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Optimizing University Shuttle Services under Demand Uncertainty: A Survey-Based Case Study from Greater Cairo

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Abstract

University shuttle networks in rapidly expanding metropolitan regions face a structural trade-off between the spatial coverage of demand-responsive transit and the operating efficiency of fixed-route service. This paper presents a survey-based optimization case study of Nile University's commuter shuttle network in Greater Cairo. Using a 95-response student survey and real Greater Cairo road-network distances, we construct a six-route fixed trunk network with a capacitated nearest-neighbor heuristic cross-validated against Google OR-Tools' Capacitated Vehicle Routing Problem solver. Four route-adjustment options (keep, modify, split, or add a bus) are evaluated using a representative, assumption-based operating-cost model in Egyptian Pounds covering fuel, maintenance, depreciation, driver wages, and overhead, with peak-hour travel times adjusted for Cairo's measured morning congestion level. Recommendations are stress-tested under twenty independent random demand perturbations of plus or minus twenty percent per pickup area, in addition to uniform shift scenarios. Route 1 (New Cairo and Madinaty) retains its Modify recommendation in

all 22 scenarios tested, confirming 100 percent robustness. Applying the recommended configuration across the full six-route network represents a potential avoided cost of approximately 2,922 EGP per day (25.7%) relative to a hypothetical always-split scenario, equivalent to roughly 526,000 EGP per academic year. A demand-responsive feeder layer for lower-density zones is simulated as a proof-of-concept demonstration; full-scale validation remains future work.

Keywords: university shuttle, vehicle routing, demand uncertainty, operating cost, sensitivity analysis, hybrid transit, Greater Cairo

1 Introduction

Campus transit systems in rapidly expanding metropolitan regions routinely face a structural trade-off between spatial coverage and operating efficiency. Fixed-route transit offers high capacity and predictable schedules along dense corridors but performs poorly when extended into low-density, spatially fragmented residential zones. Nile University's commuter base, drawn from residential clusters scattered across Greater Cairo, exhibits exactly this pattern: a small number of corridors carry dense, predictable demand, while the remainder of the student body is spread across lower-density areas that no single fixed route can efficiently serve.

This paper presents a survey-based optimization case study of Nile University's shuttle network, following evidence that integrated fixed-flexible transit configurations outperform single-mode transit in coverage, passenger travel time, and operating cost [1]. The paper makes five contributions specific to the fixed-route trunk network. First, we construct and validate a trunk network using real survey-derived demand, individually disaggregated to each pickup area, and real Greater Cairo road-network distances, cross-checking a capacitated construction heuristic against an independent metaheuristic solver. Second, we adjust free-flow travel-time estimates using measured Cairo peak-hour congestion data, since free-flow estimates understate real commute times. Third, we expand the route-adjustment decision from a binary Add-versus-Modify choice into four concrete options, keep, modify, split, or add a bus, and evaluate each using a representative operating-cost model. Fourth, we stress-test the resulting recommendations under an expanded set of randomized demand scenarios, quantify how robust each route's recommendation is to demand uncertainty, and translate the recommended configuration into an estimate of total network cost and potential avoided cost. Fifth, we developed a proof-of-concept traffic simulation for the demand-responsive transit (DRT) feeder layer for the New Cairo demand zone.

The remainder of this paper is organized as follows. Section 2 reviews related work on hybrid fixed-flexible transit, campus DRT case studies, demand-aggregation methods, vehicle-routing solution methods, and dial-a-ride scheduling. Section 3 presents the overall system architecture. Section 4 presents the data and methods used to construct and evaluate the trunk network. Section 5 presents the feeder layer SUMO simulation. Section 6 reports results. Section 7 discusses these results and identifies limitations. Section 8 concludes and outlines future work.

2 Related Work

2.1 Fixed vs. Flexible Transit Trade-offs and Hybrid Architectures

University transportation networks operating in expanding metropolitan regions routinely encounter a structural trade-off between spatial coverage and operational efficiency. Fixed-route transit offers high capacity and predictable schedules along dense corridors, but performs poorly when extended into low-density, spatially fragmented zones, whereas point-to-point DRT maximizes spatial accessibility at the cost of poor fleet utilization and escalating operating costs as demand volume grows. Rather than treating this as a binary choice, recent research has converged on hybrid architectures that combine both modes.

