)$ where sets of arcs $A = \left\{(i,j) \mid i,j \in V_{d,N+1}, i \neq j\right\}$. The set $V_{d,N+1}$ is composed of the depot V_d, the set of customers V_c, the set of dummy stations $\tilde{V}_s$, where the set of dummy stations $\tilde{V}_s$ allows several visits to each recharging station. Also, the set of homogenous vehicles $K = \{1, \dots, w\}$ is located at the depot V_d so that the total number of vehicles w are starting the trip from $V_d = \{0\}$ and finishing at $V_d = \{N + 1\}$, located at the same

point. Therefore, sets, parameters, and decision variables of EVRPTW-PR model are reported in Table 1.

Table 1: Nomenclature of the proposed EVRPTW-PR

Sets	
V_d	Depot, $V_d = \{0\}$, $V_d = \{N+1\}$
V_s	Set of stations, $V_s = \{1, \dots, m\}$
$\tilde{V}_s$	Set of dummy stations
V_c	Set of customers, $V_c = \{1, \dots, n\}$
$\tilde{V}_{N+1}$	Set of dummy stations and customers, $\tilde{V}_{N+1} = \tilde{V}_s \cup V_c \cup \{N+1\}$
K	Set of vehicles, $K = \{1, \dots, w\}$
$V_{d,N+1}$	Set of all nodes, $V_{d,N+1} = V_d \cup \tilde{V}_{N+1}$
Parameters	
n	Number of customers
m	Number of stations
w	Number of vehicles
d_{ij}	Distance between vertices i and j
t_{ij}	Travel time between vertices i and j
C	Capacity of vehicles in K
g	Recharging rate of vehicles in K
h	Fuel consumption rate of vehicles in K
v	Average speed of vehicles in K
Q	Battery capacity of vehicles in K
$[e_i, l_i]$	Time window of each vertex $i \in \tilde{V}_{V_d,N+1}$
s_i	Service time of each vertex $i \in \tilde{V}_{V_d,N+1}$ where $s_{V_d}, s_{\tilde{V}_s}, s_{N+1} = 0$
q_i	Demand of each vertex $i \in \tilde{V}_{V_d,N+1}$ $[kg]$
c_e^w	Electric energy cost of vehicles w $[€/km]$
c_v^w	Vehicle's w initial investment cost $[€/h]$
c_d^w	Driver's salary cost of vehicles w $[€/h]$
Decision variables	
τ_{ki}	Arrival time at vertex $i \in \tilde{V}_{V_d,N+1}$ for all $k \in K$
u_{ki}	Remain cargo on arrival at vertex $i \in \tilde{V}_{V_d,N+1}$ for all $k \in K$
y_{ki}	Remain charge level on arrival at vertex $i \in \tilde{V}_{V_d,N+1}$ for all $k \in K$
Y_{ki}	Battery state of charge on departure from vertex $i \in \tilde{V}_{V_d,N+1}$
x_{kij}	Binary decision variable where $k \in K$ and $i, j \in \tilde{V}_{V_d,N+1}$

The mathematical formulation of the EVRPTW-PR is then specified as follows:

$$f\left(x\right) = \sum_{k \in K} \sum_{i,j \in V_{d,N+1}} d_{ij} \cdot x_{kij} \cdot c_e^w + c_v^w \cdot w + c_d \cdot \left(w + \left(t_{ij} + s_{ij}\right) \cdot x_{kij}\right),\ i \neq j \tag{1}$$

