A validated heuristic approach for a mixed-fleet routing problem with time windows

and optimal location of multiple charging stations



Presented by **Bernard A. Adjei**

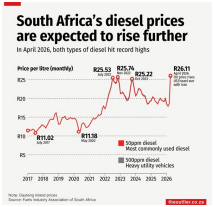
MOOCTA Workshop - Pretoria, South Africa

7-10 September 2026

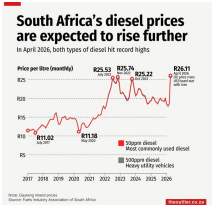
Overview

1. Introduction & Motivation
2. Methodology & Model
3. Numerical Results
4. Case Study & Regional Context
5. Sensitivity of Battery Capacity
6. Implications for Sub-Saharan Africa

Urban EV Logistics – An Emerging Priority for Africa



Urban EV Logistics – An Emerging Priority for Africa



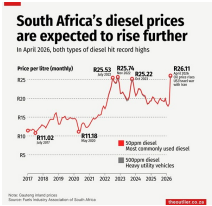
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Vehicle emissions control strategy and action plan for

THE CITY OF JOHANNESBURG

a world class African city

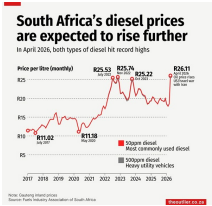
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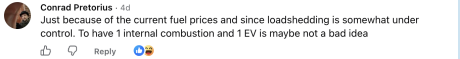
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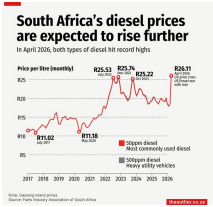




sparks reaction



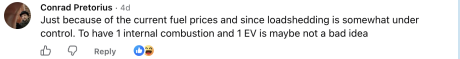
Urban EV Logistics – An Emerging Priority for Africa







sparks reaction



So what's actually stopping EV adoption from keeping up?

Barriers to EV Adoption

Three core barriers slow EV adoption:



1. **Limited battery range** (Keskin and Çatay, 2016)

Barriers to EV Adoption

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↓

2. **Long charging times** (Dixon and Bell, 2020)

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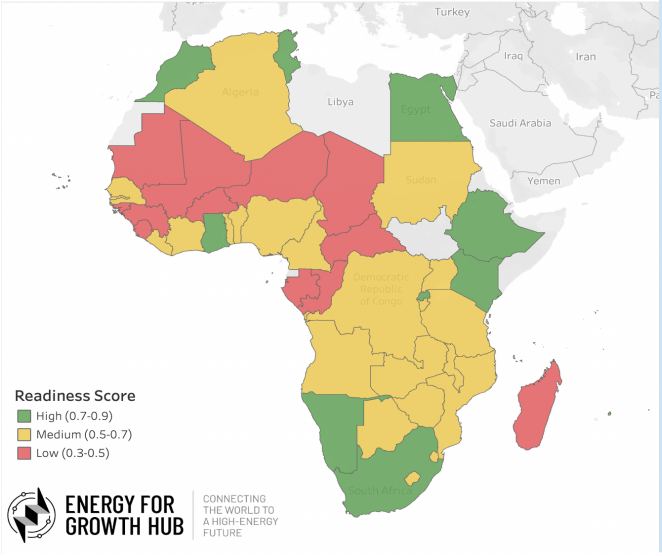
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2. **Long charging times** (Dixon and Bell, 2020)

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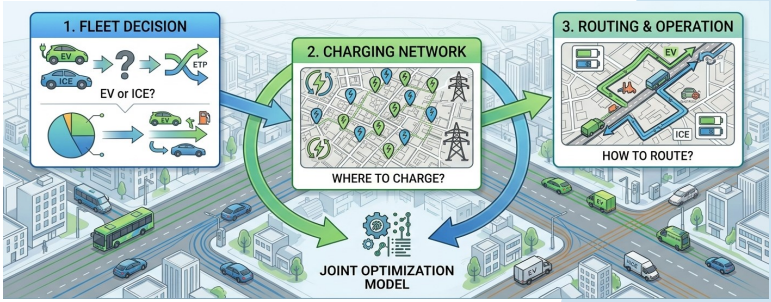
3. **Poorly-sited charging infrastructure** (Dixon and Bell, 2020; He et al., 2019)

Readiness Map: Preparedness to adopt EVs at scale



A question to consider

How should a city transitioning to electric mobility jointly decide which vehicles (EV & ICEV) to use, where to charge them, and how to route them?



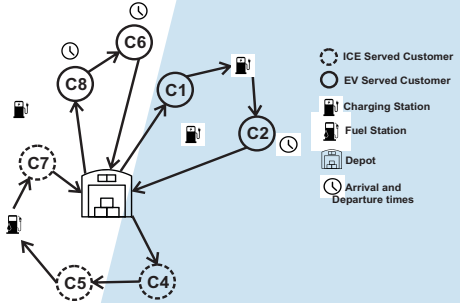
Problem Definition

Network nodes

- Single depot – start/end point for all vehicles.
- Customers $\mathcal{C}$ – each with multi-product, time-windowed demand.
- EV charging stations $\mathcal{CS}$ – offering a choice between slow and fast charger.
- Fuel stations $\mathcal{FS}$ – instantaneous ICEV refuel.

Heterogeneous fleet

- $\mathcal{K}_{EV}$ – battery capacity, rechargeable at $\mathcal{CS}$.
- $\mathcal{K}_{ICEV}$ – fuel tank, refuelable at $\mathcal{FS}$.



NB: EV policy (soft) $\geq$ 50% of total fleet-km driven by EVs.

Objective Functions – Seven Criteria

Seven minimisation objectives

$$\text{total travel distance} \quad (\mathcal{O}_1) = \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{V}} \sum_{j \in \mathcal{V}} d_{ij}\, x_{ij}^{k}$$

$$\text{total travel time} \quad (\mathcal{O}_2) = \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{V}} \sum_{j \in \mathcal{V}} t_{ij}\, x_{ij}^{k}$$

$$\text{total charging cost} \quad (\mathcal{O}_3) = \sum_{i \in \mathcal{CS}} \sum_{k \in \mathcal{K}_{EV}} \sum_{p \in \mathcal{P}} z_i^{k,p}$$

$$\text{total infrastructure cost} \quad (\mathcal{O}_4) = \sum_{i \in \mathcal{CS}} \sum_{p \in \mathcal{P}} \text{cost}_p\, y_i^{p}$$

$$\text{total waiting time} \quad (\mathcal{O}_5) = \sum_{i \in \mathcal{C}} \sum_{k \in \mathcal{K}} \text{waiting}_i^{k}$$

$$\text{total fueling cost} \quad (\mathcal{O}_6) = \sum_{i \in \mathcal{FS}} \sum_{k \in \mathcal{K}_{ICEV}} r_i^{k}$$

$$\text{shortfall} \quad (\mathcal{O}_7) = \text{ev distance shortfall}$$

Objective-wise Benchmarks

Each objective is optimised individually using the MILP model:

$$v_r^* = \min\ \mathcal{O}_r, \qquad r = 1, \ldots, 7$$

These values provide single-objective benchmark values for evaluating NSGA-III.