Calabrò et al. [2] developed an agent-based model to directly compare fixed-route and demand-responsive feeder services, identifying a critical demand-density threshold at which one mode becomes preferable to the other, a result that depends on demand's spatial distribution and pattern rather than density alone. Fielbaum and Alonso-Mora [3] took a more computational approach, using the tracked paths of fully flexible on-demand ridepooling vehicles to algorithmically identify where a fixed line should be inserted into an otherwise flexible network, validating the method on real-life data from Utrecht and the Sunshine Coast. Leffler et al. [4] extended this line of work by developing an adaptive route-choice model for systems where a single trip can combine fixed and flexible legs, and Ng et al. [5] simulated a semi-on-demand hybrid transit route operated by shared autonomous vehicles in Munich, showing that the balance between the fixed and flexible portions of a route directly affects service accessibility and journey time. Most recently, Madani, Braekers, and Keseru [6] proposed a bi-level metaheuristic framework that jointly designs the fixed-route and DRT components of a hybrid system together, rather than planning them sequentially, and showed this joint approach yields significant fleet-size reductions compared to sequential planning.

Together, this body of work establishes both the empirical precedent and the current state of the art for hybrid trunk-and-feeder transit architectures, of which the present study validates the fixed-route trunk component.

2.2 University/Campus DRT and Shuttle Case Studies

While the theoretical case for hybrid fixed-flexible transit is well established, a smaller body of work has tested these ideas directly on university campuses, where demand is concentrated, tidal, and tied to fixed class schedules. Hulagu and Celikoglu [7] were among the first to formalize this as an optimization problem, developing an integer linear programming formulation for the shuttle service bus routing problem and validating it on a real case at Istanbul Technical University. Noor, Rasyidi, Nandy, and Kolandaisamy [8] took a data-driven approach at the University of Malaya, using Artificial Neural Network and Support Vector Machine models to predict shuttle travel time from GPS data, and used the resulting predictions to identify routes that could be merged to reduce cost and emissions. Attard, Camilleri, and Muscat [9] examined the technology requirements for a shared demand-responsive transport service centered

on the University of Malta, finding that focusing DRT around a university campus addressed concerns raised in earlier Malta-wide DRT trials about excessive service-area size and travel time. Alahmadi and Alzahrani [10] studied the feasibility of introducing DRT at Al-Baha University in Saudi Arabia, and found through comparison with the existing fixed-route system that a DRT approach could serve students with fewer total rides at equivalent fleet size, ultimately recommending a hybrid fixed-route-and-DRT configuration rather than either mode alone. Kutty et al. [11] addressed a related but distinct problem, congestion, at Qatar University, developing a bi-objective goal programming model to select among alternative shuttle routes during peak hours and validating fleet capacity against demand using Monte Carlo simulation. Most recently, Sánchez-Carmona, Marcial-Romero, Loza-Hernandez, and Hernández-Servín [12] proposed a university school bus routing model that uses DBSCAN to identify candidate bus stops from student location data, then solves a combined vehicle routing and maximum flow integer program to assign students to routes, validated on a real case at the Autonomous University of the State of Mexico with over 38,000 student records.

Together, these case studies confirm that university settings are a setting where the tidal, schedule-bound nature of demand makes the coverage-versus-efficiency trade-off especially sharp, and that campus shuttle networks specifically, not only generic urban transit, are a proven target for this kind of optimization.

2.3 Demand Aggregation and Clustering for Flexible Feeder Systems

A separate strand of literature addresses how to aggregate scattered, individual travel requests into a manageable set of pickup locations for a flexible feeder mode, relevant to this study's future-work discussion in Section 8. Xu, Liang, and Zuo [13] proposed a two-stage clustering model for Mobility-as-a-Service systems that first groups reservation requests by temporal preference, then applies a preference-weighted DBSCAN for spatial clustering, reporting a 95% demand-coverage rate in simulation. Yuan, Li, Qin, Li, and Yang [14] used three sequential rounds of ST-DBSCAN to progressively cluster reservation demand for customized passenger transport, reducing unclustered noise points to just 5%, validated on real ticketing data from a Chongqing-to-Tongliang passenger line. Stiglic, Agatz, Savelsbergh, and Gradisar [15] examined how ride-sharing can function specifically as a feeder mode into scheduled public transit, and found that offering riders a modest incentive to walk to a nearby meeting point rather than requiring exact door-to-door pickup substantially increases the share of trips that can be matched and shared.

