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Evolving School Transportation: A Comprehensive Approach to Bus Electrification with Dynamic Route Optimization and Partial Charging for Mixed Fleets

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Rationale and Justification

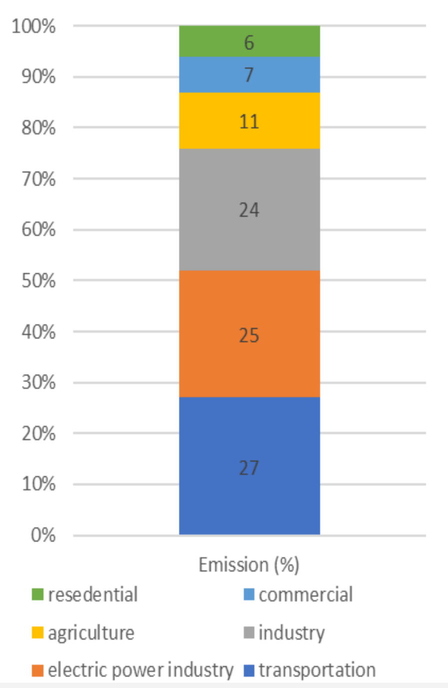


Fig 1: sector wise Emission, USEPA 2022

Scenarios

- 5 Mn Tons annually
- Effect on student's health & academic performance
- Bipartisan Infrastructure Bill

Motivation

- ESB (Electric School Bus) costs twice of its CBD
- No or limited research in ESBRP
- SB has tight time, on-route full charging disrupts the bell schedule
- Rapid electrification through cost optimization under practical constraints

Fig 2: Diesel bus emission

Objectives

1. Simultaneous solution for dynamic bus route optimization, school bell schedule and bus stop time tabling by considering fleet mixes
2. Student ride time minimization including on-route bus charging time and charging cost optimization
3. On-route partial charge amount & optimal charging location selection

Constraints

⇒ **Routing Constraints**
- bus stop visit
- charging station visit

⇒ **Schedule Constraints**
- school bell time (SBT)
- maximum riding time (MRT)
- stop time window (STW)

⇒ **Range Constraints**
- battery state of charge (SoC)
- upper & lower battery bound

⇒ **Capacity Constraint**
- maximum bus capacity

⇒ **Fast Charging Constraints**
- location & charging time

Problem Setting

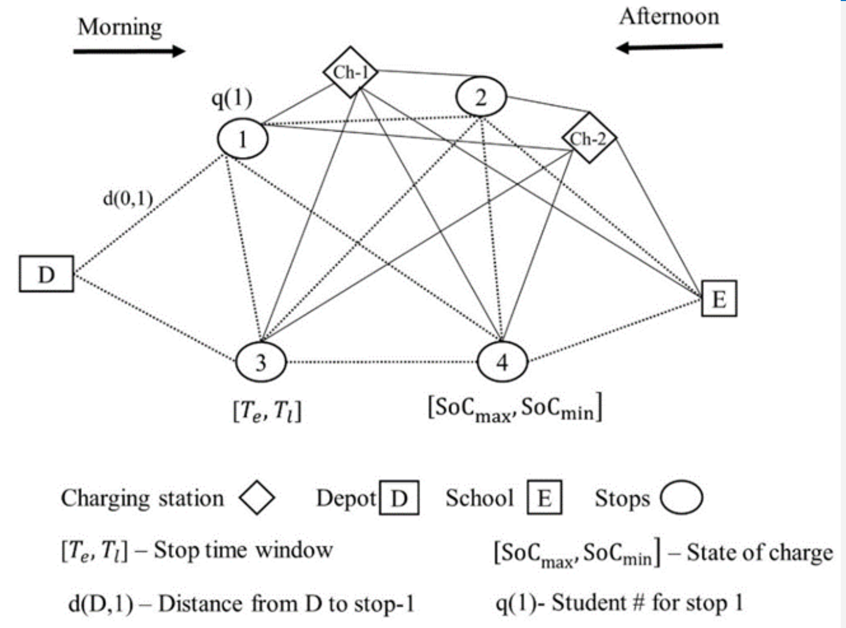
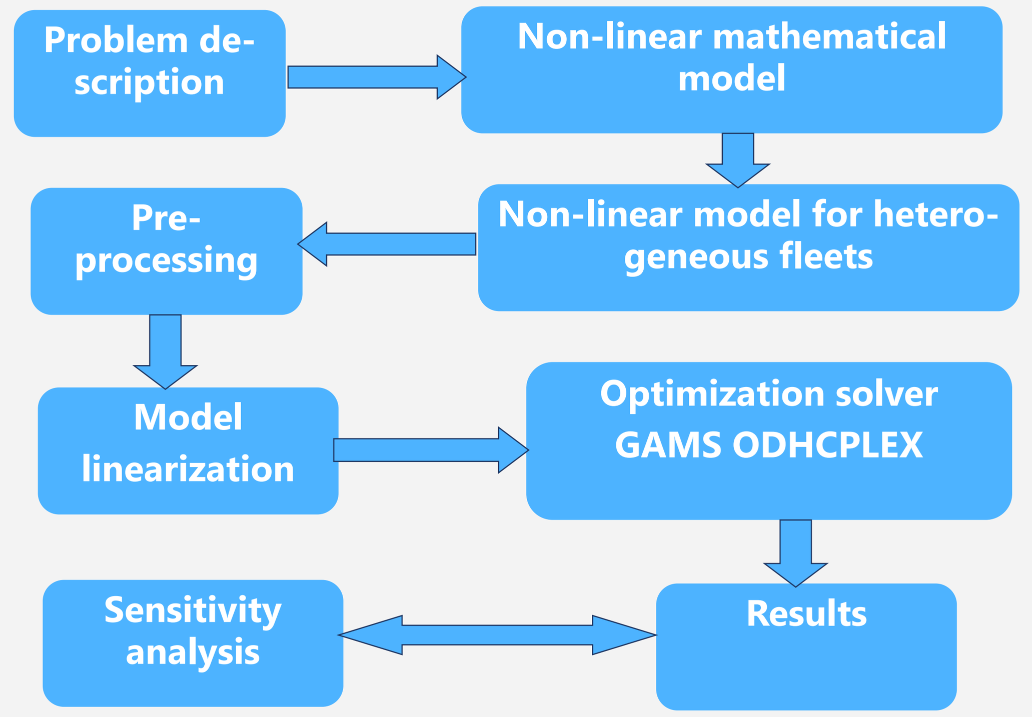