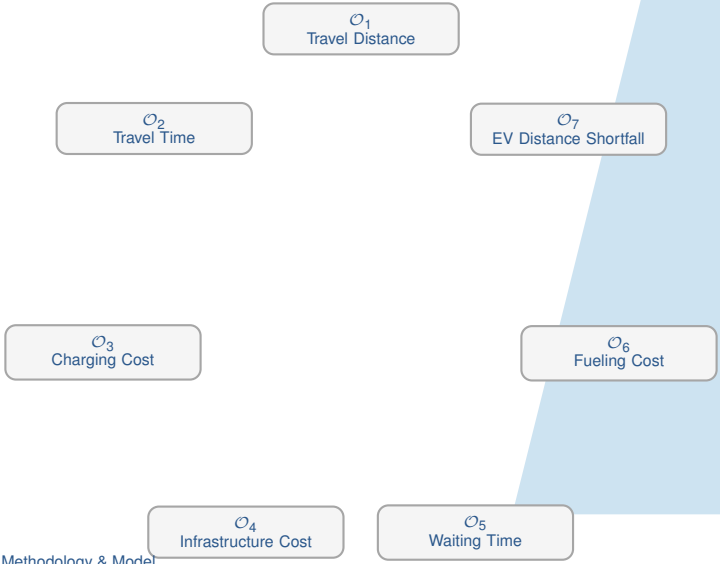
Simultaneous Optimisation

All seven objectives are optimised simultaneously:

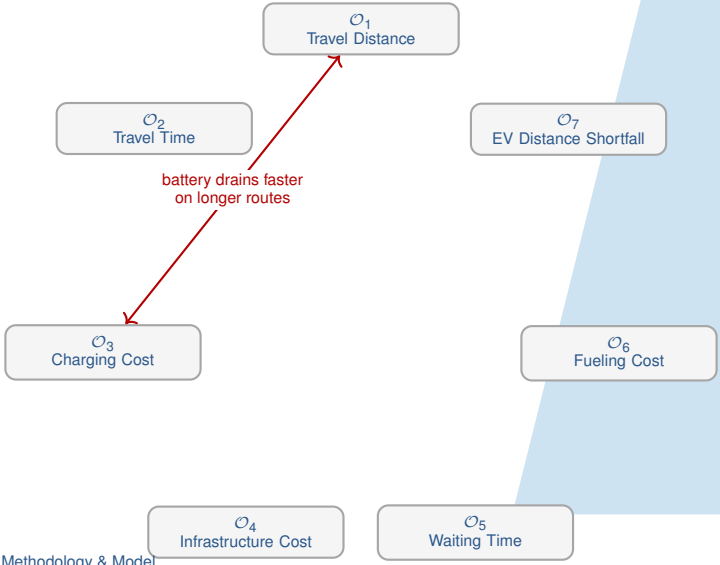
$$\min\,(\mathcal{O}_1, \ldots, \mathcal{O}_7)$$

Produces a diverse approximation of the Pareto-optimal solution set.

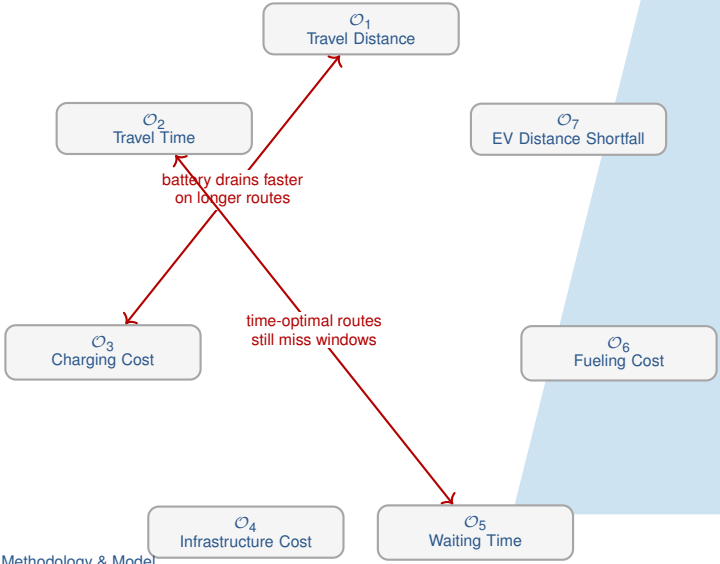
Why Multi-Objective Optimization?



