Optimizing EV Charging Routes in Inner London with Reinforcement Learning (Proximal Policy Optimization)

*Integrating tariff heterogeneity, nonlinear charging curves, and traffic simulation*

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**Abstract:**

**Keywords:**

# 1 Introduction

The rapid adoption of electric vehicles (EVs) is reshaping transport and energy systems, driven by ambitious decarbonisation targets and urban air quality policies [8]. In London, this transition has been supported by an expansion of charging infrastructure [10], yet challenges persist. The charging landscape remains fragmented across multiple operators, with uneven station distribution [9] and tariffs that combine per-kWh energy rates, session fees, idle penalties, and membership discounts [12, 13]. For drivers, key concerns include minimising costs, reducing delays, and ensuring trip feasibility, while operators and regulators focus on infrastructure adequacy and grid stability. Existing optimisation efforts have often prioritised the grid perspective [1–3] but struggle to capture the complex, user-centred realities of urban charging.

Several gaps in the literature limit the applicability of current approaches to dense metropolitan contexts like Inner London. Many studies assume uniform or simplified tariffs, overlooking operator heterogeneity, idle fees, and subscription models [32, 13–15]. Charging dynamics are frequently simplified as well: constant or generic rates are used in place of vehicle-specific nonlinear charging curves [17, 33, 34]. Hybrid objectives balancing cost and time remain underexplored; weighted-sum and Pareto methods are sometimes applied, but their calibration is often ad hoc [35–37]. Reinforcement learning (RL) has shown promise in this domain [5–7, 21, 22], yet many implementations rely on oversimplified environments that neglect congestion, unrealistic station cycling, or other real-world constraints [16, 25, 41]. Reward design also poses difficulties: prior work often fixes objective priorities or under-utilises shaping and penalties [38–40]. Collectively, these gaps indicate that a new, driver-centric approach is needed. One that captures real-world variability in tariffs, charging behaviour, and urban constraints.

This thesis addresses these challenges by applying Proximal Policy Optimisation (PPO) to model EV charging decisions in Inner London. Using structured datasets, the study integrates operator-specific tariffs, detailed station metadata, and vehicle charging curves to simulate realistic charging costs and times. A custom RL environment was built using SUMO for traffic modelling and OpenAI Gym for training, with rules to prevent implausible behaviours such as repeated station cycling. Reward functions were designed for cost, time, and hybrid objectives, incorporating potential-based shaping and feasibility penalties. The methodology emphasises reproducibility through structured data inputs, fixed random seeds, and consistent evaluation protocols.

The research is guided by four questions:

Q1: How can reinforcement learning minimise total trip cost while ensuring state of charge (SoC) remains above a safe reserve threshold?

Q2: How can reinforcement learning minimise total trip duration while maintaining SoC for journey completion?

Q3: How can a hybrid reinforcement learning framework balance cost and time objectives under varying operational constraints?

Q4: How do cost-based, time-based, and hybrid optimisation objectives differ in shaping charging behaviour and route selection, and what trade-offs emerge between them?

By addressing these questions, the study contributes a reinforcement learning framework that captures the technical and behavioural complexities of EV charging in Inner London.

# 2 Literature Review

Before reinforcement learning gained prominence, EV charging optimisation was approached with deterministic and heuristic methods. Mixed-integer linear programming (MILP) can yield optimal solutions under fixed assumptions [19] but scales poorly for real-time, city-wide applications as the number of vehicles and stations grows. Metaheuristic techniques (e.g. genetic algorithms, particle swarm optimisation) improve scalability [20], yet early electric vehicle routing formulations still overlooked critical dynamics like traffic congestion, waiting queues, and nonlinear charging rates [16]. These limitations prompted a shift towards adaptive, data-driven methods, with RL offering a compelling alternative.

Many prior studies oversimplified key technical factors. Battery charging is nonlinear, power input tapers as the battery fills. Yet models often assume a constant rate, underestimating charging duration [17, 18]. Vehicle-specific differences are usually ignored due to limited data availability [33]; only recently have large datasets revealed broad heterogeneity in EV charging behaviour across models [34]. Real-world pricing is likewise complex, operators impose varying energy rates, session fees, idle penalties, and membership discounts [13, 32]. However, much of the earlier optimisation literature assumed uniform or flat pricing schemes [13–15, 32], which can yield unrealistic recommendations. Incorporating these tariff nuances (for example, discounted member-only rates vs. higher guest prices, or per-minute idle fees) can significantly change optimal charging decisions [15]. Any practical framework must therefore reflect such tariff heterogeneity and realistic charging dynamics, especially in dense urban settings.