Figure 3:Typical school layout depot, the student stops, and school with a possible charging location

Methodology



Mathematical Model Formulation

$$Min \sum_{k\in K} f^k \sum_{j\in V'} x_{0j}^k + \sum_{k\in K} c_t^k \sum_{i\in V_0', j\in V_{0,E}'} t_{ij} x_{ij}^k + \sum_{k\in K} (c_r + g c_t^k) \sum_{i\in F, j\in V_E'} (Y_i^k - v_i^k) z_i^k \quad (1)$$

Subject to,

$$\sum_{k\in K} \sum_{j\in V_E'} x_{ij}^k = 1 \quad \forall i \in V \quad (2)$$

$$\sum_{k\in K} z_i^k \leq 1 \quad \forall i \in F \quad (3)$$

$$\sum_{i\in V_0'} x_{ip}^k = \sum_{j\in V_E'} x_{pj}^k \quad \forall k \in K, \forall p \in V' \quad (4)$$

$$t_i^k + (t_{ij} + s_i) x_{ij}^k \leq t_j^k + M(1 - x_{ij}^k) \quad \forall k \in K, \forall i \in V_0, \forall j \in V_E' \quad (5)$$

$$t_i^k + t_{ij} x_{ij}^k + g(Y_i^k - v_i^k) z_i^k \leq t_j^k + M(1 - x_{ij}^k) \quad \forall k \in K, \forall i \in F, \forall j \in V_E' \quad (6)$$

$$T_j^e \sum_{i\in V_0'} x_{ij}^k \leq t_j^k \leq T_j^l \sum_{i\in V_0'} x_{ij}^k \quad \forall k \in K, \ \forall j \in V_E' \quad (7)$$

$$\sum_{i\in S} q_i \sum_{j\in V_E'} x_{ij}^k \leq C^k \quad \forall k \in K \quad (8)$$

$$v_j^k \leq v_i^k - r^k d_{ij} x_{ij}^k + B^k (1 - x_{ij}^k) \quad \forall k \in K, \forall i \in V, \forall j \in V_E' \quad (9)$$

$$v_j^k \leq Y_i^k - r^k d_{ij} x_{ij}^k + B^k (1 - x_{ij}^k) \quad \forall k \in K, \forall i \in F, \forall j \in V_E' \quad (10)$$

$$v_i^k \leq Y_i^k \leq B^k \quad \forall k \in K, \forall i \in F \quad (11)$$

$$x_{ij}^k \in \{0,1\} \quad \forall i \in V_0', \forall j \in V_E', \forall k \in K, \ i \neq j \quad (12)$$

$$z_i^k \in \{0,1\} \quad \forall i \in F, \ \forall k \in K \quad (13)$$

$$z_i^k = \sum_{j\in V_E'} x_{ij}^k \quad \forall i \in F, \forall k \in K \quad (14)$$