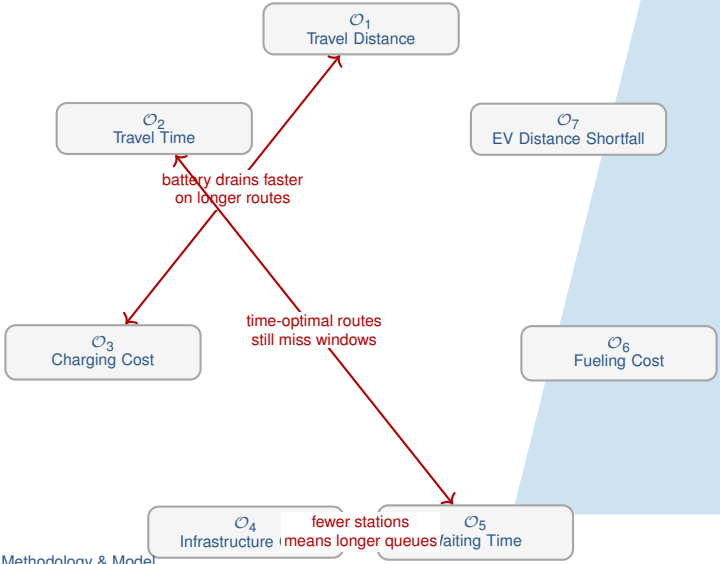
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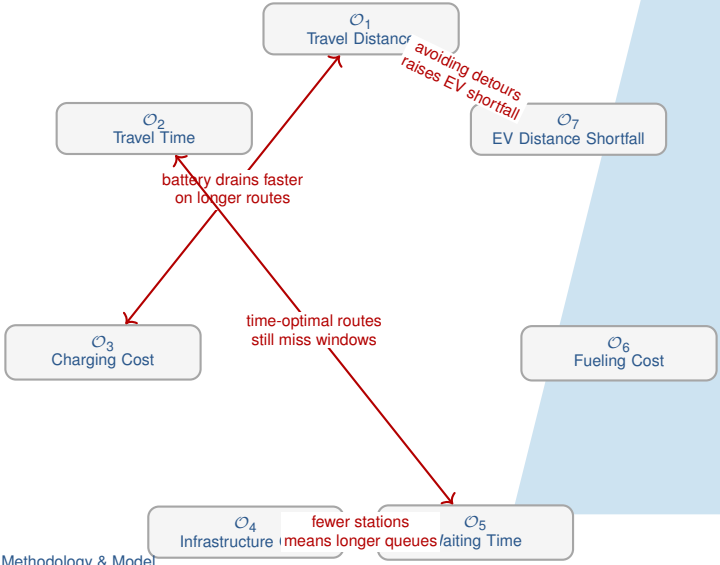
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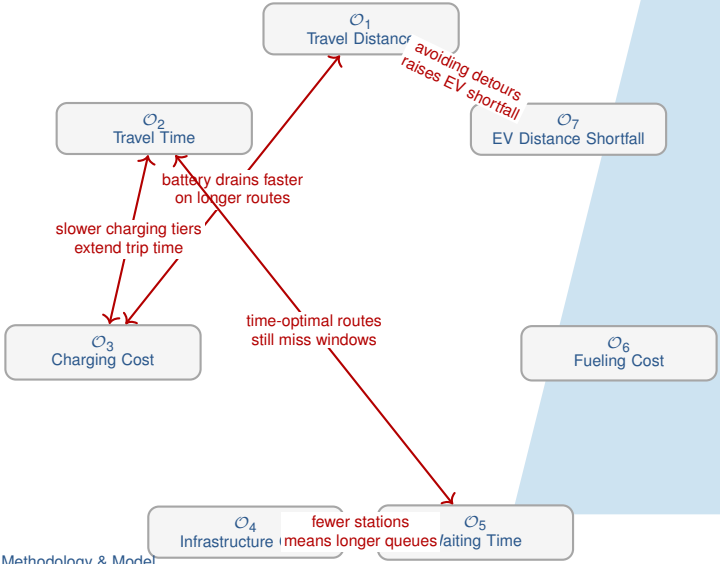
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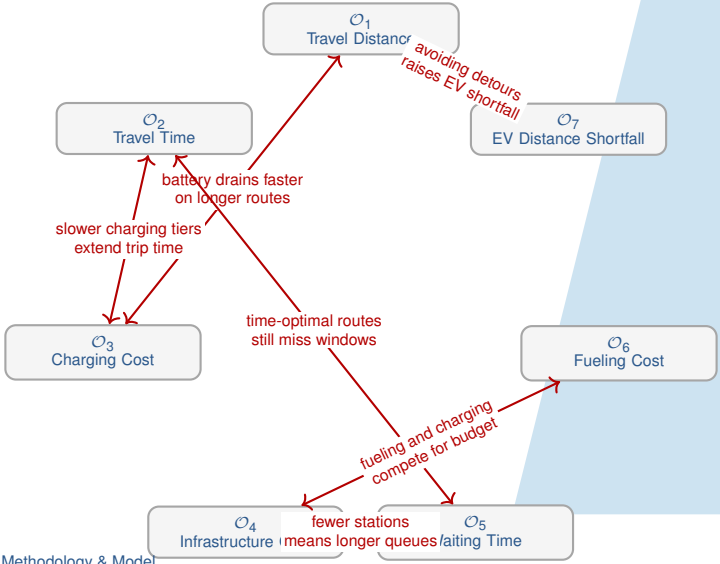
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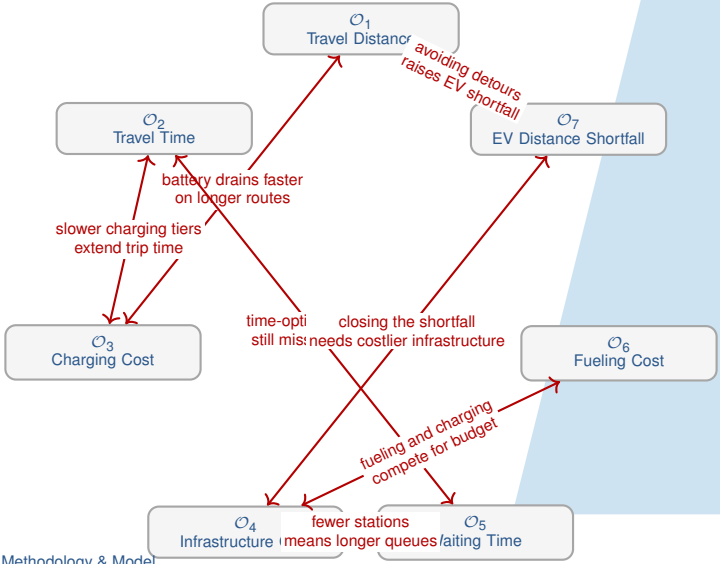
Why Multi-Objective Optimization?



Why Multi-Objective Optimization?



Why Multi-Objective Optimization?



Representative Constraints

The full model has 28 constraints across six families – routing, energy/fuel, charging, refuelling, time windows, and delivery/capacity.

$$\sum_{k \in \mathcal{K}} \sum_{j \in \mathcal{V},\, j \neq i} x_{ji}^{k} = 1 \qquad \forall i \in \mathcal{C} \qquad \text{(visit each customer once)}$$

$$\text{battery}_{j}^{k} = \text{battery}_{i}^{k} - e_{ij}^{k} + \sum_{p \in \mathcal{P}} z_{j}^{k,p} \mathbf{1}_{j \in \mathcal{CS}} \qquad \forall k \in \mathcal{K}_{EV} \qquad \text{(state of charge)}$$

