STAGE–3 REPORT: UPDATED PLAN & REVISED RESEARCH PAPER STRUCTURE

Project Title:

Hybrid MILP–GA–RL Framework for EV Charging Station Placement in Urban India

Stage:

Stage-3: Revised Model Design, Expanded Requirements, and Final Paper Blueprint

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1. Purpose of Stage-3

Stage-3 integrates all of previous meeting feedback into the design and structure of the upcoming research paper and implementation pipeline.

This document outlines:

- Modified system requirements
- New datasets to integrate
- New constraints to model
- New benchmarking protocols
- Final research-paper structure (headings, metadata, section layout)
- What will be implemented in the next cycle

This is **planning + design document**, the blueprint which shall guide us not the final paper.

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2. Updated Conceptual Framework (Reflecting Sir's Requirements)

Based on the discussion, the project moves beyond simply "minimizing detour + grid stress."
The model must now include:

✓ Two Core Planning Perspectives

A. Coverage Model (Baseline Planning)

- Ensure minimum number of stations such that **every zone is covered**
- No area remains underserved
- Equivalent to p-median / p-center or maximum coverage formulation

B. QoS Model (Demand-Driven Optimized Planning)

- Prioritize areas with:
  - Higher EV adoption
  - Higher population density
  - Higher purchasing capacity
- Use demand weights from EV sales data
- Provide *quality of service* where usage is high

These two perspectives must appear in the problem formulation and experiments.

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3. New Requirements Introduced by Sir

All points below MUST be implemented and included in the research paper.

3.1 EV Sales Data Integration (NEW)

Sir emphasized:

“Use district-level EV sales data to model real adoption.”

What to add:

- Fetch UP district-level EV sales dataset
- Map sales density to Lucknow wards
- Introduce new demand term:

$$Demand_i = 0.7 \cdot BuildingArea_i + 100 \cdot POI_i + \lambda \cdot EVSales_i$$

- λ controls importance of EV adoption

This converts our model from general → demand-aware, QoS-oriented.

3.2 Power Grid Distance Penalty (NEW, HIGH PRIORITY)

Required additions:

- Include power grid layers:
    - transmission lines
    - distribution substations
- Compute distance of each candidate site to nearest substation
- Add cost penalty:

$$Cost_k = BaseCost + \alpha \cdot DistanceToGrid_k$$

We will show both:

- Distance map
- Histogram of distances
- Its effect in the optimization

3.3 Vehicle-Type Filtering (4W EV Charging Only)

Because:

- e-rickshaw charging is different
- Government-built stations mainly serve cars
- Power demand differs

What to add:

- Restrict demand to **4-wheelers**
- Use fast/slow charger power ratings
- Remove 2W & e-rickshaw demand clusters

3.4 Policy Zones (NEW)

Model to be usable by policymakers.

Define zones:

- **Zone 1: Commercial, high EV concentration**
- **Zone 2: Residential, medium density**
- **Zone 3: Remote / underserved regions**

Required constraints:

- Zone-specific minimum coverage:
  - Zone 1 → high QoS requirement
  - Zone 2 → moderate coverage
  - Zone 3 → coverage with incentives

Introduce policy variable:

$$Coverage_z \geq MinCoverage_z$$

3.5 Baseline Benchmark Experiments (NEW)

Evaluation MUST compare against **baselines**, not just GA.

These baselines must be included:

A. Random Station Placement

- Choose k random candidates
- Measure coverage, cost, detour

B. Uniform Grid Placement

- Stations placed evenly in a grid

C. Greedy (Highest-Demand First)

- Select k sites with highest demand weights

D. MILP (Small area)

- Optimal “gold-standard” for small region

E. GA-Optimized (Full area)

- Pareto-optimal solution

F. Q-learning Routing (Operational Layer)

- Evaluate queue length reduction

These produce:

- Coverage curves
- Detour curves
- Cost vs quality trade-off
- Comparison graphs

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4. Updated Mathematical Model

Compared to Stage-1 & 2, Stage-3 adds:

- EV sales–weighted demand
- power-grid–distance cost penalty
- zone-specific coverage constraints
- filtering for 4W-only demand
- dual-mode (coverage/QoS) objective formulation

Additions required:

A. Demand with EV sales

Already written.

B. Cost with grid-distance penalty

As above.

C. Zone-based coverage constraints

Add new constraints for each zone.

D. Vehicle-type selection

Restrict demand to 4W.

E. Two separate objectives: Coverage & QoS

Use either as:

- dual-mode optimization
- or multi-objective vector
- or weighted combination

All this will appear in the “Problem Formulation” section of final research paper.

