FEIC 2026 | TRACK ST5: INDUSTRIAL & SYSTEMS | PAPER ID: CMT-40

Stochastic Modelling and Optimisation of Campus Shuttle Dispatch Systems Using Discrete Event Simulation

A Case Study of University of Lagos (UNILAG) Campus Cabs

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The 'Fill-and-Go' Paratransit Paradox at UNILAG Main Gate

Morning Peak Surge (07:00 – 11:00 AM)

- Lecture schedules trigger violent tidal student arrival waves.
- Capacity-triggered dispatch (depart only when B(t) = 6) causes multiple cabs to fill and leave in uncoordinated clusters.
- Results in severe terminal queues and downstream vehicle bunching.

Midday Off-Peak Stagnation (12:00 – 02:00 PM)

- Low passenger trickle leaves early-boarding students trapped in stationary vehicles waiting for the 6th passenger.
- Terminal service throughput drops sharply during lull periods.
- 'Exact Fare Friction' (₦200 change disputes) delays loading.

Real-World Stochastic Disruptions Absent in Classical Models

- Preemptive Fuel Excursions: Drivers abruptly exit the service loop for ~12-minute jerry-can fuel runs, removing active servers.
- Weather Shocks: Early-morning rainfall dampens and shifts arrival peaks, altering demand patterns.
- Core Engineering Gap: Static analytical queues (M/G/c) fail under non-stationary arrivals, capacity-triggered departures, and server preemption.

Aim, Objectives & Bounded System Scope

Research Aim & Specific Objectives

- Aim: Develop a stochastic Discrete Event Simulation (DES) digital twin to evaluate and optimise campus shuttle dispatch protocols.
- Objective 1: Acquire empirical arrival, loading-duration, and queue-snapshot data at the Main Gate Shuttle Park.
- Objective 2: Parameterise non-stationary arrivals (NHPP) and skewed service durations via MLE and bootstrap goodness-of-fit.
- Objective 3: Build a verified Python/SimPy model incorporating preemptive fuel-run interrupts and weather sensitivity.
- Objective 4: Evaluate coordinated dispatch heuristics (CPOP & H-ROC) balancing passenger wait times and operator feasibility.

Explicit System Boundary (Terminal Focus)

- Bounded strictly to Main Gate terminal queue dynamics (Lq), passenger wait times, and inter-vehicle departure headways.
- Models 4 physical loading bays and 6-seater petrol cabs (plus 14-seater eRide EVs as surge reserves).
- Does NOT simulate macroscopic campus road-network traffic.

Key Model Assumptions & Limitations

- Non-simultaneous field phases combined under comparable weekday operating conditions.
- eRide EVs modelled as capacity-rolling surge servers without battery state-of-charge degradation.
- Fixed ₦200 fare without dynamic passenger modal jockeying.

Three-Phase Empirical Data Acquisition (5–16 January 2026)

Dataset & Phase	Observation Dates	Sample Size (n)	Measured Variable & Protocol
Data Sheet A (Phase I)	5–9 Jan 2026 (Days 1–5)	216 Epochs	5-minute passenger arrival counts across peak & off-peak windows
Data Sheet B (Phase II)	12–13 Jan 2026 (Days 6–7)	342 Records	Micro-motion stopwatch loading duration (door open to departure)
Data Sheet C (Phase III)	15–16 Jan 2026 (Days 8–9)	15-Min Intervals	Instantaneous physical passenger queue counts (Lq) & active bays