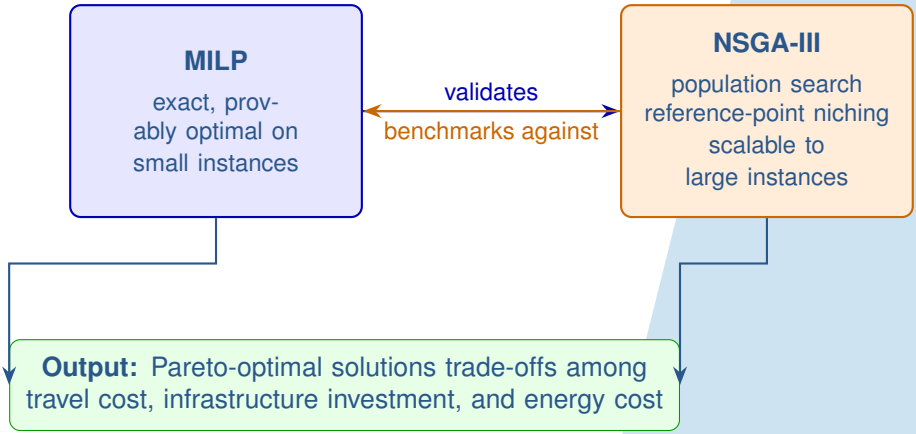
$$\sum_{p \in \mathcal{P}} z_{i}^{k,p} \leq Q_{\text{type}(k)} - \text{battery}_{i}^{k} \qquad \forall i \in \mathcal{CS} \qquad \text{(charge up to capacity)}$$

$$a_i \leq \text{arrival}_{i}^{k} \leq b_i \qquad \forall i \in \mathcal{C} \qquad \text{(time windows)}$$

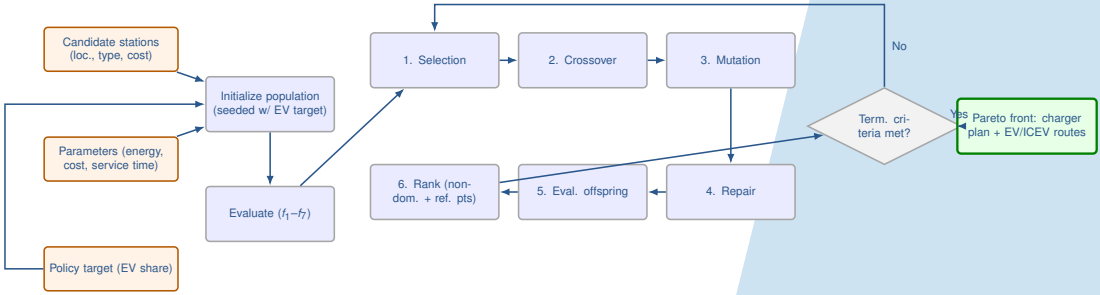
$$\text{ev_shortfall} \geq 0.5 \sum_{k \in \mathcal{K}} \sum_{i,j} d_{ij} x_{ij}^{k} - \sum_{k \in \mathcal{K}_{EV}} \sum_{i,j} d_{ij} x_{ij}^{k} \qquad \text{(EV policy)}$$

Full constraint set available in the appendix.

Dual - Solution Framework



NSGA-III Framework Overview

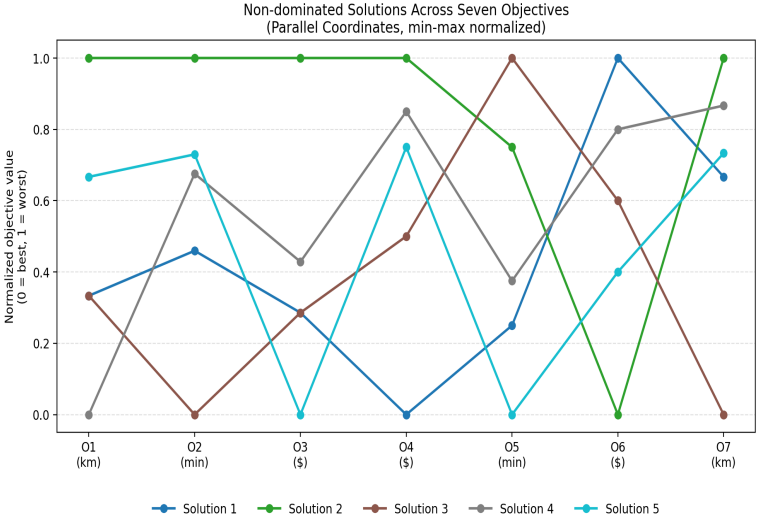


Validating the NSGA with MILP Anchor Points

The optimal MILP solution: $[450, 1.33, 2.3, 0, 110, 0, 55]$

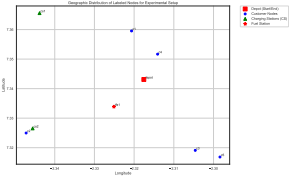
Five non-dominated dummy solutions.

Solution	$\mathcal{O}_1$ (km)	$\mathcal{O}_2$ (min)	$\mathcal{O}_3$ ($)	$\mathcal{O}_4$ ($)	$\mathcal{O}_5$ (min)	$\mathcal{O}_6$ ($)	$\mathcal{O}_7$ (km)
1	500	1.50	2.5	0	120	5	65
2	600	1.70	3.0	2.0	140	0	70
3	500	1.33	2.5	1.0	150	3	55
4	450	1.58	2.6	1.7	125	4	68
5	550	1.60	2.3	1.5	110	2	66

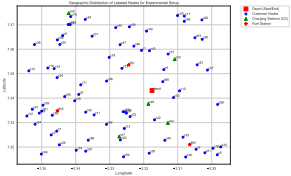

Non-dominated Solutions Across Seven Objectives
(Parallel Coordinates, min-max normalized)
Normalized objective value
(0 = best, 1 = worst)
1.0
0.8
0.6
0.4
0.2
0.0
O1
(km)
O2
(min)
O3
($)
O4
($)
O5
(min)
O6
($)
O7
(km)
Solution 1
Solution 2
Solution 3
Solution 4
Solution 5

Test Instances

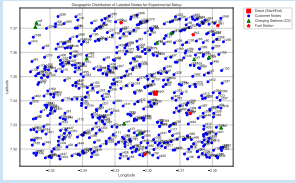
Class	Customers	$\mathcal{CS}$	$\mathcal{FS}$	Fleet
Small (S1–S3)	5, 10, 15	2	1	2
Medium (M1–M3)	25, 50, 75	5	3	6
Large (L1–L3)	100, 250, 500	10	5	15



(a) S3



(b) M3



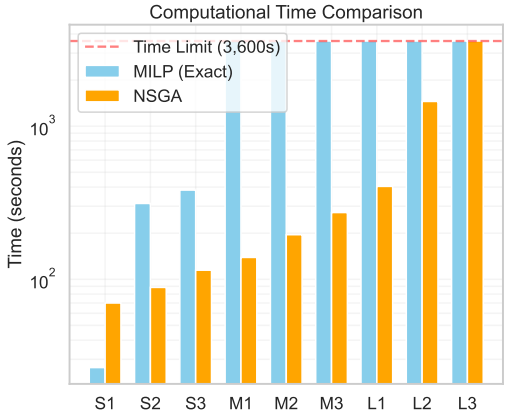
(c) L3

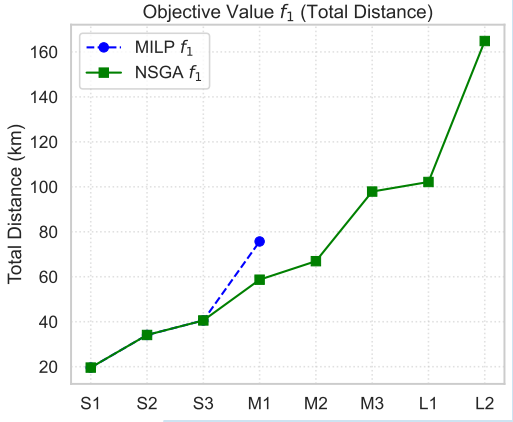
MILP vs. NSGA-III: Validation and Scalability