Together, this body of work indicates that a bounded walking radius to a shared pickup point, together with DBSCAN-family clustering, is an effective way to keep feeder demand aggregation tractable, a design direction we return to briefly in Section 8.

2.4 Vehicle Routing Solution Methods

The construction of the trunk backbone in this study (Section 4.3) draws directly on established solution methods for the Capacitated Vehicle Routing Problem (CVRP). CVRP is a combinatorial optimization problem generalizing the Traveling Salesman Problem, and is NP-hard, meaning exact optimization methods are computationally insufficient for solving large-scale, real-world instances within acceptable time limits [16–19]. Approximation algorithms are therefore deployed to obtain high-quality solutions efficiently. Classical construction heuristics can generate initial, feasible routing configurations, but are structurally limited and prone to becoming trapped in local optima [17, 18]. Metaheuristics, in contrast, employ diversification strategies and local search controls to escape local minima and navigate complex search spaces; Guided Local Search (GLS) in particular has proven to be a validated metaheuristic approach that dynamically penalizes undesirable solution features to guide the search toward high-quality, near-optimal neighborhoods [16, 20]. Modern implementations use optimization frameworks such as Google's OR-Tools to operationalize CVRP and GLS in practice [20]. This study follows that precedent directly, using an OR-Tools GLS solver to independently verify the routes established by a greedy nearest-neighbor heuristic (Section 4.3).

2.5 Dial-a-Ride Scheduling and Feeder-to-Backbone Synchronization

A parallel stream of research, relevant to the feeder-layer future work discussed in Section 8, addresses how vehicles are scheduled to serve pickup points optimally once they have been aggregated (Section 2.3): the Dial-a-Ride Problem with Time Windows (DARPTW). DARPTW designs minimum-cost vehicle routes and schedules to transport passengers between pickup and destination points within chosen time constraints [21], and operators of demand-responsive transit must balance reducing passenger inconvenience against increasing operating cost [21, 22], a problem made especially difficult by its NP-hard nature and the need to enforce vehicle capacity, route duration, and customer time-window constraints simultaneously [21]. Classical location-based DARPTW formulations suffer from numerically unfavorable big-M constraints and exponentially growing subtour-elimination conditions [21, 23]; more recent event-based formulations capture vehicle occupancy states implicitly and have been shown to reduce computational time while maintaining solution quality [23]. Flexible DRT services are commonly combined with fixed scheduled networks to form mixed-mode systems in which flexible vehicles act as first-and-last-mile feeders [22]; achieving seamless connectivity in such systems requires feeder-to-backbone synchronization, where DRT vehicles must arrive at fixed trunk stops before scheduled departures to avoid missed connections [22], precisely the connectivity requirement any future feeder layer for this study's trunk network would need to satisfy.

2.6 Positioning of the Present Study

The reviewed literature establishes that hybrid fixed-flexible architectures outperform single-mode transit (Section 2.1) and that university settings are a particularly

sharp instance of the underlying coverage-efficiency trade-off (Section 2.2), while also establishing the specific solution methods, CVRP metaheuristics (Section 2.4) and DARPTW scheduling (Section 2.5), that a complete hierarchical system would draw on. However, few of the campus-specific studies reviewed in Section 2.2 combine real survey demand, real road-network distances, a representative operating-cost model, and an explicit treatment of demand uncertainty within a single fixed-route case study. This paper addresses that combination directly for Nile University's trunk network, while the demand-responsive feeder layer is simulated as a proof-of-concept to explore its potential.

3 System Architecture Overview

The Nile Ride concept is a two-tier hierarchical system: a fixed-route trunk backbone for high-demand corridors, and a demand-responsive feeder layer for lower-density peripheral zones, following evidence that integrated fixed-flexible architectures outperform single-mode transit configurations in coverage, passenger travel time, and operating cost [1], and that confining DRT operation to low-density feeder zones while preserving fixed routes along high-demand trunk corridors reduces required vehicle assets and operating expenditure [9, 10]. This paper empirically constructs, validates, and stress-tests the trunk layer, while the demand-responsive feeder layer is simulated as a proof-of-concept for the New Cairo demand zone.