Model Linearization

$$p_i^k \leq B z_i^k \quad \forall i \in F \quad (16)$$

$$p_i^k \leq (Y_i^k - v_i^k) \quad \forall i \in F \quad (17)$$

$$p_i^k \geq (Y_i^k - v_i^k) - (1 - z_i^k) B^k \ \forall i \in F \quad (18)$$

$$p_i^k \geq 0 \quad \forall i \in F \quad (19)$$

Revised objective function

$$\sum_{k\in K} f^k \sum_{j\in V'} x_{0j}^k + \sum_{k\in K} c_t \sum_{i\in V_0', j\in V_{0,E}'} t_{ij} x_{ij}^k + \sum_{k\in K} (c_r + g c_t^k) \sum_{i\in F, j\in V_E'} p_i^k \quad (20)$$

Constraint (6)

$$t_i^k + t_{ij} x_{ij}^k + g p_i^k \leq t_j^k + M(1 - x_{ij}^k) \quad \forall k \in K, \forall i \in F, \forall j \in V_E' \quad (21)$$

Results for Small & medium-sized Networks

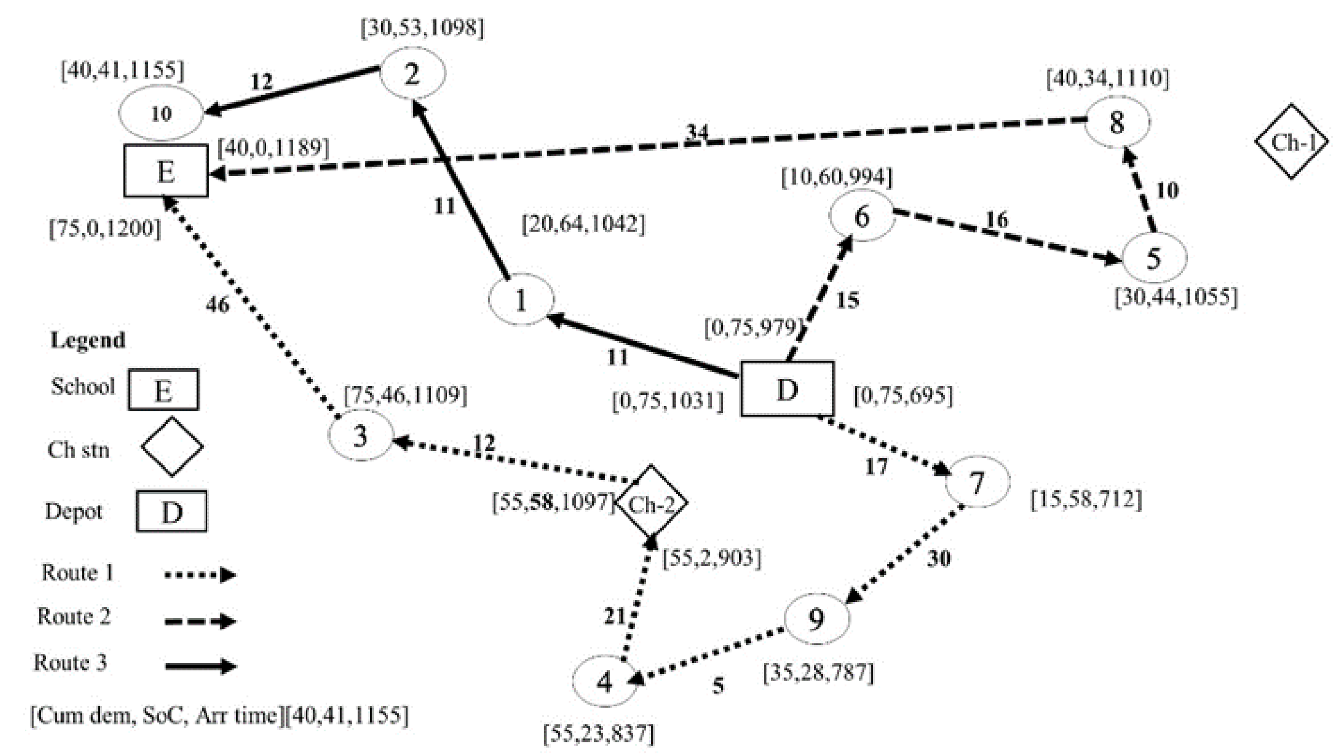


Figure 4:ESBRP for 14 nodes test network: route optimization with partial charging

