A two-echelon vehicle routing problem involving electric vehicles with time windows

Dan Wang\(^1\), Hong Zhou\(^1,3\) and Ruxin Feng\(^2\)

\(^1\)School of Economics and Management, Beihang University, Beijing 100191, China
\(^2\)Huaneng Coal Industry CO., LTD, Beijing 100070, China
\(^3\)Email: h_zhou@buaa.edu.cn

Abstract. This paper addresses a two-echelon vehicle routing problem involving electric vehicles considering time windows and battery swapping stations (2E-EVRPTW-BSS), which aims at determining the delivery strategy under battery driving range and time windows for city logistics. Unilateral time windows and time windows are considered to guarantee the timeliness of transportation. The electric vehicles (EVs) operating at the 2\(^{nd}\)-echelon have battery swapping costs. A mathematical model is constructed to formulate the problem in which the total of shipping cost, handling cost, battery swapping costs, fixed cost of vehicles, and penalty cost due to tardiness is minimized. Numerical experiments with 14 randomly-generated instances have been conducted to demonstrate the effective of the model.

1. Introduction

With industrial development and urbanization, air pollution in cities becomes increasingly serious in recent years. Now more and more people and governmental departments have realized the importance of environmental protection. For China, haze has long been a national concern [1] and the emission by fossil fuel-based internal combustion vehicle (ICVs) is considered one of the main causes of haze. Hence city managers began to set limitation to large ICVs for entering the core zones of the city. With the restriction, large ICVs are usually used to transport demands from a depot located at the outskirts of the city to satellites in the vicinity of customers, while small vehicles are used to transport demands from satellites to customers, which leads to the study on two-echelon distribution systems [2]. At the neighborhood level, a satellite operates on a small scale and has no storage equipment.

Cuda, Guastaroba and Speranza [3] reviewed the foremost related papers on two-echelon distribution systems. In their survey, the two-echelon location routing problem (2E-LRP) and the two-echelon vehicle routing problem (2E-VRP) were considered. The nodes set of 2E-LRP are composed of potential locations for the depots, potential locations for satellites which are small intermediate platforms as intermediated points for the freight distribution, and the customers. The location of the depots and the satellites to use is not determined a priori, and the vehicles must return to the main depots (satellites) after serving satellites (customers). The 2E-LRP aims at minimizing the total system cost. Considering the daily distribution of newspapers through transfer nodes, Jacobsen and Madsen [4] first applied the routing problem into a two-echelon system with an explicit minimization of the total transportations costs. The concept of a 2E-VRP was first introduced by Crainic, Ricciardi, and Storchi [5]. They developed a two-tier freight distribution system for congested urban areas including satellites. This system is developed for a specific case study and a generalization of such a system has not been formulated. In 2016, 2E-VRP was first formulated by Perboli, Tadei, and Vigo [6]. With the rapid
development, EVs are beginning to be used in logistics and transportation problems. Pelletier et.al [7] provided researchers with technological and marketing background of goods distribution by EVs. From their work, they found that EVs have many advantages such as frequent stop-and-go movements, reduced pollution and low noise in urban logistics. Desaulniers et.al [8] gave four variants of the EV routing problem with time windows, which are classified by the allowed recharge times per route and battery charge strategy (full recharges or partial recharges). Yang and Sun [9] introduced a BSS location routing problem with capacitated EVs, which focuses on simultaneously determining the location of BSSs and the routing plan of EVs under battery driving range constraints. The EVRP combined with the two-echelon networks have drawn attention for academic research and practical application in literature. Jie W et.al [10] firstly discussed capacitated EVs used in both echelons of the two-echelon transportation system with battery swapping stations. The constrains contained in their model including capacity of demands and electric powers of EVs.

At present, there are few literatures on the two-echelon electric vehicle routing problem (2E-EVRP) considering unilateral time windows of satellites and the time windows of the customers at the same time. To improve the timeliness of transportation, this paper addresses a two-echelon vehicle routing problem involving electric vehicles considering time windows and battery swapping stations (2E-EVRPTW-BSS). Large ICVs employed at the 1st-echelon to transport demands from the depot to satellites before unilateral time windows, and then return to the depot. Unilateral time windows of the satellites represent the latest time for ICVs arriving at the satellites. EVs employed at the 2nd-echelon to deliveries demands from the satellite to customers during time windows, and then back to the satellite. Multiple battery swapping stations (BSSs) are considered at the 2nd-echelon.