ID	Gurobi MILP		NSGA-III	
	$(\mathcal{O}_1, \mathcal{O}_7)$	Time (s)	$(\mathcal{O}_1, \mathcal{O}_7)$	Time (s)
S1	(19.61, 0.70)	26.5	(19.61, 0.70)	70.0
S2	(34.11, 0.00)	312.8	(34.11, 0.00)	88.5
S3	(40.57, 0.00)	382.5	(40.57, 0.00)	114.7
M1	(75.70, 12.24)	3600*	(58.70, 12.24)	138.9
M2	N/A	3600†	(66.93, 15.98)	195.5
L1–L2	N/A	3600†	feasible	up to 1451
L3 (500 cust.)	N/A	3600†	N/A	3600†

$\mathcal{O}_1$: total distance (km); $\mathcal{O}_7$: EV shortfall (km). * Gurobi reaches the time limit with a suboptimal incumbent. † No feasible integer solution within the time limit. The L3 was solved at 5900s

Performance Comparison

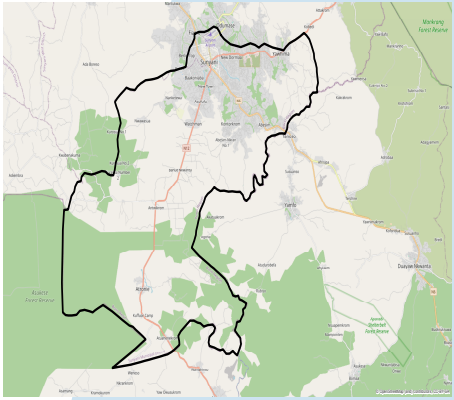


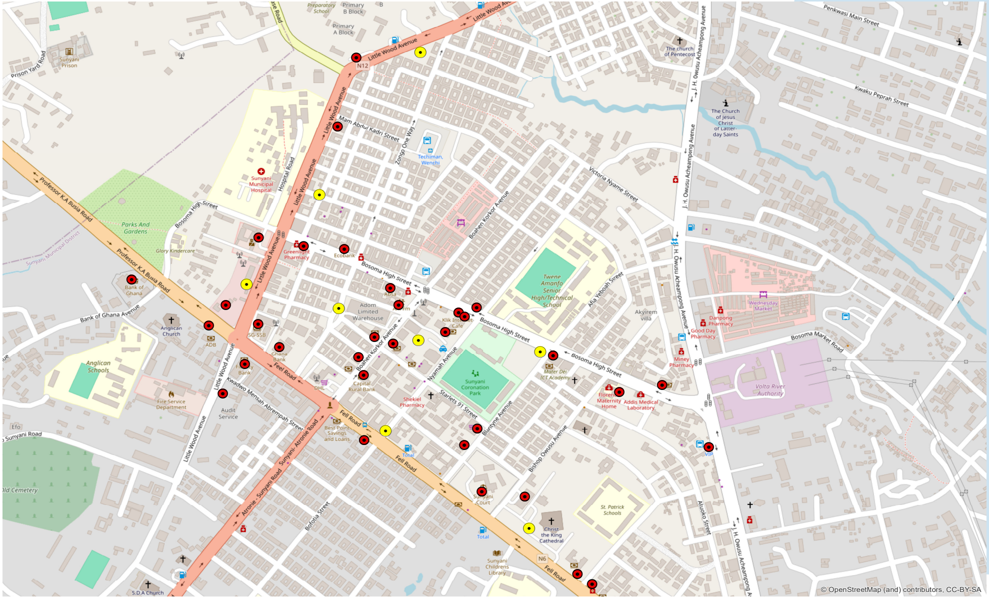


Case Study Setup

Network Configuration

- Depot - Esbak Depot
- Customers - 39 delivery locations (lunch meals)
- Fuel stations (TFS) - 9 existing
- Candidate CS – 11 locations (universal design guideline)
- Fleet - Mixed EVs + ICEVs
- Data - Google maps distance matrix API
- Energy model EV from (Miri et al., 2021); ICEV from (Ben-Chaim et al., 2013).




Preparatory School
Primary B Block
Primary A Block
Little Wood Avenue
N12
Sunyani Prison
Prison Yard Road
Mam Abdul Kadri Street
Zongo One Way
Techiman, Wenchi
The church of Pentecost
J. H. Owusu Acheampong Avenue
The Church of Jesus Christ of Latter-day Saints
Penkwasi Main Street
Kwaku Peprah Street
Victoria Nyame Street
Sunyani Municipal Hospital
Hospital Road
Professor K.A Busia Road
Parks And Gardens
Glory Kindercare
Bosoma High Street
Greenlight Pharmacy
Ecobank
Boahen Korkor Avenue
Twene Amanfo Senior High/Technical School
Afia Yeboah Street
Akyirem Villa
Bank of Ghana
Bank of Ghana Avenue
Absa
Adom Limited Warehouse
Klik Internet Cafe
Wednesday Market
Danpong Pharmacy
Good Day Pharmacy
Bosoma Market Road
Anglican Church
ADB
SG-SSB
Ghana Bank
Anglican Schools
Feel Road
Nyamah Avenue
Sunyani Coronation Park
Mater Dei ICT Academy
Miney Pharmacy
Volta River Authority
Florence Maternity Home
Addis Medical Laboratory
DHL
Capital Rural Bank
Shekiel Pharmacy
Starlets 91 Street
Fire Service Department
Audit Service
Kwadwo Mensah Abrempah Street
Sunyani-Atronie Road
Best Point Savings and Loans
Fell Road
Total
Efo
Sunyani Road
Old Cemetery
Bishop Owusu Avenue
Sunyani Court
VIP
Christ the King Cathedral
St. Patrick Schools
Atuoko Street
Bofotia Street
Atronie - Sunyani Road
Sunyani Childrens Library
N6
S.D.A Church
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Two Pareto-Optimal Strategies

Solution	TD (km)	IC ($)	CC ($)	FC ($)	TT (min)	EV Shortfall
A (Economy)	39.17	73,700	4.52	2.66	30.32	0.00
B (Speed)	45.05	242,000	5.31	2.79	12.62	0.00

Key points

- Solution B invests 3.28$\times$ more in infrastructure for a 58% reduction in transport time.
- Both solutions keep **zero EV shortfall** ($>$80% of distance by EV).
- Showing the $\geq$ 50 % EV-share policy is achievable without over-building.