RL offers the ability to learn adaptive policies through interaction with the environment, something static optimisations cannot achieve. Applications of RL in energy and transportation show it can reduce costs and improve operational efficiency [21, 22]. Early work on EV charging used value-based RL (e.g. Deep Q-Networks) to coordinate charging and reduce user cost peaks [5, 6], but the discrete action space in those approaches was not suitable for continuous routing decisions. Policy-gradient methods like Proximal Policy Optimization (PPO) can handle continuous actions [7] and are known for stable training; indeed, PPO has demonstrated strong performance on complex or multi-objective tasks in simulations [23]. Despite this promise, few studies to date have applied PPO for individual driver routing in dense cities, where variable tariffs, nonlinear charging curves, and traffic congestion all intersect. Other advanced RL algorithms (e.g., DDPG and SAC) have also been tested for EV charging control [31], but they similarly have not been deployed at the driver-route level in a congested urban context.

A realistic simulation environment is essential for training RL agents effectively. Many earlier studies made simplifying assumptions such as deterministic travel times or unconstrained charger availability, ignoring urban traffic and station queues [16]. In contrast, recent works stress simulation realism by integrating traffic models and operational constraints. Using tools like OpenAI Gym with the SUMO traffic simulator allows an agent to experience time-varying congestion and competition for charging stalls during training [41]. This added fidelity prevents overly optimistic strategies and yields policies that, for example, learn to avoid heavily congested routes or anticipate waiting times at busy stations, behaviours crucial for real-world feasibility.

Designing an effective reward function is another challenge when multiple objectives must be balanced. Past works often focused on a single goal (either cost or time) or used a fixed weighted sum of both [21, 22]. Some researchers even convert time into an equivalent monetary cost via a value-of-time factor to merge objectives into one metric [35, 37]. Alternatively, evolutionary and Pareto-based methods have been explored to avoid preset weights and generate a spectrum of cost–time trade-off solutions [36]. In practice, careful reward shaping is needed. One proven technique is potential-based shaping, which adds an extra incentive (e.g. rewarding reductions in remaining travel time or distance) without changing the optimal policy [38]. Strong penalty terms are also common: for instance, a very large negative reward if the vehicle depletes its battery en route trains the agent to avoid infeasible paths [39]. Effective use of shaping and penalties significantly improves learning efficiency and policy realism in EV charging simulations [38, 39]. Notably, a few multi-objective RL approaches for EV charging have been proposed in recent years [29, 30], but these remain limited in scope and have yet to tackle the full real-world complexity (heterogeneous prices, nonlinear charging, traffic congestion) that this study addresses.

In summary, the existing literature highlights the need for a driver-centric EV charging strategy that can adapt to complex urban conditions. No prior work fully integrates fine-grained tariff differences, realistic charging curves, and dynamic traffic into a single optimisation framework. The present study therefore applies PPO in a realistic Inner London simulation, explicitly integrating these real-world factors into a unified RL approach for EV routing and charging.

# 3 Methodology

## 3.1 Data Preparation

Four key data sources were compiled to drive the simulation:

**1. Tariffs**:Real world pricing data were collected from multiple charging network operators [44 -58] (see Fig. 1) and standardized into a unified format (converted into £/kWh units) to enable accurate cost calculations.

A screenshot of a computer

AI-generated content may be incorrect.A close-up of a message

AI-generated content may be incorrect.

Figure 1: Raw Tariff Information Examples

Tariffs were split into three structured datasets. This ensured realistic and provider-specific cost estimation in the simulation environment (see Fig. 2).

A diagram of a manual selection

AI-generated content may be incorrect.

Figure 2 Conversion Process

**2. Stations:** The UK National Chargepoint Registry [42] provided station metadata, which were cleaned and split into station-level metadata (e.g. location, operator, number of connectors) and connector-level attributes (power output, plug type, tariff info) for use in the simulation (see Fig. 3).