4 Trunk Backbone: Data and Methods

4.1 Survey Data Collection and Demand Estimation

An online student survey was circulated to the Nile University student body and collected 95 timestamped responses between June 30 and August 16, 2026. Respondents selected their residential area from a fixed list of options; eight areas accounted for the large majority of flagged unmet shuttle demand and were carried forward as the pickup areas used throughout this study: New Cairo, Nasr City/Heliopolis, Ain Shams/Matareya/Shubra, Madinaty, Masr El Gedida, Downtown Cairo/Garden City/Zamalek, Mohandessin/Agouza/Dokki, and 6th of October/Sheikh Zayed. Of the 95 responses, 33 fell within these eight flagged pickup areas; the other 62 were outside the scope of this study and are not used in the per-area demand figures. The out-of-scope responses most commonly represented Giza/Haram/Faisal (30 respondents) and Maadi (6 respondents), together with a long tail of single-respondent locations. Table 1 reports the raw number of survey respondents selecting each in-scope area.

The per-area passenger demand values used throughout this study are scenario-based estimates adopted for trunk-route capacity planning and analysis; they are not intended as a rigorous statistical projection of the full university commuter population. Areas A2, A6, A7, and A8 were surveyed as standalone routes and their scenario demand is used directly. Areas A1/A4 and A3/A5 are combined onto shared trunk routes (Section 4.3); their combined scenario demand (26 passengers for A1+A4, and 35 for A3+A5, with the latter reaching the 35-seat capacity) is disaggregated back to the individual area level in proportion to each area's share of raw survey respondents

Table 1 Raw survey respondent counts per pickup area (33 of the 95 total responses that selected one of the eight flagged areas; June 30–August 16, 2026).

Area ID	Pickup Area	Raw Survey Respondents
A1	El Tagamoa / New Cairo	15
A2	Nasr City / Heliopolis	3
A3	Ain Shams / Matareya / Shubra	3
A4	Madinaty	1
A5	Masr El Gedida (Heliopolis area)	1
A6	Downtown Cairo / Garden City / Zamalek	2
A7	Mohandessin / Agouza / Dokki	3
A8	6th of October / Sheikh Zayed	5

within its pair:

$$Demand_{area} = Demand_{pair} \times \frac{Respondents_{area}}{Respondents_{pair}} \tag{1}$$

Applying Equation 1 to the raw counts in Table 1 (A1 = 15, A4 = 1; A3 = 3, A5 = 1) yields the per-area scenario estimates reported in Table 4 (Section 6.1). We flag this disaggregation as a secondary estimate derived from raw response counts rather than from a fully independent area-level demand model, and recommend revisiting it once real ridership data are available (Section 7). The smaller, approximately 22-point New Cairo feeder demand scenario in Section 5 is a separate, independently constructed scenario for the microsimulation; it is not a subdivision of the 24-passenger New Cairo trunk estimate, and the two numbers should not be read as conflicting.

4.2 Real Road Network Distance and Peak-Adjusted Travel-Time Estimation

The actual drivable road network of Greater Cairo was extracted using OpenStreetMap data via the OSMnx library [24], covering a radius sufficient to include the university and all eight pickup areas. Real driving distances between the university, each pickup area, and inter-area pairs were computed from this network using shortest-path routing. Travel times were initially computed under default free-flow speed profiles per road segment; because free-flow speeds substantially understate real commute times during Cairo's morning rush hour, all travel times reported in this paper are adjusted using the TomTom Traffic Index 2025 measurement of Cairo's morning peak congestion level, 42.7%, meaning morning-peak travel times run 42.7% longer than free-flow travel times on average across the city's road network [25]. Reported travel time T_{peak} is therefore computed as:

$$T_{peak} = T_{free\text{-}flow} \times (1 + 0.427) \tag{2}$$

This is a citywide average adjustment rather than a corridor-specific measurement, and should be treated as a first-order correction; corridor-level congestion data, where available, would refine it further (Section 7).

4.3 Trunk Network Construction via Capacitated Vehicle Routing

The trunk backbone connecting Nile University's eight demand areas is constructed as a capacitated vehicle routing problem (CVRP). The objective is to minimize total distance driven across all routes, subject to two constraints: every pickup area must be visited by exactly one route, and the total passenger demand assigned to any one route must not exceed the 35-seat capacity of a single bus. Routes are seeded from campus as the depot node.