Optimised Routes - Solution B (Speed Strategy)

- EV-dominant operation: 5 EVs + 1 ICEV
- Fast chargers installed at CS3, CS5, CS6, CS8
- Vehicles arrive at low state-of-charge, recharge quickly, and complete delivery legs with a 15–20% safety buffer

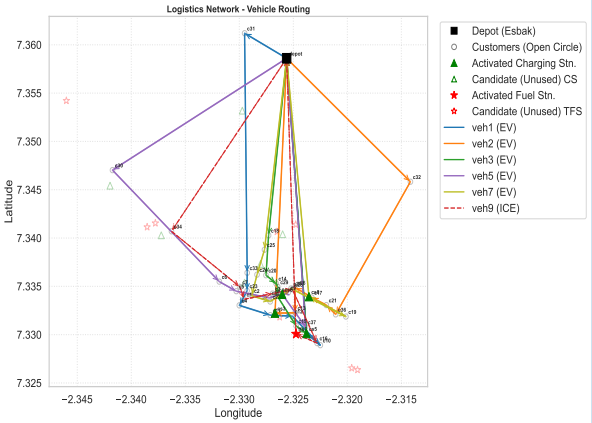
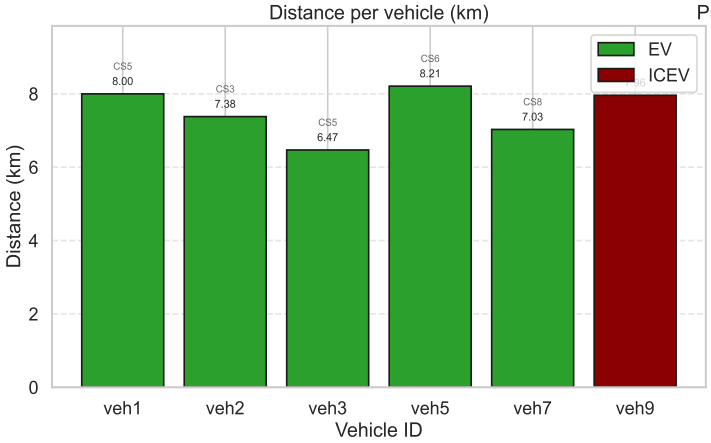
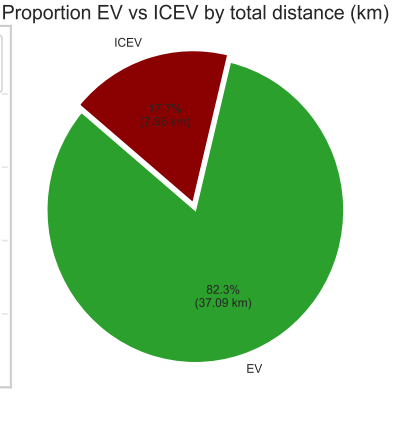
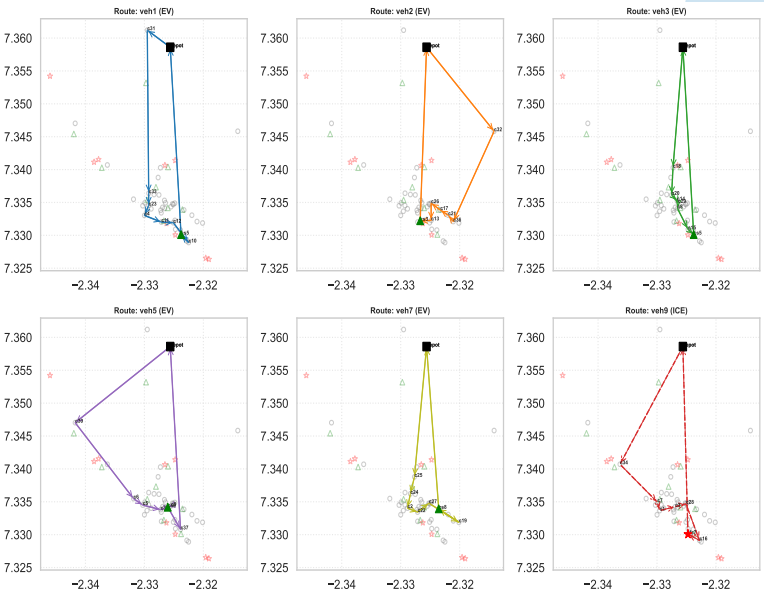


Figure: Consolidated routing network – Solution B

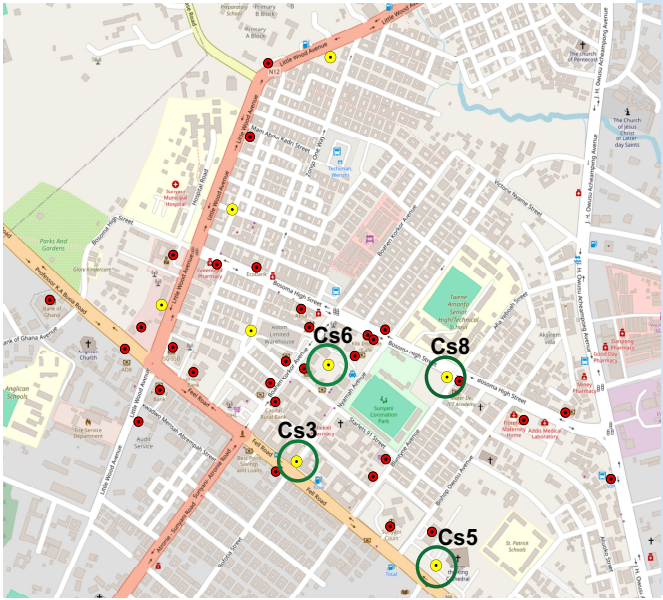

Distance per vehicle (km)
EV
ICEV
Distance (km)
0
2
4
6
8
C$5
8.00
C$3
7.38
C$5
6.47
C$6
8.21
C$8
7.03
veh1
veh2
veh3
veh5
veh7
veh9
Vehicle ID


Proportion EV vs ICEV by total distance (km)
ICEV
17.7%
(7.36 km)
82.3%
(37.09 km)
EV