A diagram of a diagram

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Figure 3 Splitting the Charging Data

**3. Vehicles:** Specifications such as battery capacity and charging curves were sourced from the Open EV Data project [43], enabling realistic modelling of charging times.

A diagram of an electrical system

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Figure 4 Splitting the EV Data

**4. User trips:** A set of simulated trip scenarios was generated, each specifying an origin, destination, and start time along with an initial SoC (with a set reserve margin), a particular EV model, the driver’s membership status (for tariff effects), and the chosen optimisation objective (cost, time, or hybrid).

These structured datasets ensured that the RL environment had access to rich, realistic information on costs, infrastructure, vehicle behaviour and driver preferences.

## 3.2 Environment Design

A custom OpenAI Gym environment was implemented with SUMO as the traffic simulator. At each decision step, the agent observes the current state and chooses either to continue driving or divert to a charging station.

The environment is a Markov Decision Process (MDP) defined in Eq. (1).

**(1)**

Driving energy use and state-of-charge (SoC) updates follow Eq. (2), with travel times obtained from SUMO or congestion-scaled estimates Eq. (3).

**(2)**

**(3)**

Charging respects connector limits and vehicle-specific charging curves (Eq. 4), with a fixed 3-minute session overhead.

**(4)**

**(4)**

**(4)**

Episodes terminate when the destination is reached with SoC above reserve, or when depletion occurs. Invalid actions (e.g. selecting unreachable or repeated stations, charging before cooldown, exceeding trip charge limits) incur penalties and may trigger termination.

Traffic dynamics can be run in full SUMO microsimulation or in a lightweight congestion mode, applying peak-hour multipliers (1.6 for AM, 1.5 for PM) to represent travel delays.

The environment supports three optimisation objectives (time, cost, hybrid). A global preference is set by default, but if enabled, the objective can be overridden per trip to allow heterogeneous agent behaviour. When operating in pure time mode, stabilization heuristics reduce per-minute penalties, boost completion rewards, amplify shaping, and halve charging overheads to prevent value-function collapse.

Design trade-offs are summarised in **Table 1**.

Table 1: Environment Design Trade-Offs

|  |  |  |  |
| --- | --- | --- | --- |
| Aspect | Real-world baseline | Simulation choice | Rationale |
| Initial SoC | Often >50% | Sampled 10–30% | Ensures charging is frequently required, avoids trivial trips |
| Trip lengths | Many <10 km | Calibrated 12–25 km | 30–60% of trips require ≥1 charge, providing a learning signal |
| Charging | Overheads vary | Fixed 3-min per session | Penalises “nibbling” charges and station hopping |
| Traffic | Complex congestion patterns | SUMO microsim (vs. constant speed or multipliers) | Provides realistic congestion while keeping simulation deterministic |
| Station use | Drivers may revisit stations | No repeats, cooldowns, max charges | Prevents unrealistic cycling behaviour |
| Variability | High randomness in trips | Fixed seeds (environment + training) | Enables reproducibility and controlled comparisons |

### 3.3 Reward Design

Three optimisation objectives were supported: cost, time, and hybrid (via a value-of-time conversion). Per-step rewards are given in Eqs. (5–7).

**Cost objective (per step)**

**(5)**

**Time objective (per step)**

**(6)**

**Hybrid objective with value-of-time**

**(7)**

Potential-based shaping (Eq. 8) was used to provide incremental feedback based on reductions in estimated arrival time:

**Potential-based shaping and penalties**

**(8)**

**(8)**

**(8)**

Charging steps were always net-negative, as both energy and time costs are incurred. Terminal rewards penalised stranding while rewarding successful completion. Constraint violations, such as repeated station visits or cooldown breaches, introduced additional penalties to guide exploration.

The specific values for terminal rewards, penalties, and shaping parameters, along with their rationale, are summarised in Table 2.