Two independent methods are used to solve this problem, following the CVRP solution-method literature reviewed in Section 2.4. The first is a nearest-neighbor greedy construction heuristic: each route is seeded from an unassigned area and grown by repeatedly attaching the nearest remaining area subject to the capacity constraint, after which stops within each route are ordered by nearest-neighbor sequencing from campus. As a classical construction heuristic, this method is structurally prone to becoming trapped in local optima [17, 18], so its output is independently checked using Google OR-Tools' CVRP solver [26], configured with the same 35-seat capacity constraint, a fleet size upper bound sufficient for one bus per area, the PATH_CHEAPEST_ARC first-solution strategy, and the Guided Local Search (GLS) metaheuristic to escape local optima by searching a substantially larger space of groupings and stop orderings [16, 20]. Agreement between the two independent methods is used as convergent evidence that the resulting grouping sits in a strong local optimum for this dataset; it is not, on its own, a formal proof of global optimality, which we identify as a limitation in Section 7.

4.4 Route Adjustment Framework: Keep, Modify, Split, or Add a Bus

As demand on a trunk route grows or shifts, four concrete response options are evaluated for that route:

- **Keep:** retain the route exactly as currently operated, with no change to stops or fleet.
- **Modify:** retain the route as a single combined route, but re-order its stops to the most efficient sequence found.
- **Split (Add route):** divide the combined route into two dedicated single-area routes, each with its own bus.
- **Add bus:** retain the combined route's stop sequence, but assign a second bus to the same route to add capacity headroom without changing its geography.

Feasibility is checked first: a Keep or Modify option is only viable if combined demand fits within the 35-seat capacity of a single bus; if it does not, Split or Add bus is mandatory. Among feasible options, each is compared on the operating-cost model

in Section 4.5, with distance and travel time per passenger served (Section 6.1) as a secondary, structurally biased tiebreaker, since splitting a route into two dedicated routes roughly doubles total distance for the same passengers, as each new route must independently return to campus.

4.5 Operating Cost Model

Operating cost is modeled using a representative, assumption-based cost structure in Egyptian Pounds (EGP), rather than an audited institutional budget. The following per-kilometer and per-day cost figures are used for a university-owned 35-seat bus:

- Fuel consumption: approximately 0.25 liters/km at a diesel price of 20 EGP/liter, giving a fuel cost of approximately 5 EGP/km (planning assumption).
- Routine maintenance and tires: approximately 4 EGP/km (planning assumption).
- Depreciation and insurance: approximately 3 EGP/km (planning assumption).
- Driver wages: approximately 600 EGP/day (planning assumption).
- Administrative and operational overhead: approximately 300 EGP/day (planning assumption).

Summing the per-kilometer components ($5+4+3=12$ EGP/km) and the fixed daily components ($600+300=900$ EGP/day) gives the owned-bus daily cost for a single bus:

$$Cost_{owned} = 12 \times km_{bus} + 900 \tag{3}$$

For a scenario using multiple buses, total fleet cost sums this formula across each bus in the fleet, i.e., $Cost_{fleet} = 12 \times km_{total} + 900 \times n_{buses}$, where km_{total} is the combined distance driven by all buses in that scenario. As an alternative to an owned bus, a rented 35-seat bus with driver is estimated at approximately 4,500 EGP/day, or approximately 5,500 EGP/day if fuel is also included in the rental; this is a flat daily rate independent of distance driven, and is relevant when a scenario requires more buses than the university's owned fleet can supply. All distances and costs in this analysis represent a single one-way morning trip per route per day; no return trip, afternoon run, or multiple daily cycle is included.

4.6 Sensitivity Validation Procedure

To assess the robustness of route-adjustment recommendations to uncertainty in demand estimates, each comparison from Section 4.3 is re-evaluated under a uniform +20% demand increase, a uniform −20% demand decrease, and an expanded set of twenty independent random perturbations in which each area's disaggregated demand (Section 4.1) is varied independently within ±20% using twenty distinct random seeds. Bus capacity is held fixed across all scenarios; only demand is varied. For each of the twenty random scenarios, the two areas sharing a route are perturbed independently and summed, and the route's feasibility on a single bus and its Keep/Modify/Split/Add-bus recommendation are re-evaluated.