Results

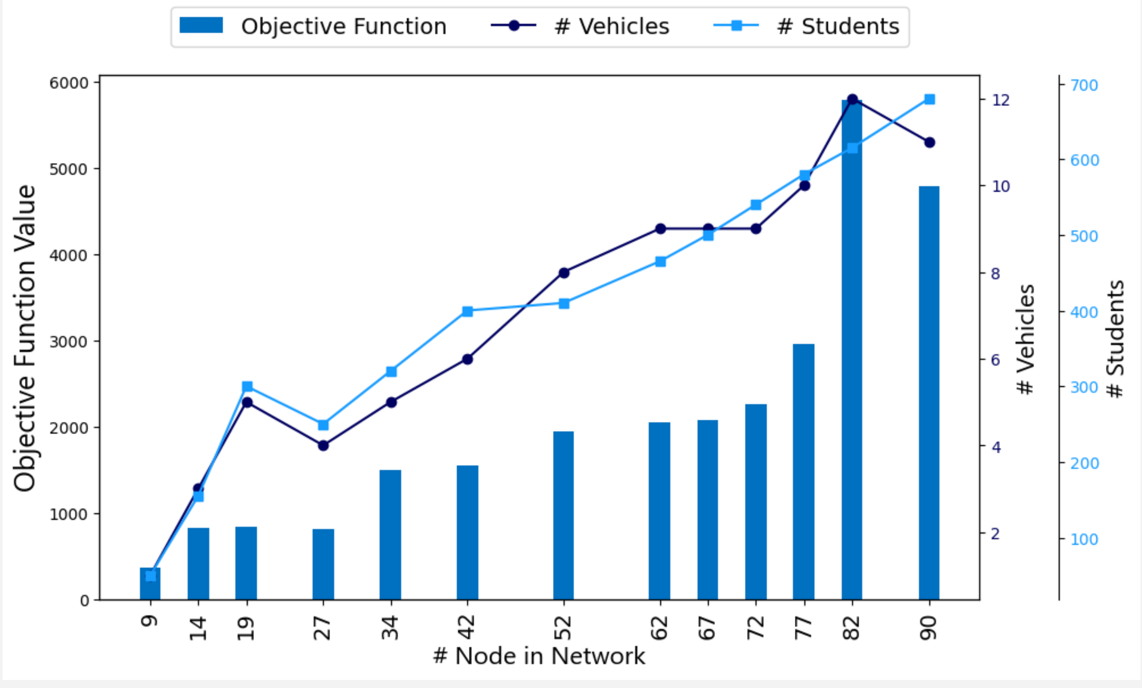
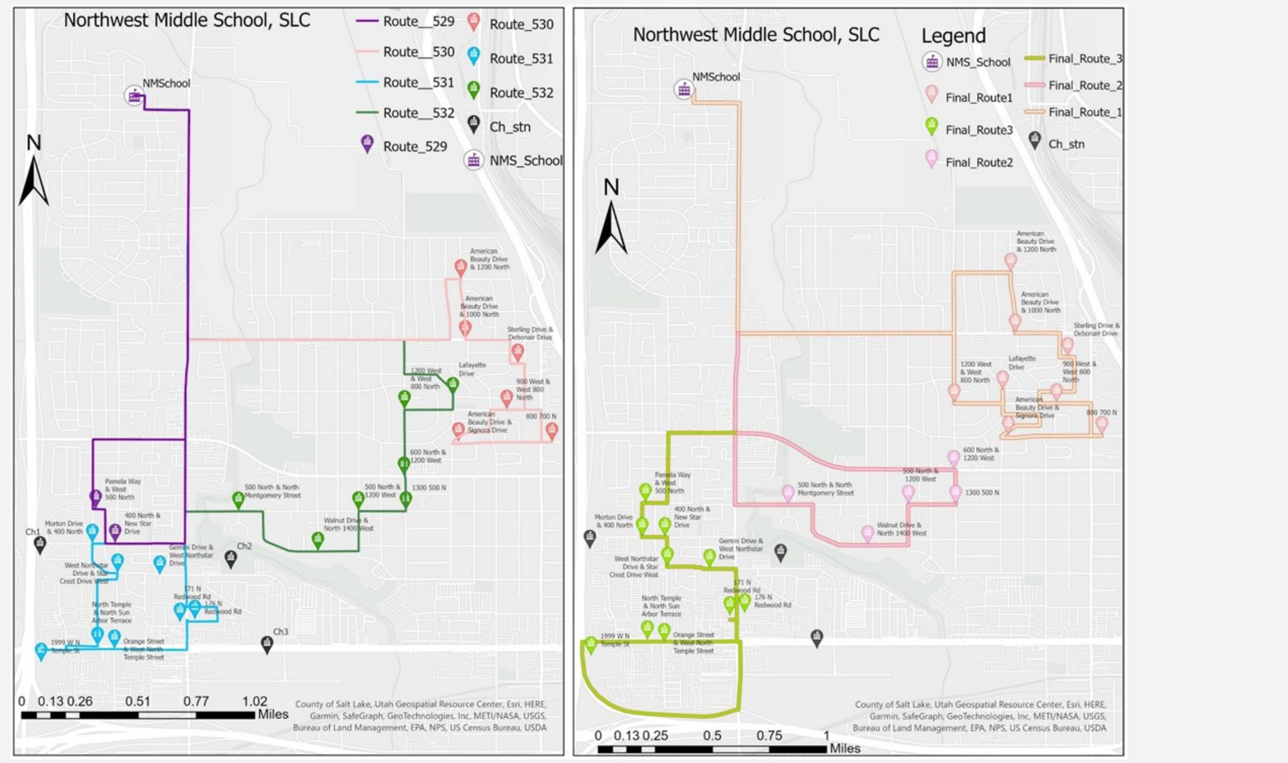