The rest of the paper is organized as follows. First, a mixed integer linear programming model is developed for the 2E-EVRPTW-BSS which integrates capacity constraints of ICVs and EVs, unilateral time windows constraints of satellites, the split delivery at the 1st-echelon and multiple routes at the 2nd-echelon, time window constraints of customers, and electric power constraints of EVs. Then the proposed model is tested with GUROBI by using 14 randomly-generated instances. The computational results show that the proposed formulation is effective and environmentally friendly.

2. The 2E-EVRPTW-BSS definition and mathematical formulation

2.1. Problem description
In this paper, one depot, multiple satellites, multiple customers and multiple BSSs are considered. 2E-EVRPTW-BSS considers large ICV type at the 1st-echelon and small EV at the 2nd-echelon. Of each customer, the demand with time window is known and cannot be split. Demand is transported from the depot to satellites by multiple large ICVs at the 1st-echelon, and several small EVs will be dispatched from each satellite to serve customers at the 2nd-echelon. The EVs should visit BSSs to swap their batteries before their battery power runs out [9].

2.2. Assumptions
- The depot has enough demands.
- Split deliveries are allowed at the 1st-echelon but not at the 2nd-echelon.
- EVs have a limited driving range.
- No storage capacity is available at satellites.
- Each satellite also hosts a charging station at its location.
- Each customer can be satisfied by a single EV.
- The same BSS can be visited several times by multiple EVs.
- The service time for swapping batteries and customers can be ignored.
2.3. **Variables and parameters**

- $x_{ijk}$: Binary decision variable; 1 if the arc $(i,j)$ is traveled by the vehicle $k$ at the $1^{st}$-echelon; 0, otherwise.
- $z_{ijk}$: Binary decision variable; 1 if 2$^{nd}$-echelon vehicle $k$ goes from node $i$ to node $j$ from the satellite $s$; 0, otherwise, \[10\]
- $u_{ik}$: The quantity of demand transported to the node $i$ by vehicle $k$.
- $l_s$: The unilateral time window of each satellite.
- $t_{ik}$: Arrival time at the node $i$ of the vehicle $k$.
- $b_{ik}$: The remaining battery power when the vehicle $k$ arrives at the node $i$.
- $b_{ik}$: The remaining battery power when the vehicle $k$ leaves node $i$.
- $V_0$: Depot, \( V_0 = \{0\} \).
- $V_s$: Set of satellites.
- $V_c$: Set of customers.
- $V_B$: Set of battery swapping stations (BSSs).
- $V_i$: \( V_i = V_0 \cup V_s \)
- $V_2$: \( V_2 = V_s \cup V_c \cup V_B \)
- $V$: \( V = V_0 \cup V_s \cup V_c \cup V_B \)
- $K_1, K_2$: Set of the ICVs and set of EVs
- $K$: \( K = K_1 \cup K_2 \)
- $c_1, c_2$: Shipping cost for the vehicle from $i$ to $j$ of unit time.
- $c_b$: Cost of the battery swapping at the 2$^{nd}$-echelon.
- $c_s$: The unit handling cost of demand in the satellite $s$.
- $c_f$: The fixed cost of the vehicle.
- $h_s$: The inventory cost of unit demand at the satellite $s$.
- $t_{ij}$: Travel time of vehicle from $i$ to $j$.
- $a$: The electric consumption rate of the EVs of unit time.
- $[e_i, l_i]$: The time window of the node $i$. $e_i$ is the earliest time for vehicle arriving at the node $i$, $l_i$ is the latest time for vehicle arriving at the node $i$.
- $Q_1, Q_2$: The capacity of the vehicles at the 1$^{st}$-echelon and at the 2$^{nd}$-echelon.
- $B$: Battery capacity of the EVs at the 2$^{nd}$-echelon.
- $q_i$: The demand of node $i$.
- $M$: A big positive number.