A. Updated Demand Model (Incorporating EV Sales Data)

Stage-1/2 Demand:

$$Demand_i = 0.7 \cdot BuildingArea_i + 100 \cdot POI_i$$

Stage-3 Demand (new):
To include EV adoption patterns (sir's requirement), the new formulation becomes:

$$Demand_i = 0.7 \cdot BuildingArea_i + 100 \cdot POI_i + \lambda \cdot EVSales_i$$

Where:

- **EVSales_i** = district-level EV sales density mapped to local wards
- λ= calibration weight for EV adoption influence

Purpose: Allows Quality-of-Service planning by prioritizing high-EV-density zones.

Note: Building area, POI counts, and EV sales are in very different units and scales. We defined a composite demand score with weights chosen so that each component contributes meaningfully for typical values in Lucknow's urban core. The initial values (e.g., 0.7, 100, λ) are heuristic but guided by the relative magnitude of features. We then perform sensitivity analysis over these weights to ensure that our optimization results are robust and do not collapse if the exact values change.

Strategy 1: Data-driven scaling + manual interpretation

1. **Inspect the ranges** in your data:
   - Compute mean / median of building area per cell.
   - Compute mean / median of POI count per cell.
   - Compute mean / median of EV sales per zone.
2. **Normalize each feature** (optional but nice):

For example, min-max to [0, 1]:

$$\widetilde{B_i} = \frac{BuildingArea_i - B_{min}}{B_{max} - B_{min}}, \widetilde{P_i} = \frac{POI_i - P_{min}}{P_{max} - P_{min}}, \widetilde{E_i} = \frac{EVSales_i - E_{min}}{E_{max} - E_{min}}$$

3. **Then choose simple weights like**:

$$Demand_i = w_B\widetilde{B_i} + w_P\widetilde{P_i} + w_E\widetilde{E_i}$$

For example:

   - $w_B = 1$(baseline)
   - $w_P = 2$(POI is ~2× more important)
   - $w_E = 3$(actual EV sales strongest signal)

This is more interpretable than 0.7 and 100, and you can explain **why each term is stronger**.

4. **Do sensitivity analysis**:

- Try several combinations, e.g.
  $w_P \in \{1,2,3\}$, $w_E \in \{1,2,3,4\}$, etc.
- Run your optimization for each combination.
- Check whether station locations change drastically or remain stable.

Strategy 2: Treat weights as hyperparameters and tune

If you have any partial ground truth (e.g., where existing EV stations are, or EV adoption pockets):

1. Define a **score function** that rewards solutions which:
   - place more stations in high-EV-sales areas,
   - cover more existing station clusters, etc.
2. Search over:
   - $0.3 \leq 0.7 \leq 1.0$(building weight)
   - $10 \leq 100 \leq 300$(POI weight)
   - several λ values (EV weight)
3. Pick the weights that:
   - produce good station layouts,
   - match known EV-hotspot intuition.

B. Updated Cost Model (Power Grid Distance Penalty)

Stage-1/2 Cost: flat installation cost per site.

Stage-3 Cost (new):
Sir emphasized that cost increases sharply if the location is far from the grid.

$$Cost_k = BaseCost + \alpha \cdot DistanceToGrid_k$$

Where:

- **DistanceToGrid_k** = shortest distance from candidate site k to nearest feeder/substation
- α= grid-extension cost factor

This aligns economic feasibility with infrastructure constraints.

C. Zone-Based Coverage Constraints (Policy Layer)

To incorporate policy recommendations:

Define zones $Z = \{Z_1, Z_2, Z_3\}$:

- **Zone 1 (Commercial, high demand)**
- **Zone 2 (Residential, medium demand)**

- **Zone 3 (Remote/underserved)**

Each zone enforces minimum coverage:

$$Coverage_z \geq MinCoverage_z$$

Additionally, assignment must respect zoning:

$$y_{ik} = 0 \text{if } k \notin Zone(i)$$

This ensures equitable distribution and prevents clustering.

D. Vehicle-Type Filtering (4-Wheeler Demand Only)

Stage-1/2 considered total population-derived demand.

Stage-3:
We restrict to 4-wheelers only, because:

- e-rickshaw charging is very different
- govt-level infrastructure focuses on cars

Thus, only demand nodes with 4W relevance are included:

Demand_i = 0 if EVType_i !=4W

This results in more realistic infrastructure sizing (fast chargers, 7.2–50 kW).