Table 2: Summary of Design Choices

|  |  |  |
| --- | --- | --- |
| Design Choice | Implementation (Value) | Rationale |
| Success / failure | +50 (completion), –200 (stranding) | Encourages feasibility and strongly penalises infeasible trips |
| Infeasible action | –2 | Discourages wasted steps while keeping exploration possible |
| Repeat station penalty | –5 | Prevents unrealistic cycling behaviour |
| Cooldown violation | –5 | Discourages immediate re-charging |
| Over-limit penalty | –20, terminate trip if enabled | Prevents unrealistic charging frequency |
| Unreachable station | –3 | Penalises unroutable charger selections |
| Charging overhead | 3 minutes per session | Discourages micro-charging |
| Efficiency | η = 0.92 | Reflects real-world charging inefficiency |
| Hybrid scaling | λ = £0.05/min | Balances cost and time in comparable units |
| Shaping reference speed | 25 km/h | Provides consistent ETA estimate |
| Time-mode stabilisers | Reduced per-minute penalty (×0.35), success bonus ≥500, shaping ×3, overhead ×0.5 | Prevents collapse of value function in pure time optimisation |
| Anti-idle penalty | Default 0 (optional >0) | Prevents wasted driving steps |
| Micro-charge penalty | Default 0 (optional >0) | Prevents nibbling charges |

### 3.4 Proximal Policy Optimization

Policies were trained with PPO using Stable-Baselines3. The clipped surrogate objective and Generalized Advantage Estimation (GAE) followed Eqs. (9–10). Hyperparameters, rollout settings, and network configurations are listed in Appendix A (Table A.1). Training used DummyVecEnv with fixed seeds and a KPI logger to ensure reproducibility and comparability.

**Clipped surrogate objective**

**(9)**

**(9)**

**Generalized Advantage Estimation (GAE)**

**(10)**

Evaluation uses a fixed test set and seeds to compare cost, time and hybrid-optimised agents under identical conditions.

# 4 Training

Training was conducted using Proximal Policy Optimization (PPO) implemented in Stable-Baselines3. The agent interacted with the custom Gym–SUMO environment, receiving sequential decisions for driving and charging under traffic and infrastructure constraints.

All experiments used fixed seeds for environment sampling, PPO updates, and network initialisation to ensure reproducibility. A single-environment DummyVecEnv was adopted for deterministic interaction with SUMO.

The policy and value networks were two-layer multilayer perceptrons (256 units, ReLU activations). Gradient norm clipping and entropy regularisation were applied to stabilise updates and maintain exploration. Hyperparameters such as rollout length, batch size, discount factor, clipping ranges, and learning rate schedule are listed in Appendix A (Table A.1**)**. A linear learning rate decay was applied and clamped after 100k steps. Training stability was monitored through KL divergence, with early stopping triggered if the threshold was exceeded.

Progress was tracked using an episode logger that recorded completion rate, stranding frequency, number of charges, cumulative time, and charging costs. Policies were periodically validated on a fixed set of trips to provide consistent baselines for comparing cost-, time-, and hybrid-optimised agents.

This setup prioritised stability, reproducibility, and comparability across different reward structures.

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**Appendix A: PPO Hyperparameters**

Table A.1 lists the hyperparameters used in the training script. Values reflect the exact settings in the code; they can be adjusted for ablation without changing the main text.

**Table A.1 PPO training hyperparameters**

|  |  |  |
| --- | --- | --- |
| Parameter | Value | Notes |
| Vector env | DummyVecEnv (1 env) | Single-process training |
| n\_steps | 4096 | Rollout length per update |
| batch\_size | 2048 | Minibatch size |
| n\_epochs | 10 | Optimisation epochs per update |
| gamma | 0.995 | Discount factor |
| gae\_lambda | 0.95 | GAE parameter |
| clip\_range | 0.2 | Policy clip |
| clip\_range\_vf | 0.2 | Value function clip |
| ent\_coef | 0.01 | Entropy regularisation |
| vf\_coef | 0.7 | Value loss weight |
| target\_kl | 0.02 | Early‑stop heuristic |
| max\_grad\_norm | 0.5 | Gradient clipping |
| learning rate | Linear decay from 1e‑4, clamp to **7.5e−5** after 100k steps | Clamp to 7.5e‑5 after 100k steps |
| policy network | MLP [256, 256] (actor & critic) | ReLU activations; orthogonal init |
| seeding | Fixed seeds (env + PPO + numpy/torch) | Reproducibility |
| logging | Episode KPI callback | Writes cost, time, success/stranding, charges |