4.7 Ethical Considerations and Institutional Approval

The study was conducted in accordance with the relevant institutional guidelines and regulations governing research involving human participants. Prior to data collection, the survey protocol received approval from the institutional ethics committee of **Nile University**. The Transportation Department at **Nile University** served as the institutional contact for the study and provided the relevant transportation regulations and requirements that informed the development of the survey instrument. Following institutional approval, **Nile University** facilitated the distribution of the survey through official university channels and communicated information about the study to eligible students and staff. Informed consent was obtained from all participants prior to participation. Participation was voluntary, and participants were informed about the purpose of the study and the intended use of the collected data.

4.8 Use of Large Language Models

Large language models (LLMs) were used during the preparation of this manuscript to assist with language polishing, grammar correction, clarity, and readability. The use of these tools was limited to editorial and language-related assistance and did not replace the authors' scientific judgment or decision-making. All AI-assisted modifications were reviewed and verified by the authors, who remain fully responsible for the accuracy, integrity, interpretation, and conclusions of the work.

5 DRT Feeder Layer: Demand Aggregation and Simulation

5.1 Simulation Pipeline

Testing that the demand-responsive transit (DRT) feeder layer specification is operationally feasible, a traffic simulation was built for the student demand in New Cairo (Tagamoa/Rehab) using the Eclipse SUMO (Simulation of Urban Mobility). Given the students' preferred pickup locations obtained from the 95-response survey, we filtered the survey responses to retain only New Cairo demand and created fifteen extra synthetic demand points based on New Cairo's real demand distribution using Kernel Density Estimation (KDE). This approximately 22-point feeder demand scenario is independently constructed for the microsimulation and is not a subdivision of the 24-passenger New Cairo trunk estimate in Table 4; the two figures should not be read as conflicting. We then used the DBSCAN algorithm to group students into clusters that become the Virtual Pickup Points (VPUPs) in our hybrid feeder layer, with outliers assigned to cluster$_{-1}$. For every student assigned into a cluster, we calculated the walking distance between the student location and the VPUP. A 600-meter maximum walking distance is enforced to make sure that the proposed walking distances are convenient for students. If a DBSCAN cluster is too geographically large and some students are more than 600 m away from the cluster centroid, the K-Means algorithm is iteratively used to split that cluster into smaller clusters until achieving the 600-meter maximum walking distance requirement. Outliers are not automatically abandoned;

we first check if the nearest VPUP is less than or equal to 600 meters away. If true, the outlier gets assigned to this VPUP. Otherwise, it's flagged as unserviceable. The student-VPUP assignment and VPUP locations are then used inside the SUMO simulation with New Cairo SUMO road network obtained from OpenStreetMap data. OR-Tools Vehicle Routing Problem (VRP) groups the resulting eight VPUPs into 2 optimized shuttle routes (shuttle_0 VPUPs [3,4,5,0]; shuttle_1 VPUPs [2,1,7,6]) using Haversine distance matrix and GLS metaheuristic. Finding the shortest path between consecutive VPUPs and the trunk stop (the exchange point between the DRT feeder layer and the fixed bus routes), we used sumolib's `getFastestPath()` method that finds the fastest path between two network edges using Dijkstra's Algorithm. The resulting VPUP layout and routing are shown in Fig. 1.



Fig. 1 DBSCAN-derived Virtual Pickup Points (VPUPs) and optimized shuttle routes overlaid on the New Cairo SUMO simulation network. Markers indicate student pickup locations; coloured route lines show the two OR-Tools VRP shuttle routes connecting VPUPs to the trunk stop.

To compare our hybrid DRT-feeder system, we compared it against an illustrative pure fixed-route baseline in New Cairo with nine fixed stops under identical conditions. These nine stops are arbitrary comparison points chosen for this exercise, not a claim about Nile University's actual currently operated stop locations. To achieve comparison consistency, we simulated, using Eclipse SUMO, this fixed-route system using the same demand data and the destination as the trunk stop as it is in the hybrid system.

To test the proposed system's robustness, we conducted 50 independent trials of the feeder layer simulation. In the KDE-based demand synthesization step, we resampled the generated demand by using a different seed, ranging from 0 to 49, in each trial. This produces 15 different synthetic student locations while keeping the 7 real survey points fixed. Before the simulation pipeline starts, we check that synthetic demand points fall within New Cairo's coordinates, which sometimes results in fewer than 22 total demand points (real + synthetic). The nine-stop baseline remains fixed

across all trials because fixed-route stops, by definition, do not adapt to each demand realization; only the demand realization is resampled. By contrast, the hybrid system's VPUPs are demand-adaptive and are recomputed in every trial. The full pipeline is then applied to each trial's demand: DBSCAN clustering, VPUP generation and assignment, splitting large clusters, reassigning DBSCAN outliers within 600 m to the nearest VPUP, OR-Tools VRP routing, and SUMO traffic simulation on the New Cairo road network. KPIs were recorded, and 95% confidence intervals (CIs) were computed for all successful trials.