Route: veh1 (EV)
Route: veh2 (EV)
Route: veh3 (EV)
Route: veh5 (EV)
Route: veh7 (EV)
Route: veh9 (ICE)
depot
7.360
7.355
7.350
7.345
7.340
7.335
7.330
7.325
−2.34
−2.33
−2.32

Optimal Charging Station Locations

CS	Vehicles	Role	Rationale
CS5	V1, V3	Central hub	Mid-point for north & east loops
CS3	V2	East sector	Near a major demand cluster
CS8	V7	Southern anchor	Covers peripheral south routes
CS6	V5	Western support	Enables western loop


Cs6
Cs8
Cs3
Cs5

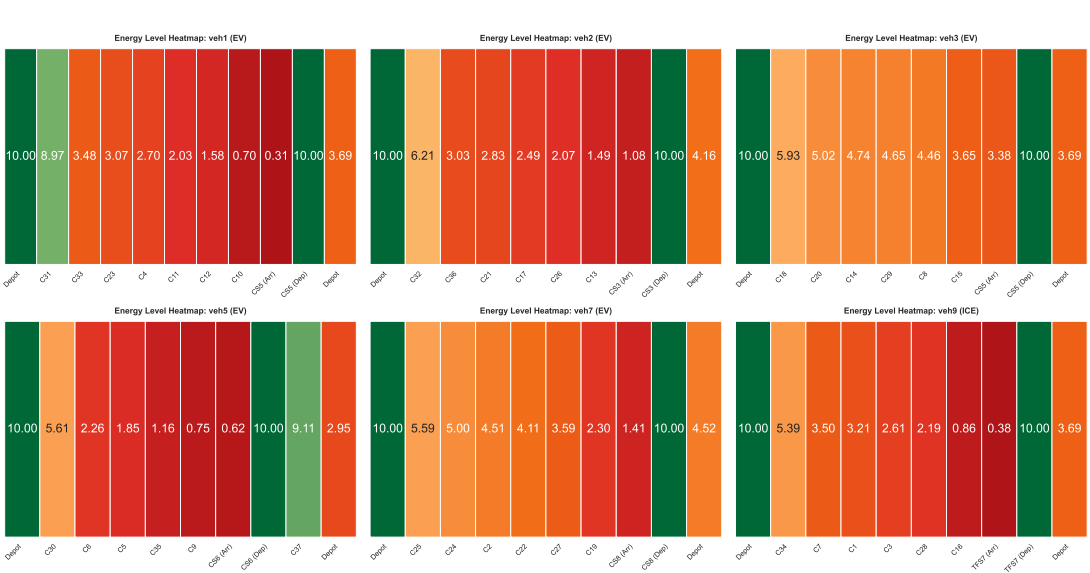
Battery Capacity Sensitivity

Scenario	Total Dist. (km)	Battery Increment	EV Dist. (km)
S1 – Baseline	45.05	–	37.09
S2	24.39	+10%	17.84
S3	23.95	+20%	17.39

Critical Threshold Effect

A **10% increase in battery capacity**:

- Reduces total travel distance by **45.8%**.
- A further 10% (S3) yields only marginal gains.


Vehicle Energy Propagation Heatmap - Solution B Strategy
Energy Level Heatmap: veh1 (EV)
10.00 8.97 3.48 3.07 2.70 2.03 1.58 0.70 0.31 10.00 3.69
Depot C31 C33 C23 C4 C11 C12 C10 CS5 (Arr) CS5 (Dep) Depot
Energy Level Heatmap: veh2 (EV)
10.00 6.21 3.03 2.83 2.49 2.07 1.49 1.08 10.00 4.16
Depot C32 C36 C21 C17 C26 C13 CS3 (Arr) CS3 (Dep) Depot
Energy Level Heatmap: veh3 (EV)
10.00 5.93 5.02 4.74 4.65 4.46 3.65 3.38 10.00 3.69
Depot C16 C20 C14 C29 C9 C15 CS5 (Arr) CS5 (Dep) Depot
Energy Level Heatmap: veh5 (EV)
10.00 5.61 2.26 1.85 1.16 0.75 0.62 10.00 9.11 2.95
Depot C30 C8 C5 C35 C9 CS6 (Arr) CS6 (Dep) C37 Depot
Energy Level Heatmap: veh7 (EV)
10.00 5.59 5.00 4.51 4.11 3.59 2.30 1.41 10.00 4.52
Depot C25 C24 C2 C22 C27 C19 CS4 (Arr) CS4 (Dep) Depot
Energy Level Heatmap: veh9 (ICE)
10.00 5.39 3.50 3.21 2.61 2.19 0.86 0.38 10.00 3.69
Depot C34 C7 C1 C3 C28 C16 TFS7 (Arr) TFS7 (Dep) Depot

Implications for Sub-Saharan Africa

The transition to electric logistics does not require replacing the entire fleet at once.

A strategically designed **mixed fleet**, combined with **demand-driven charging infrastructure**, can achieve the EV target while balancing **cost and service time**.

A practical pathway for the transition to electric logistics

Limitations & Future Work

Current Limitations

- Deterministic demand only

Future Directions

- Multi-seed validation of NSGA-III
- Multi-depot extensions
- Benders decomposition for L3+
- Multi-city validation across the SSA region

Thank you

Questions and comments welcome.

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Routing constraints

$$\sum_{k \in \mathcal{K}} \sum_{j \in \mathcal{V}, j \neq i} x_{ji}^k = 1 \qquad \forall i \in \mathcal{C} \tag{1}$$

$$\sum_{i \in \mathcal{V}, i \neq v} x_{iv}^k = \sum_{j \in \mathcal{V}, j \neq v} x_{vj}^k \qquad \forall v \in \mathcal{V},\ k \in \mathcal{K} \tag{2}$$

$$\sum_{j \in \mathcal{V}, j \neq \text{depot}} x_{\text{depot},j}^k = \text{used}_k \qquad \forall k \in \mathcal{K} \tag{3}$$

$$\sum_{i \in \mathcal{V}, i \neq \text{depot}} x_{i,\text{depot}}^k = \text{used}_k \qquad \forall k \in \mathcal{K} \tag{4}$$

$$\sum_{j \in \mathcal{V}, j \neq i} x_{ij}^k = \text{visit}_i^k \qquad \forall i \in \mathcal{V},\ k \in \mathcal{K} \tag{5}$$

$$u_i^k - u_j^k + M x_{ij}^k \leq M - 1 \qquad \forall k \in \mathcal{K},\ i,j \in \mathcal{V},\ i \neq j,\ i \neq \text{depot},\ j \neq \text{depot} \tag{6}$$