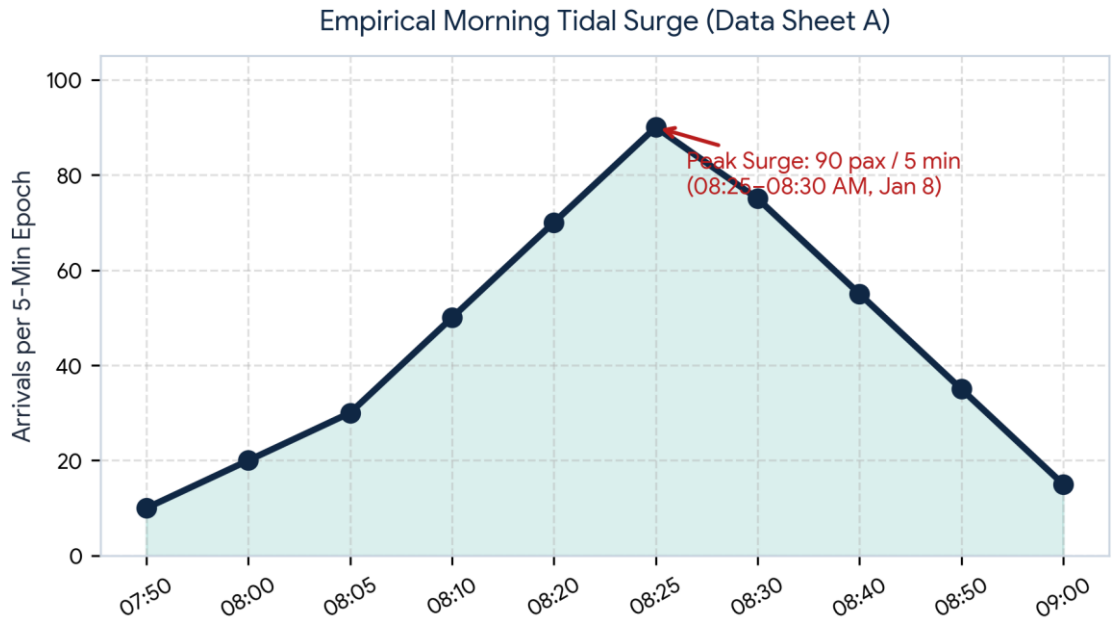
Field Nuances & Methodological Rigour

- Discrete Seat Counting: Accompanied children occupying seats were counted as distinct arrival entities (Jan 6).
- Non-Simultaneous Phases: Datasets capture separate weekday windows rather than a single continuous time series.
- Empirical Disruptions Logged: 12-min jerry-can fuel runs and 03:00–05:00 AM rainfall delay (Jan 9).

Observed Operational Extremes

- Peak Arrival Intensity: 90 passengers in 5 minutes (08:25–08:30 AM, Jan 8).
- Off-Peak Lull: Dropped to 12 passengers in 5 minutes (12:50 PM, Jan 7).
- Peak Observed Queue: 28 waiting students at 09:30 AM (Jan 15).

Verified Statistical Input Models: NHPP & Lognormal Fit



Non-Homogeneous Poisson Process (NHPP)

- Pooled mean = 41.76 pax/5-min; variance = 296.63 (Dispersion Index = 7.10).
- Piecewise-constant rate λ(t) updated every 5 min via Lewis–Shedler thinning.

Service-Time Distribution Fitting (n = 342, loc = 0)

- Parameters estimated via MLE with zero-location support (t > 0).
- Evaluated via 5,000-sample parametric bootstrap Kolmogorov–Smirnov test.
- Lognormal (σ = 0.5643, scale = 0.5014 min) provides the closest fit.

Distribution	Shape	Scale (min)	K-S Stat	Bootstrap p
Lognormal (Best)	**0.5643**	**0.5014**	**0.0413**	**0.1654 (Pass)**
Gamma	3.5624	0.1630	0.0464	0.0860 (Pass)
Weibull Min	2.0018	0.6578	0.0703	0.0002 (Reject)

Python / SimPy Digital Twin & Preemptive Interrupt Logic

1. Arrival Engine

NHPP Thinning λ(t)
Injects students into
FIFO Container (Lq)