$s.t.$

$$\sum_{j \in V_{N+1}} x_{kij} = 1, \forall k \in K, \quad i \in V_d = \left\{0\right\},\ i \neq j \tag{2}$$

$$\sum_{j \in V_{N+1}} x_{kji} = 1, \forall k \in K, \quad i \in V_d = \left\{N+1\right\},\ i \neq j \tag{3}$$

$$\sum_{k \in K} x_{kij} + \sum_{k \in K} x_{kji} \leq 1, \quad \forall i \in V_d,\ \forall j \in V_{N+1},\ i \neq j \tag{4}$$

$$\sum_{k\in K}\sum_{i\in V_d} x_{kij} = 1\,,\quad \forall j\in V_c\,,\, i\neq j \tag{5}$$

$$\sum_{k\in K}\sum_{i\in V_{N+1}} x_{kji} = 1\,,\quad \forall j\in V_c\,,\, i\neq j \tag{6}$$

$$\sum_{i\in V_d} x_{kij} - \sum_{i\in V_{N+1}} x_{kji} = 0\,,\quad \forall j\in V_c\,, \forall k\in K\,, i\neq j \tag{7}$$

$$\sum_{i\in V_{N+1}} x_{kij} \geq 0\,,\ \forall j\in V_s,\quad \forall k\in K\,,\ i\neq j \tag{8}$$

$$\sum_{i\in V_{N+1}} x_{kji} \geq 0\,,\quad \forall j\in V_s, \forall k\in K\,,\ i\neq j \tag{9}$$

$$\sum_{i\in V_d} x_{kij} - \sum_{i\in V_{N+1}} x_{kji} = 0\,,\quad \forall j\in V_s\,, \forall k\in K\,, i\neq j \tag{10}$$

$$x_{kij} + x_{kji} \leq 1\,,\quad \forall i\in V_{N+1}, \forall j\in V_s, \forall k\in K\,,\ i\neq j \tag{11}$$

$$0\leq u_{ki}\leq C\,,\quad \forall k\in K\,,\ i\in V_d = \{0\} \tag{12}$$

$$0\leq u_{kj}\leq u_{ki} - q_{ki}\cdot x_{kij} + C\cdot\left(1-x_{kij}\right)\,,\quad \forall i\in V_d, \forall j\in V_{N+1}, \forall k\in K\,,\ i\neq j \tag{13}$$

$$0\leq y_{kj}\leq y_{kj} - h\cdot d_{kij}\cdot x_{kij} + Q\cdot\left(1-x_{kij}\right)\,,\quad \forall i\in V_d\cup V_c\,, \forall j\in V_{N+1}, \forall k\in K\,,\ i\neq j \tag{14}$$

$$y_{kj}\leq Y_{ki} - h\cdot d_{kij}\cdot x_{kij} + Q\cdot(1-x_{kij}),\quad \forall i\in V_d\cup V_s, \forall j\in V_{N+1}, \forall k\in K\,,\ i\neq j \tag{15}$$

$$y_{ki}\leq Y_{ki}\leq Q\,,\quad \forall i\in V_d\cup V_s, \forall k\in K \tag{16}$$

$$\tau_{ki} + \left(t_{kij} + s_{ki}\right)\cdot x_{kij} - l_0\left(1-x_{kij}\right)\leq \tau_{kj}\,,\quad \forall i\in V_d\cup V_c\,, \forall j\in V_{N+1}, \forall k\in K\,,\ i\neq j \tag{17}$$

$$\tau_{ki} + t_{kij}\cdot x_{kij} + g\cdot\left(Y_{ki} - y_{ki}\right) - \left(l_0 + g\cdot Q\right)\cdot\left(1-x_{kij}\right)\leq \tau_{kj}\,,\quad \forall i\in V_s, \forall j\in V_{N+1}, \forall k\in K\,,\ i\neq j \tag{18}$$

$$x_{kij}\in\{0,1\}\,,\quad \forall i,j\in V_{d,N+1},\ \forall k\in K\,,\ i\neq j \tag{19}$$

$$u_{ki}, y_{ki}, Y_{ki}, \tau_{ki}\geq 0\,,\quad \forall i\in V_{d,N+1}, \forall k\in K \tag{20}$$