E. Coverage vs QoS: Two-Mode Objective

We now support dual objectives, depending on planning style:

1. Coverage Mode:

$$\min \sum_i d_{ik} \text{ s.t. coverage constraints}$$

2. QoS Mode:

$$\min \left(Detour + \beta \cdot GridStress + \gamma \cdot Cost\right)$$

3. Multi-objective Vector Version:

$$\min(D(x), G(x), C(x))$$

4. Weighted Combination Version:

$$\min \quad Z = w_1 \cdot D(x) + w_2 \cdot G(x) + w_3 \cdot C(x)$$

These modes allow both policy-driven and demand-driven solution styles.

5. Updated System Architecture for Stage-3

LAYER 1 — DATA LAYER (Expanded)

This layer now includes all required datasets:

- **OSMnx Road Network**
- **OSM Building Footprints**
- **OSM/OCM Charging Stations**
- **POIs (commercial, institutional, transit)**
- **EV Sales Dataset (district/ward-level)**
- **Power Grid Nodes + Feeder Lines**
- **Ward / Zonal Polygons** (for policy constraints)

Compared to Stage-1 & 2, the additions are:
✓ EV Sales
✓ Power Grid
✓ Zonal Polygons

LAYER 2 — PREPROCESSING LAYER (Enhanced)

New preprocessing tasks:

- **Zone Classification (Z1, Z2, Z3)**
- **Demand Calculation v2 (includes EV sales)**
- **Candidate Grid Generation (500m)**
- **Compute Grid-Distance Penalty for each candidate**
- **4W EV demand filtering**

Compared to Stage-1 & 2, the additions are:
✓ zoning
✓ grid-distance penalty
✓ EV-sales injection
✓ vehicle-type filtering

LAYER 3 — OPTIMIZATION LAYER (Updated)

Now includes:

- **MILP (small-scale for validation)**
- **GA / NSGA-II (full-scale city optimization)**
- **Baseline Models (NEW)**
    - random placement

- uniform grid placement
- greedy (highest demand first)

Compared to Stage-1 & 2, the additions are:
✓ baseline models
✓ NSGA-II integration
✓ zone-aware GA fitness function
✓ cost-penalty integration

LAYER 4 — RL LAYER (Operational Optimization)

- Q-learning for real-time routing
- State includes:
  - queue length
  - station availability
  - detour cost
- Reward includes:

$$r = -(wait\_time + \alpha \cdot queue\_length + \beta \cdot overload)$$

Same as Stage-2, but now enhanced with zone information.

LAYER 5 — ANALYTICS LAYER (Expanded)

Now supports:

- Coverage % per zone
- Detour distribution
- Cost per station including grid penalty
- Cost–quality trade-off curves (NEW)
- Grid-load imbalance
- QoS scoring
- Benchmark comparisons

LAYER 6 — VISUALIZATION LAYER

- Folium Interactive Maps
- Heatmaps (demand, grid distance)
- Pareto Front from NSGA-II
- Zonal visualizations

- Baseline vs optimized overlays

Same as Stage-2 with expanded layers.

FULL RESEARCH PAPER OUTLINE:

Title

Hybrid MILP–GA–QL Framework for EV Charging Station Optimization in Urban India

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Abstract (200–250 words)

I. Introduction (600–800 words)

A. Background
B. EV Adoption in India
C. Coverage vs QoS
D. Cost & Grid Proximity
E. Challenges
F. Contributions

II. Related Work (700–1000 words)

A. Station Placement
B. MILP Models
C. Metaheuristics
D. Reinforcement Learning
E. Policy & Zoning
F. Research Gaps

III. Preliminary Observations (300–500 words)

From sir's talk:

- EV sales
- Purchasing capacity
- Power-grid distance
- Zone definitions
- Clustering issues

IV. Problem Definition (Full mathematics)

A. Sets
B. Variables
C. New demand model
D. New cost model
E. Coverage/QoS models
F. Zone constraints
G. Objective formulation
H. Complexity classification (NP-hard)

V. Data Model & Preprocessing

A. EV sales integration
B. Grid nodes and distances
C. Candidate generation
D. Zone assignment
E. Demand modelling v2
F. Vehicle filtering

VI. Methodology

A. MILP approach
B. GA/NSGA-II
C. RL (Q-learning)
D. Baseline models
E. End-to-end pipeline
F. Pseudocode/diagrams

VII. Experimental Setup

A. Hardware
B. Software
C. Datasets
D. Parameter settings
E. City polygon

VIII. Results

A. Coverage curves
B. Detour curves
C. Cost-quality trade-offs
D. Random vs uniform vs optimized
E. RL improvements
F. Grid-load maps
G. Statistical analysis

IX. Policy Implications

A. Incentives
B. Minimum coverage zones
C. Budget decisions
D. EV adoption strategy

X. Conclusion

XI. Future Work