2. Terminal Staging

4 Loading Bays
simpy.Resource(c=4)
6-Seater Cab Queue

3. Boarding & Dispatch

Lognormal(0.564, 0.501)
Departs when B(t)=6
or Hold Cap expires

4. Campus Turnaround

Stochastic Transit Loop
U(10, 15) min
Returns to Park Queue

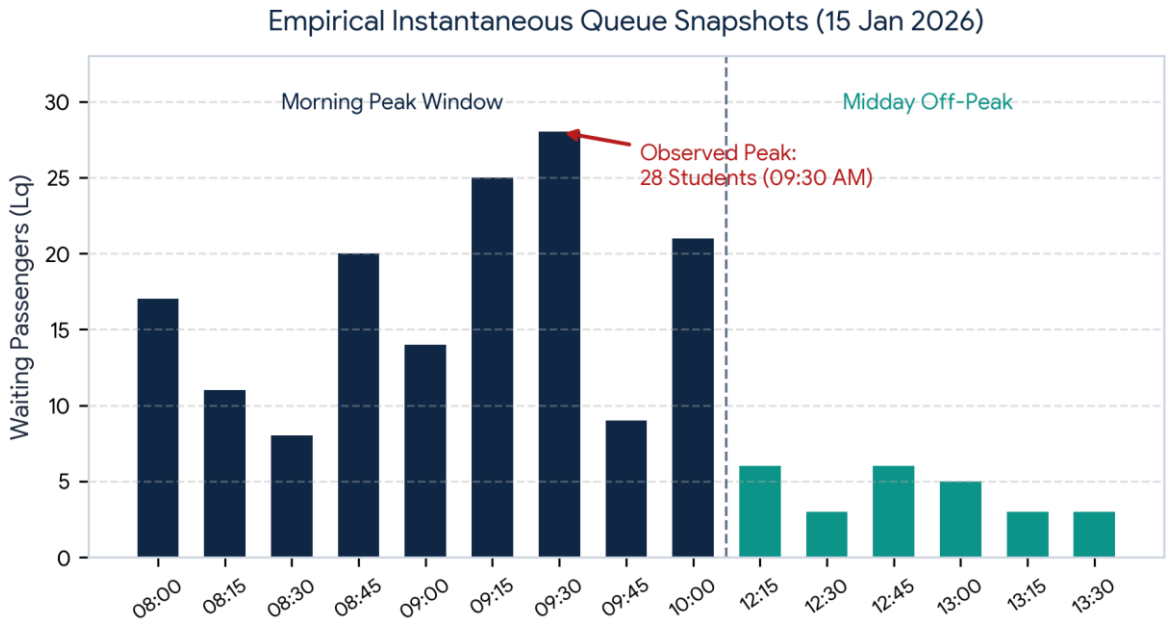
Priority-1 Preemptive Fuel Excursions

- Refuelling modelled via simpy.PreemptiveResource & simpy.Interrupt().
- Priority 1 (Jerry-can fuel run, TTR = 12.0 min) immediately preempts Priority 2 passenger loading.
- Captures sudden server capacity drops during scarcity shocks.

Weather Sensitivity Parameterisation

- Heavy rainfall modelled as a structured sensitivity experiment.
- Arrival intensity scaled by $\lambda_{rain}(t) = \gamma_{rain} \cdot \lambda(t)$ ($\gamma_{rain} = 0.65$).
- Transit turnaround scaled by δ_{rain} to test delayed morning surges.

Deterministic Verification & Empirical Queue Baseline



15 January 2026 Snapshot Benchmark (Data Sheet C)

- Morning queue builds sharply after 08:30 AM, peaking at 28 students at 09:30 AM.
- Midday off-peak snapshots stabilise between 3 and 6 waiting students.

Computerised Model Verification (6/6 Passed)

- TC-01 (FIFO Discipline): Passengers board in exact arrival order (PASS).
- TC-02 (Load-Limit Dispatch): Cabs dispatch immediately upon 6th passenger boarding (PASS).
- TC-03 (Off-Peak Hold Cap): Partially loaded cabs depart at t = 3.0 min (PASS).
- TC-04 (Headway Spacing): Simultaneous departures separated by 30s minimum gap (PASS).
- TC-05 (Fuel Interrupt): Preemptive interrupt removes cab for 12.0 min (PASS).
- TC-06 (EV Reserve Injection): Reserve 14-seater EVs enter pool when Lq ≥ 18 (PASS).
- Methodological Note: Time-matched stochastic validation metrics (ME, MAE, RMSE) are being finalised on the unified NHPP script.