The objective function (1) minimizes the total costs, such as travel costs, initial vehicles' investment costs, drivers' salary costs. Constraints (2) – (3) ensure that each vehicle starts and finishes its route at the depot. Constraint (4) avoid the cycles between nodes. Constraints (5) – (6) ensure that each customer could be visited by one vehicle once. Constraint (7) ensures the number of arcs leaving and entering at each customer node. Constraints (8) – (9) ensure that each station can be visited more times by one or more vehicles. Constraints (10) – (11) are related to the number of links entering and leaving from each station by avoiding cycles between stations. Constraints (12) – (13) are meeting the demand request at each node and ensure nonnegative remaining cargo load. Constraints (14) – (16) are related to the battery's partial charging for each vehicle at the station. Constraints (17) – (18) are related to the time window constraints and subtour elimination. Constraint (19) is related to the binary variable that is equal to 1 if the vehicle k is traveling on arc (i, j), 0 otherwise. Constraint (20) ensures that remaining cargo level u, remaining charge level y, battery state of charge Y, and arrival time τ are greater or equal than zero.

4. NUMERICAL APPLICATION AND RESULTS

We implemented the EVRPTW-PR in CPLEX 12.10 that uses the exact method as a solution approach. The proposed model was run with an Intel(R) Core (TM) i7-8550U CPU (1.80GHz)

and 16GB of RAM. We validated the proposed model on the instances with 10 and 15 customers proposed by Colovic and Prencipe, (2020) and tested by Caggiani et al. (2020).
We set the values of capacity C , average speed v , capacity of battery Q , and recharging rate g for e-scooters equal to 175 kg, 16 km/h, 4 kWh, and 0.571 kWh/h, while the values for e-cargo bikes are equal to 80 kg, 17 km/h, 0.54 kWh, and 0.135 kWh/h, respectively (see Nocerino et al., 2016). Additionally, we set the value of fuel consumption rate h for e-scooters as 0.035 kWh/km, and for e-cargo bikes as 0.01 kWh/km. Moreover, the value c_e^w related to the electric energy costs was set as 0.0021 €/km for e-scooters and 0.0006 €/km for e-cargo bikes. The value c_v^w related to the vehicle's initial investment costs was set as 8.3 €/day for e-scooters and for e-cargo bikes as 0.274 €/day. The value c_d^w related to the drivers' salary costs was set as 10 €/day for e-scooters and e-cargo bikes €/day. Therefore, we reported these values in Table 2.

Table 2: The values of the parameter used in EVRPTW-PR

Parameter	**e-scooter**	**e-cargo bike**
C [kg]	175	80
v [km/h]	16	17
Q [kWh]	4	0.54
g [kWh/h]	0.035	0.01
c_e^w [€/km]	0.0021	0.0006
c_v^w [kWh/km]	8.3	0.274
c_d^w[€/day]	10	10

The results of the comparison between e-scooters and e-cargo bikes are reported in Table 3. For all instances of 10 customers and some instances with 15 customers we obtained a good-quality solutions in a low computation time. For other instances with 15 customers, we fixed the time limit as 3600 s. In general, the number of used e-scooters for the instances of 10 customers is up to 2, while for e-cargo bikes is up to 3. However, the number of used vehicles for instances of 15 customers increased up to 4 for e-cargo bikes and up to 3 for e-scooters, which is due to the higher payload capacity of e-scooters. In specific, we can observe that e-cargo bikes are the more economically convenient solution when the number of used vehicles (e-cargo bikes/e-scooters) is the same, as reported for the instances r102C10, rc102C10 and r102C15. Additionally, the instance r102C15 resulted in the highest gap in the terms of objective function gap $\Delta f = f_1 - f_2$, where the values of f_1 and f_2 are the objective functions of e-scooters and e-cargo bikes, respectively. Also, the values of $w_1$and w_2 are related to the optimal number of used e-scooters and e-cargo bikes, respectively.