Energy and fuel constraints

$$\text{battery}^k_{\text{depot}} = Q_{\text{type}(k)} \cdot \text{used}_k \qquad \forall k \in \mathcal{K}_{EV} \qquad (7)$$

$$\text{fuel}^k_{\text{depot}} = Q_{\text{type}(k)} \cdot \text{used}_k \qquad \forall k \in \mathcal{K}_{ICEV} \qquad (8)$$

$$\text{battery}^k_j - \left(\text{battery}^k_i - e^k_{ij} + \sum_{p \in \mathcal{P}} z^{k,p}_j \cdot \mathbf{1}_{j \in \mathcal{CS}}\right) \leq M(1 - x^k_{ij}) \qquad \forall k \in \mathcal{K}_{EV},\ i \neq j \qquad (9)$$

$$\text{battery}^k_j - \left(\text{battery}^k_i - e^k_{ij} + \sum_{p \in \mathcal{P}} z^{k,p}_j \cdot \mathbf{1}_{j \in \mathcal{CS}}\right) \geq -M(1 - x^k_{ij}) \qquad \forall k \in \mathcal{K}_{EV},\ i \neq j \qquad (10)$$

$$\text{battery}^k_i \leq Q_{\text{type}(k)} \qquad \forall i \in \mathcal{V},\ k \in \mathcal{K}_{EV} \qquad (11)$$

$$\text{fuel}^k_i \leq Q_{\text{type}(k)} \qquad \forall i \in \mathcal{V},\ k \in \mathcal{K}_{ICEV} \qquad (12)$$

Charging constraints

$$z_i^{k,p} \leq M \cdot w_{i,k,p} \qquad \forall i \in \mathcal{CS}, k \in \mathcal{K}_{EV}, p \in \mathcal{P} \qquad (13)$$

$$w_{i,k,p} \leq \text{charge decision}_i^k \qquad \forall i \in \mathcal{CS}, k \in \mathcal{K}_{EV}, p \in \mathcal{P} \qquad (14)$$

$$w_{i,k,p} \leq y_i^p \qquad \forall i \in \mathcal{CS}, k \in \mathcal{K}_{EV}, p \in \mathcal{P} \qquad (15)$$

$$w_{i,k,p} \geq \text{charge decision}_i^k + y_i^p - 1 \qquad \forall i \in \mathcal{CS}, k \in \mathcal{K}_{EV}, p \in \mathcal{P} \qquad (16)$$

$$\text{charge decision}_i^k \leq \sum_{j \in \mathcal{V}, j \neq i} x_{ji}^k \qquad \forall i \in \mathcal{CS},\ k \in \mathcal{K}_{EV} \qquad (17)$$

$$z_i^{k,p} \leq Q_{\text{type}(k)} \qquad \forall i \in \mathcal{CS},\ k \in \mathcal{K}_{EV},\ p \in \mathcal{P} \qquad (18)$$

$$\sum_{p \in \mathcal{P}} z_i^{k,p} \leq Q_{\text{type}(k)} - \text{battery}_i^k + M\left(1 - \sum_{j \in \mathcal{V}, j \neq i} x_{ji}^k\right) \qquad \forall i \in \mathcal{CS},\ k \in \mathcal{K}_{EV} \qquad (19)$$

$$z_i^{k,p} = 0 \qquad \forall i \in \mathcal{CS},\ k \in \mathcal{K}_{ICEV},\ p \in \mathcal{P} \qquad (20)$$

Refueling constraints

$$r_i^k \leq M \cdot \text{refuel decision}_i^k \qquad \forall i \in \mathcal{FS},\ k \in \mathcal{K}_{ICEV} \quad (21)$$

$$r_i^k \leq Q_{\text{type}(k)} - \text{fuel}_i^k + M\Big(1 - \sum_{j \in \mathcal{V}, j \neq i} x_{ji}^k\Big) \qquad \forall i \in \mathcal{FS},\ k \in \mathcal{K}_{ICEV} \quad (22)$$

$$r_i^k = 0 \qquad \forall i \in \mathcal{FS},\ k \in \mathcal{K}_{EV} \quad (23)$$

Infrastructure constraints

$$\sum_{p \in \mathcal{P}} y_i^p \leq 1 \qquad \forall i \in \mathcal{CS} \quad (24)$$

Time constraints

$$\text{departure}_i^k = \text{arrival}_i^k + s_i \qquad \forall i \in \mathcal{C},\ k \in \mathcal{K} \qquad (25)$$

$$\text{departure}_i^k = \text{arrival}_i^k + \sum_{p \in \mathcal{P}} \frac{z_i^{k,p}}{\text{charge rate}_p} \qquad \forall i \in \mathcal{CS},\ k \in \mathcal{K}_{EV} \qquad (26)$$

$$\text{arrival}_j^k \geq \text{departure}_i^k + t_{ij} - M(1 - x_{ij}^k) \qquad \forall i \neq j,\ k \in \mathcal{K} \qquad (27)$$

$$\text{arrival}_i^k \geq a_i - M(1 - \text{visit}_i^k) \qquad \forall i \in \mathcal{C}, k \in \mathcal{K} \qquad (28)$$

$$\text{arrival}_i^k \leq b_i + M(1 - \text{visit}_i^k) \qquad \forall i \in \mathcal{C}, k \in \mathcal{K} \qquad (29)$$

$$\text{waiting}_i^k \geq a_i - \text{arrival}_i^k \qquad \forall i \in \mathcal{C}, k \in \mathcal{K} \qquad (30)$$

$$\text{waiting}_i^k \geq 0 \qquad \forall i \in \mathcal{C}, k \in \mathcal{K} \qquad (31)$$

Delivery and capacity constraints

$$\text{deliver}_{i,k,g} \le M \cdot \text{visit}_i^k \qquad \forall i \in \mathcal{C},\ k \in \mathcal{K},\ g \in \mathcal{G} \quad (32)$$

$$\sum_{k \in \mathcal{K}} \text{deliver}_{i,k,g} = \text{demand}_{i,g} \qquad \forall i \in \mathcal{C},\ g \in \mathcal{G} \quad (33)$$

$$\sum_{i \in \mathcal{C}} \sum_{g \in \mathcal{G}} \text{size}_g \cdot \text{deliver}_{i,k,g} \le Q_k \cdot \text{used}_k \qquad \forall k \in \mathcal{K} \quad (34)$$

EV policy constraint

$$\text{ev distance shortfall} \ge 0.50 \cdot \sum_{k \in \mathcal{K}} \sum_{i,j \in \mathcal{V}} d_{ij}\, x_{ij}^k - \sum_{k \in \mathcal{K}_{EV}} \sum_{i,j \in \mathcal{V}} d_{ij}\, x_{ij}^k \quad (35)$$