2.4. **Mathematical formulation**

Minimize:

\[
\begin{align*}
&c_1 \sum_{k \in K_1} \sum_{i \in V} \sum_{j \in V_s} t_{ij} x_{ijk} + c_2 \sum_{k \in K_2} \sum_{i \in V_s} \sum_{j \in V_c} \sum_{j' \in V_s} t_{ij} z_{ijk} + c_s \sum_{i \in V_s} \sum_{k \in K_1} u_{ik} + c_b \sum_{k \in K_1} \sum_{i \in V_s} \sum_{j \in V_s} \sum_{j' \in V_s} z_{ijk} \\
&+ c_f \left( \sum_{k \in K_1} \sum_{i \in V_s} x_{ijk} + \sum_{i \in V_s} \sum_{j \in V_s} \sum_{j' \in V_s} z_{ijk} \right) + \sum_{i \in V_s} \sum_{j \in V_s} h_i \cdot \max \left( \sum_{k \in K_1} u_{ik} - \sum_{k \in K_2} \sum_{i \in V_s} \sum_{j \in V_s} q_j z_{ijk}, 0 \right)
\end{align*}
\]  

Subject to:

\[
\sum_{i \in V_j} x_{ijk} = \sum_{i \in V_j} x_{jik} \quad \forall j \in V, i \neq j, k \in K_1
\]
\[
\sum_{j \in V} x_{ijk} \geq 1 \quad \forall j \in V, i \neq j
\] (3)
\[
\sum_{j \in V} x_{ijk} = 0 \quad \forall k \in K
\] (4)
\[
\sum_{i \in V} u_{ik} \leq Q_i \quad \forall k \in K
\] (5)
\[
u_{jk} \leq \sum_{i \in V} x_{ijk}M \quad \forall j \in V, k \in K
\] (6)
\[
\sum_{j \in V} z_{ijk} = \sum_{j \in V} z_{jik} \quad \forall i \in V, i \neq j, k \in K_i, s \in V_s
\] (7)
\[
\sum_{k \in K_j} \sum_{i \in V} \sum_{j \in V} z_{ijk} = 1 \quad \forall j \in V, i \neq j
\] (8)
\[
\sum_{i \in V} z_{ijk} = 0 \quad \forall j \in V \setminus s, s \in V_s, k \in K_2
\] (9)
\[
\sum_{k \in K_j} q_j z_{ijk} \leq Q_2 \quad \forall s \in V_s, k \in K_2
\] (10)
\[
\sum_{i \in V} u_{ik} \geq \sum_{k \in K_j} \sum_{i \in V} \sum_{j \in V} q_j z_{ijk} \quad \forall s \in V_s
\] (11)
\[
u_{jk} \leq \sum_{i \in V} \sum_{j \in V \setminus i} z_{ijk}M \quad \forall j \in V, k \in K
\] (12)
\[
eq \leq t_i \leq l_i \quad \forall i \in V, k \in K
\] (13)
\[
l_j = e_j - \sum_{k \in K_s} \sum_{s \in V} t_{ijk} z_{ijk} \quad \forall j \in V, s \in V_s
\] (14)
\[
l_j \leq l_j - \sum_{k \in K_s} t_{ijk} z_{ijk} \quad \forall j \in V, s \in V_s
\] (15)
\[
t_i \leq l_i \quad \forall s \in V_s, k \in K_i
\] (16)
\[
t_i \geq t_i + t_j - M(1 - x_{ijk}) \quad \forall i \in V_s, j \in V_i, i \neq j, k \in K_1
\] (17)
\[
t_i \leq t_i + t_j + M(1 - x_{ijk}) \quad \forall i \in V_s, j \in V_i, i \neq j, k \in K_1
\] (18)
\[
t_i \geq t_i + t_j - M(1 - z_{ijk}) \quad \forall i \in V \setminus j \in V, j \in V_s, i \neq j, k \in K_1
\] (19)
\[
t_i \leq t_i + t_j + M(1 - z_{ijk}) \quad \forall i \in V \setminus j \in V, j \in V_s, i \neq j, k \in K_1
\] (20)
\[
b_{ik} = b_{ik}^+ \quad \forall i \in V, k \in K
\] (21)
\[
b_{ik} = B \quad \forall i \in V \setminus j \in V, k \in K
\] (22)
\[
b_{ik} \leq b_{ik}' - at_{ijk} z_{ijk} + B(1 - z_{ijk}) \quad \forall i, j \in V_2, i \neq j, s \in V_s, k \in K_2
\] (23)
\[
b_{ik}' \geq b_{ik} - at_{ijk} z_{ijk} - B(1 - z_{ijk}) \quad \forall i, j \in V_2, i \neq j, s \in V_s, k \in K_2
\] (24)
\[
x_{ijk} \in \{0, 1\} \quad \forall i, j \in V, i \neq j, k \in K_1
\] (25)
\[
z_{ijk} \in \{0, 1\} \quad \forall i, j \in V, i \neq j, s \in V_s, k \in K_2
\] (26)
\[
u_{jk} \geq 0 \quad \forall j \in V, k \in K
\] (27)
\[
l_i \geq 0 \quad \forall i \in V, k \in K
\] (28)
Constraints (2) and (7) ensure the flow conservation for vehicles at each satellite at the 1<sup>st</sup>-echelon and for each customer at the 2<sup>nd</sup>-echelon, respectively. Constraint (3) ensures that a satellite can be visited more than once at the 1<sup>st</sup>-echelon. Constraint (4) ensures that shipping from the depot to customers is forbidden. Constraints (5), (6), (11) and (13) are the demand flow limitation. Constraint (8) guarantees that each customer can be visited only once. Constraint (9) means there is no shipping between different satellites. Constraints (10) ensures the demands of customers should be satisfied. Constraint (12) guarantees the demands that are transported to satellites by vehicles at the 2<sup>nd</sup>-echelon satisfy all customers. Constraint (14) ensures that the arrival time of EVs at the 2<sup>nd</sup>-echelon is in the time window of each customer. Constraints (15), (16) and (17) denote the unilateral time window of each satellite. Constraints (18) and (19) are time limitations at the 1<sup>st</sup>-echelon. Constraints (20) and (21) are time limitations at the 2<sup>nd</sup>-echelon. Constraint (22) ensures that the battery power remains the same when an EV visits a customer. Constraint (23) ensures that the battery power of an EV is equal to B when it departs from a satellite or visits a BSS. Constraints (24) and (25) keep the balance of battery power of EVs arriving at the node j from the node i. They guarantee that each EV has enough battery power to visit the remaining customers or BSSs and return to the same satellite. Nonnegative variables and binary decision variables are defined in Constraints (26)-(30).