Proposed Optimisation Protocols: CPOP & H-ROC

CPOP: Coordinated Periodic & Opportunistic Dispatch

- Designed for the existing 6-seater campus cab fleet without new capital purchase.
- Rule 1 — 30-Second Minimum Departure Headway: Enforces a 30s spacing between consecutive cab departures to prevent simultaneous clustering.
- Rule 2 — 3.0-Minute Off-Peak Holding Cap: Caps vehicle dwell time at 3.0 min during lulls so cabs depart even if partially filled, ending passenger stagnation.
- Rule 3 — 3-Cab Internal Reserve Pool: Holds 3 cabs in reserve and injects them into active rotation when queue threshold Lq ≥ 18 is breached.
- Bi-Objective Formulation: Minimises $Z = w1 \cdot (Wq / Wmax) + w2 \cdot (Iv / Imax)$.

H-ROC: Heterogeneous Robust Optimal Control

- Coordinates existing 6-seater petrol cabs with UNILAG eRide 14-seater electric shuttles.
- Queue-Derivative Surge Detection: Monitors both instantaneous queue level (Lq) and 1-minute arrival growth rate ($\Delta Lq / \Delta t$).
- Targeted Peak Deployment: Deploys 3 reserve 14-seater EVs strictly as high-capacity 'surge absorbers' during 07:30–10:00 AM peaks.
- Off-Peak Role Separation: Scales back 14-seater EVs during midday lulls, preserving fast-turnaround off-peak demand for agile 6-seater union cabs.

Terminal vs. Departure-Headway Trade-Offs (Preliminary Trends)

Note: Qualitative directional insights from initial simulation runs; exact confidence intervals are undergoing final NHPP re-verification.

1. Failure of Rigid Timetables

- Enforcing a strict fixed 2.0-minute dispatch timetable regardless of demand collapses under 90-passenger surges.
- Low-capacity 6-seater cabs cannot absorb tidal campus waves on a rigid clock.
- Confirms dispatch rules must remain queue-responsive.

2. Terminal vs. Headway Trade-Off

- Enforcing a 30s minimum departure headway under CPOP holds vehicles slightly longer at the loading bay.
- Increases short-term terminal queue buffering while smoothing departure spacing.
- Eliminates multi-cab simultaneous departures without fleet expansion.

3. Fuel Shock & Surge Mitigation

- 12-minute preemptive fuel runs rapidly destabilise unbuffered queues.
- Combining CPOP rules with 14-seater eRide surge injection (H-ROC) absorbs morning arrival spikes.
- Scenario estimates indicate higher daily trip turnover for drivers.

Conditional Pilot Framework for UNILAG Stakeholders

Campus Cab Union

- Pilot the 30-second peak departure spacing and 3.0-minute off-peak holding cap.
- Maintain a 3-cab internal reserve during morning rush hours.
- Leverage fast 6-seater turnaround to lead midday off-peak service.

University Management

- Deploy 14-seater eRide EVs selectively as peak surge absorbers (07:30–10:00 AM).
- Evaluate staggered morning lecture start times (8:00 / 8:30 / 9:00 AM) to flatten tidal arrival peaks.
- Support controlled field pilot testing.

Student Commuters

- Adopt exact ₦200 fare denominations (or digital fare tokens) to eliminate boarding friction.
- Benefit from bounded off-peak holding times and structured surge capacity.

Key Takeaway & Future Work

- Conclusion: Campus shuttle bottlenecks stem primarily from uncoordinated capacity-triggered dispatch rather than fleet deficit alone.
- Next Steps: Complete unified NHPP replication audit, conduct controlled terminal pilot, and extend to EV battery state-of-charge & passenger modal-choice ABM.