Table 3: The values of the parameter used in EVRPTW-PR

Instances	EVRPTW-PR						
	w_1	f_1 (€/day)	t(s)	w_2	f_2 (€/day)	t(s)	gap $\Delta f = f_1 - f_2$ (€/day)
E1-c101C10	2	66.202	4.01	3	**60.308**	17.48	5.894
E1-c104C10	2	64.484	2.09	3	**59.225**	51.75	5.259
E1-r102C10	2	43.885	28.62	2	**27.895**	106.37	15.99
E1-r103C10	1	**23.898**	0.59	2	26.071	2	-2.173
E1-rc102C10	2	46.275	0.69	2	**40.361**	2.36	5.914
E1-rc108C10	1	**27.217**	1.25	2	29.302	8.41	-2.085
E1-c103C15	2	**77.317**	3505.18	4	82.015	3600	-4.698
E1-c106C15	1	**59.152**	24.85	3	69.795	3.95	-10.643
E1-r102C15	3	66.398	3600	3	**41.911**	3600	24.487
E1-r105C15	2	48.402	3600	3	**40.914**	161.69	7.488
E1-rc103C15	2	47.813	1717.64	3	**41.561**	3600	6.252
E1-rc108C15	2	**46.922**	353.12	4	53.287	3600	-6.365

Additionally, we analyzed the results by focusing on the costs in the objective function f_1 and f_2 which are the sum of three terms z_d - driver's salary costs, z_v - initial vehicles' investment costs, and z_e - energy costs. In specific, z_d is composed of two parts related to the z_d^f - fixed driver salary cost, and z_d^v – variable salary related to the shipment of the deliveries within the fixed time window. Therefore, in Table 3, we reported the detailed results of the objective functions f_1 and f_2 for some instances of 10 and 15 customers. According to Table 3, we can observe that the term z_d related to drivers' salary costs has the most influence on the total costs of the objective function. In specific, by considering the policy with fixed drivers' salary costs z_d^f, we obtained the solutions where for some instances is more convenient to use e-scooter, while for others is more convenient e-cargo bikes. For example, in the case of instances c101C10 and r102C10, we can observe that the costs of e-scooters are higher compared to the e-cargo bikes due to the higher vehicles' investment costs. However, the e-scooter is suitable solution in the case of the instance c106C15, since the parameter z_d related to drivers' salary costs has a higher value for e-cargo bikes. On the other side, if we do not consider fixed drivers' salary cost, we evaluated that the most convenient solution for all instances is e-cargo bike.

Table 3: The values of the parameter used in EVRPTW-PR

Instances	e-scooter					e-cargo bike				
	z_d		z_e	z_v	f_1	z_d		z_e	z_v	f_2
	z_d^f	z_d^v				z_d^f	z_d^v			
c101C10	20	29.578	0.024	16.6	**66.202**	30	29.479	0.0070	0.822	**60.308**
r102C10	20	7.269	0.016	16.6	**43.885**	20	7.342	0.0049	0.548	**27.895**
c106C15	10	40.829	0.0238	8.3	**59.152**	30	38.968	0.0053	0.822	**69.795**
r105C15	20	11.775	0.0269	16.6	**48.402**	30	10.086	0.00646	0.822	**40.914**

CONCLUSIONS

In this paper, we adopted Electric Vehicle Routing Problem with Time Windows and Partial Recharging (EVRPTW-PR) model, where we proposed the comparison between e-cargo bikes and e-scooters for evaluating the best zero-emission vehicle for last-mile urban deliveries. We evaluated the comparison considering the minimization of the overall costs that include the vehicles' initial investment costs, drivers' salary cost and the energy costs. According to the comparison, we can observe the benefits in terms of overall costs that companies can receive by using e-scooters or e-cargo bikes. The comparison was tested on a set of instances provided by Colovic and Prencipe, (2020) in which for some instances is better to use e-cargo bikes and for other e-scooters. Furthermore, we observed from Table 3 that the driver's salary costs are the ones that influence the most the objective function. Finally, we can observe that both e-cargo bikes and e-scooters are acceptable solution in the terms of the gap difference.

In general, the model could be applicable for all type of deliveries, as well as the type of zero-emission vehicles, by varying the parameters of the vehicles, as shown in Table 2. For example, for food or post deliveries could be carried out a comparison between electric kick scooters and e-bikes. This model could be perceived as a first step for evaluating costs of logistic companies, but it could be extended in further developments by applying metaheuristic/heuristics as a solution approach for solving real case study. Another development will introduce in the comparisons the Environmental Life Cycle Costing to better understand the convenience of the systems from a wider perspective.

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