Fig 5: Model Results for small and Medium-sized School Networks

Real-world case Study Result: Before & After



Sensitivity Analysis

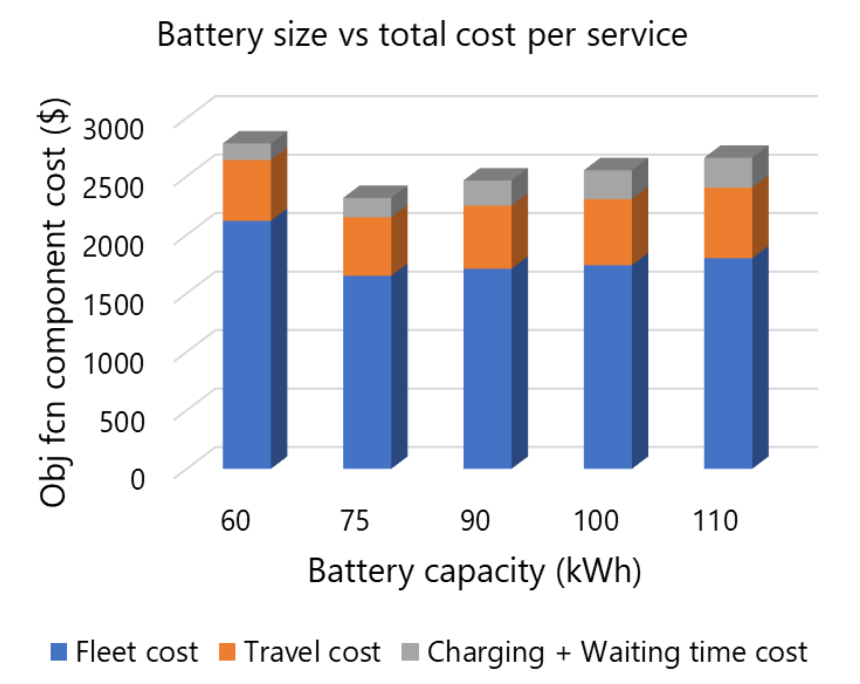


Fig 6: Sensitivity for Battery Sizes to Cost per Service

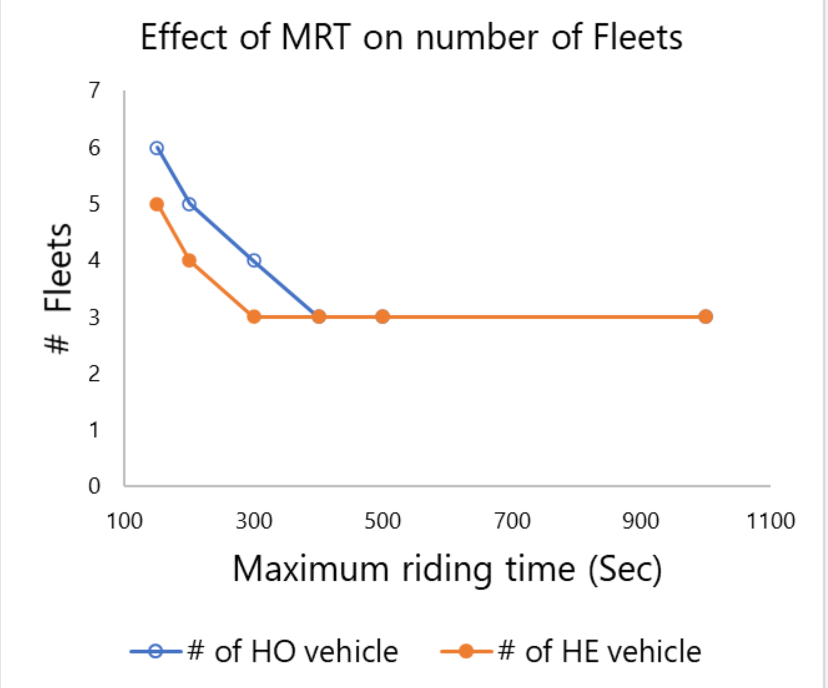


Fig 7: Effect of MRT on # Fleets for HO & HE Combination

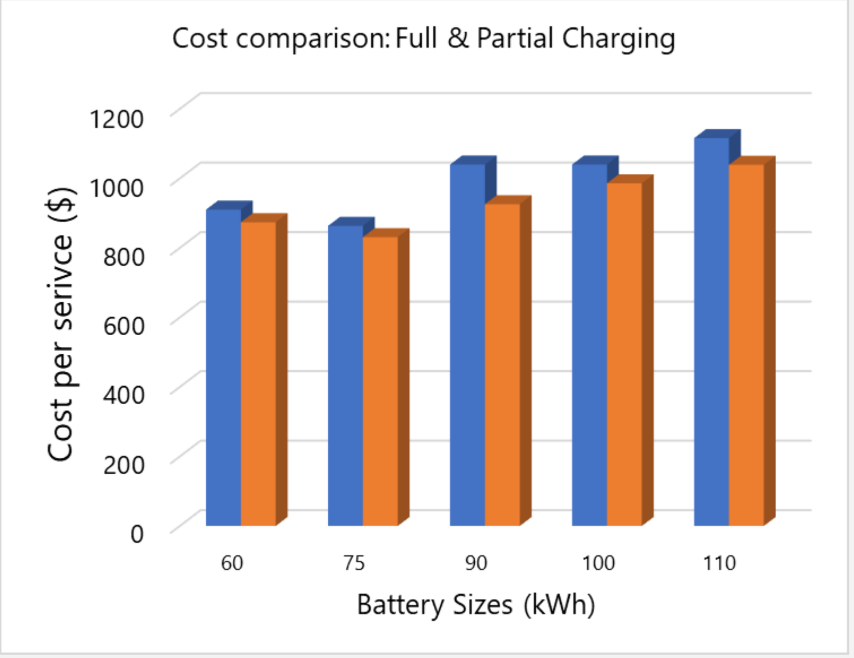


Fig 8: Benefits of Partial Charging over Full Charging

Real-world case Study Result

# node	Obj fcn value	# of vehicle	#of students	TD (miles)	# of Ch stn used	Partial charge	Remark
28	978.36	5	195	16.65	0	(50)	HO
28	923.14	4	195	14.75	1	28 (60)	
28	806.46	3	195	10.89	0	(75)	
28	874.41	3	195	11.05	1	31 (90)	
28	911.22	2	195	10.74	2	12,18(100)	
28	888.84	2	195	8.63	0	(110)	
28	778.12	3	195	10.89	0	(50,75,90)	HE

- 3 BEB is enough for the school transportation
- 56% decrease in travel distance
- 25% reduction of buses
- 3.51% total cost saving
- 5.7% saving in student's travel time
- Strong support for the bus electrification

Conclusion & Way Forward

- A new shift toward school bus electrification ESBRP was solved through simultaneous routing, scheduling, and partial charging
- Solved more than 90 node networks in a reasonable time
- Use of heterogenous bus combination proves to be economical
- 3.51% operation cost saving, 5.7% student travel time saving and 56% shorter travel time is promising result towards school bus electrification

⇒The development of heuristic & meta-heuristic methods for large-scale network optimization could be the direct extension

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