### 3. Computational experiments

#### 3.1. Description and data

14 randomly-generated instances are used to verify the effectiveness of the 2E-EVRPTW-BSS formulation. All nodes are located on the crossing of the 200×200 grids. (0,0) represents the depot. Satellites are generated close to customers but far from the depot. BSSs are located among customers and the number of BSSs is set to be 1/5 of the nodes in the network [11]. The transportation time between any two nodes is calculated from Euclidean distance divided by the speed of ICV at the 1st-echelon or speed of EV at the 2<sup>nd</sup>-echelon. Then the adjacency matrix of transportation time can be calculated.

**Table 1.** The parameter values in the 2E-EVRPTW-BSS.

| Parameters | Value (unit) | Parameters | Value (unit) |
|------------|--------------|------------|--------------|
| \(Q_1\)    | 800 (kg)     | \(c_b\)    | 3 ($)        |
| \(Q_2\)    | 150 (kg)     | \(c_f\)    | 100 ($)      |
| \(v_1\)    | 40 (km/h)    | \(c_s\)    | 3 ($)        |
| \(v_2\)    | 15 (km/h)    | \(a\)      | 5 (%/h)      |
| \(c_1\)    | 12 ($/h)     | \(B\)      | 100 (%)      |
| \(c_2\)    | 15 ($/h)     | \(M\)      | 20000        |

**Table 2.** Characteristics and results of the 2E-EVRPTW-BSS instances.

| Inst. | \(n_s\) | \(n_c\) | \(n_b\) | Obj  | Inst. | \(n_s\) | \(n_c\) | \(n_b\) | Obj  |
|-------|--------|--------|--------|-----|-------|--------|--------|--------|-----|
| 1     | 2      | 4      | 1      | 2403.21 | 8      | 3      | 8      | 2     | 3672.31 |
| 2     | 2      | 5      | 2      | 2513.34 | 9      | 2      | 9      | 2     | 3891.92 |
| 3     | 3      | 5      | 2      | 2561.00 | 10     | 3      | 9      | 2     | 3851.61 |
| 4     | 2      | 6      | 2      | 3784.82 | 11     | 2      | 10     | 2     | 3784.55 |
| 5     | 3      | 6      | 2      | 3275.63 | 12     | 3      | 10     | 3     | 4061.42 |
| 6     | 3      | 7      | 2      | 3493.77 | 13     | 3      | 12     | 3     | 5276.19 |
| 7     | 2      | 8      | 2      | 3694.75 | 14     | 4      | 15     | 4     | 6178.79 |
GUROBI can find the exact solution for each of the 14 randomly-generated instances. The proposed mathematical formulation has been implemented in GUROBI 8.0.1 and tested on Intel Xeon E3-123v3 (8 GB RAM) computer. The parameters involved in the formulation are evaluated in Table 1. The results of 14 randomly-generated instances in Table 2 suggest that the proposed mathematical formulation is effective, and as the total demand grows, the objective value grows as well.

3.2. The impact on environmental protection of 2E-EVRPTW-BSS

In order to verify the environmental protection of EVs as mentioned in the introduction, ICVs are used in both echelons of two-echelon vehicle routing problems (2E-VRPTW-ICV) to make a comparison with 2E-EVRPTW-BSS. The objective function of 2E-VRPTW-ICV is (31). The constrains of objective function (31) are Constraints (2)-(21) and Constraints (27)-(30).

\[
c_1 \sum_{k \in K_1} \sum_{i \in V_1} \sum_{j \in V_1} t_{ij} x_{ijk} + c_2 \sum_{k \in K_2} \sum_{i \in V_2} \sum_{j \in V_2} t_{ij} z_{ijk} + c_k + \sum_{i \in V_2} \sum_{j \in V_2} u_{ij} + c_f \left( \sum_{k \in K_1} \sum_{i \in V_1} \sum_{j \in V_1} y_{ijk} + \sum_{i \in V_2} \sum_{j \in V_2} z_{ijk} \right) + \sum_{j \in V_2} h_j \cdot \max \left( \sum_{k \in K_1} \sum_{i \in V_1} q_{j, ijk}, 0 \right)
\] (31)

As there is no clear formula for the emission of pollutants of ICVs and the discharge of pollutants of electricity supply of EVs, Standard Coal consumption is used as an indicator to judge the level of pollution. After getting the objective values of functions (1) and (31), the Gasoline consumption and the electric power consumption are calculated firstly, and then converted to the Standard Coal consumption. The parameters of 2E-VRPTW-ICV are presented in Table 3. Parameters \( C_1 \) and \( C_2 \) represent the Gasoline consumption per 100 km of ICVs at the 1st-echelon and the 2nd-echleon respectively. The electric power of EVs of 2E-EVRPTW-BSS is 1500W. The density of Gasoline is 0.72g/ml. 1 kg of Gasoline is converted to 1.4714 kg of Standard Coal, and 1 kW·h corresponds to Standard Coal of 0.404 kg according to The National Bureau of Statistics. The computational results are shown in Table 4 by using random-generated instances in Table 2.

### Table 3. The parameter values of 2E-VRPTW-ICV in the computational experiments.

| Parameters | Value (unit) | Parameters | Value (unit) |
|------------|-------------|------------|-------------|
| \( Q_1 \)  | 800 (kg)    | \( c_1 \)  | 12 ($/h)    |
| \( Q_2 \)  | 200 (kg)    | \( c_2 \)  | 12 ($/h)    |
| \( v_1 \)  | 40 (km/h)   | \( c_f \)  | 100 ($)     |
| \( v_2 \)  | 12 (km/h)   | \( c_s \)  | 3 ($)       |
| \( C_1 \)  | 20 (L/100 km)| \( M \)    | 20000       |
| \( C_2 \)  | 8 (L/100 km) |             |             |

In Table 4, column 1 represents the instances. Columns 2 and 5 are the Gasoline consumption of ICVs of both models. Column 3 shows the electric power consumption of EVs. Columns 4 and 6 indicate the Standard Coal consumption of both models. Column 4 is calculated as following: Standard Coal consumption = (Gasoline consumption × 0.72) × 1.4714+ Electric Power Consumption × 0.404. Column 6 is calculated as following: Standard Coal consumption = (Gasoline × 0.72) × 1.4714

It can be obtained from Table 4 that the standard coal consumption of 2E-VRPTW-ICV is much more than the standard coal consumption of the 2E-EVRPTW-BSS. The transportation system considering EVs are much more energy-efficient, environmentally friendly and sustainable than the transportation system with only ICVs in reality.
Table 4. Computational results of the 2E-EVRPTW-BSS and 2E-VRPTW-ICV.

| Inst. | Gasoline (unit: L) | Electric Power (unit: kW-h) | Standard Coal (unit: kg) | 2E-VRPTW-ICV |
|-------|-------------------|-----------------------------|-------------------------|---------------|
|       |                   |                             |                         | Gasoline (unit: L) | Standard Coal (unit: kg) |
| 1     | 46.33             | 54.14                       | 99.56                   | 141.99         | 150.28               |
| 2     | 46.33             | 63.11                       | 107.92                  | 140.01         | 148.18               |
| 3     | 47.08             | 59.28                       | 105.14                  | 141.05         | 149.28               |
| 4     | 46.33             | 92.61                       | 135.42                  | 179.70         | 190.19               |
| 5     | 47.08             | 71.16                       | 116.22                  | 171.99         | 182.03               |
| 6     | 47.08             | 80.18                       | 124.63                  | 154.74         | 163.77               |
| 7     | 46.33             | 86.65                       | 129.87                  | 180.03         | 190.54               |
| 8     | 47.08             | 85.10                       | 129.22                  | 174.56         | 184.75               |
| 9     | 75.45             | 100.85                      | 173.96                  | 243.21         | 257.41               |
| 10    | 76.80             | 95.70                       | 170.58                  | 236.56         | 250.37               |
| 11    | 75.45             | 102.85                      | 175.82                  | 246.97         | 261.39               |
| 12    | 76.81             | 113.74                      | 187.41                  | 266.69         | 282.26               |
| 13    | 76.80             | 129.76                      | 202.34                  | 268.82         | 284.51               |
| 14    | 107.96            | 556.35                      | 339.13                  | 579.45         | 613.87               |

4. Conclusions and future works
To the best of our knowledge, only few papers considered time windows in the 2-echelon electric vehicle routing problem. As time windows bring more efficient transportation, this paper presented a new problem: 2E-EVRPTW-BSS, which took time windows of customers and the unilateral time windows of the satellites into consideration at the same time. The 2E-EVRPTW-BSS model aims to solve the two routing problems simultaneously. Time windows of customers ensure the timeliness of the transportation. The mathematical formulation is tested by using 14 randomly-generated instances which are solved directly by GUROBI, and the computational results show that the proposed mathematical formulation is effective. To verify the environmental friendliness of 2E-EVRPTW-BSS, we make a comparison with 2E-VRPTW-ICV which used ICVs in both echelons. We found that the standard coal consumption of 2E-EVRPTW-BSS is much less than 2E-VRPTW-ICV, which means the 2E-EVRPTW-BSS is a better choice in transportation systems.

Future studies should focus on effective heuristics for the 2E-EVRPTW-BSS to solve the larger scale instances. Some possible extensions of the 2E-EVRPTW-BSS are, for example, considering the location of satellites and the BSSs or the possibility of passing a BSS without charging of EVs, etc. Besides, comparing the 2E-EVRPTW-BSS with similar 2E-VRP variants to find more insights may be interesting.

Acknowledgment
This work is supported by the Natural Science Foundation of China under Grant No.71471007.

References
[1] Zhao Y, Gao P, Yang W, et al. 2016 Vehicle exhaust: An overstated cause of haze in China Sci Total Environ 612 490-491
[2] Savelesbergh M and Woensel T V 2016 50th Anniversary Invited Article-City Logistics: Challenges and Opportunities Transport Sci 50 579-590
[3] Cuda R, Guastaroba G and Speranza M G 2015 A survey on two-echelon routing problems Compu Oper Res 55 185-199
[4] Jacobsen S K and Madsen O B G 1980 A comparative study of heuristics for a two-level routing-location problem Eur J of Oper Res 5(6) 378-387
[5] Crainic T G, Ricciardi N and Storchi G 2009 Models for Evaluating and Planning City Logistics
Systems *Transport Sci* **43**(4) 432-454

[6] Perboli G, Tadei R and Vigo D 2016 The Two-Echelon Capacitated Vehicle Routing Problem: Models and Math-Based Heuristics *Transport Sci* **45**(3) 364-380

[7] Pelletier S, Jabali O and Laporte G 2016 50th Anniversary Invited Article-Goods Distribution with Electric Vehicles: Review and Research Perspectives *Transport Sci* **50**(1) 3-22

[8] Desaulniers G, Errico F, Irnich S and Schneider M 2016 Exact algorithms for electric vehicle-routing problems with time windows *Oper Res* **64**(6) 1388–1405

[9] Yang J and Sun H 2015 Battery swap station location-routing problem with capacitated electric vehicles *Comput Oper Res* **55**(C) 217-232

[10] Jie W C, Yang J, Zhang M and Huang Y X 2019 The two-echelon capacitated electric vehicle routing problem with battery swapping stations: Formulation and efficient methodology *Euro J of Oper Res* **272**(3) 879-904

[11] Schneider M, Stenger A and Goeke D 2014 *The Electric Vehicle-Routing Problem with Time Windows and Recharging Stations* INFORMS