5.2 Simulation Results

Table 2 Single-run comparison of the proposed and baseline systems at seed = 42.

Metric	**Proposed system**	**Baseline system**
Number of Vehicles	2 shuttles	1 bus
Total Vehicle Kilometers Traveled (VKT) (km)	55.45	39.00
Trip Duration (min)	33.6	50.9
Number of Students Served	15	3
Average Walking Distance (m)	343	4273
VKT per student served (km)	3.70	13.00

Table 3 Monte Carlo robustness analysis over 50 trials.

KPI	**Mean**	**95% CI Lower Bound**	**95% CI Upper Bound**
Total VKT (km)	41.24	35.92	46.56
Trip Duration (min)	31.05	28.51	33.59
Number of Students Served	16.50	15.72	17.28
Average Walking Distance (m)	253.85	234.49	273.21
VKT per student served (km)	2.60	2.23	2.97

For a consistent comparison between the proposed hybrid DRT-feeder system and the existing fixed-route system, the same methodology was used to calculate the key performance indicators (KPIs) for both systems. Both Total VKT and Trip Duration were obtained directly from the SUMO `tripinfo.xml` output, ensuring that both systems were evaluated using the same SUMO road network. The average walking distance was calculated as the Haversine distance between each student's pickup coordinates and either their assigned VPUP in the hybrid system or the nearest stop in the fixed-route system.

A student was considered served by the hybrid system if they were assigned to a valid cluster (cluster ID ≥ 0). For the fixed-route system, a student was considered served if their Haversine distance to at least one fixed stop was within the 600 m

walking-distance threshold. VKT per student served was calculated as the total VKT divided by the number of students served. The single-run comparison in Table 2 reports 15 students served at seed 42, whereas Table 3 reports the 50-trial mean of 16.50 students served; these are different measurements, not contradictory results.

The comparison and robustness results, presented in Tables 2 and 3, show a substantial difference in service coverage between the two systems. Under the 600 m maximum walking-distance criterion, the fixed-route system serves only 3 out of the 22 students, whereas the hybrid system serves an average of 16.50 students, with a 95% confidence interval (CI) of $[15.72, 17.28]$, out of a maximum demand of 22 students.

Although the hybrid system results in higher total VKT on average, it serves substantially more students. Consequently, VKT per student served is considerably lower for the hybrid system, with a mean of 2.60 km (95% CI: $[2.23, 2.97]$), compared with 13.00 km for the fixed-route system. The DBSCAN-based VPUP assignment also substantially reduces the walking burden, with an average walking distance of 253.85 m (95% CI: $[234.49, 273.21]$ m) in the hybrid system, compared with 4273 m for the illustrative fixed-route system.

These results indicate that the proposed hybrid system provides substantially greater service coverage and better VKT efficiency per student served, making it a more effective solution for serving low-demand areas.

6 Trunk Backbone Results

6.1 Pickup Areas, Disaggregated Demand, and Peak-Adjusted Travel Times

Table 4 Pickup areas, real road-network distance, morning-peak-adjusted travel time (42.7% congestion factor; TomTom [25]), and disaggregated per-area passenger demand.

Area ID	Pickup Area	Distance (km)	Peak Time (min)	Demand
A1	El Tagamoa / New Cairo	58.1	59.1	24
A2	Nasr City / Heliopolis	46.0	40.5	25
A3	Ain Shams / Matareya / Shubra	40.8	31.0	26
A4	Madinaty	80.6	72.9	2
A5	Masr El Gedida (Heliopolis area)	46.0	38.5	9
A6	Downtown Cairo / Garden City / Zamalek	36.5	34.0	22
A7	Mohandessin / Agouza / Dokki	32.1	30.7	28
A8	6th of October / Sheikh Zayed	6.4	9.0	35

Table 4 reports the real driving distance, peak-adjusted travel time (Equation 2), and per-area passenger demand for each of the eight pickup areas. The demand for areas A1/A4 and A3/A5 is disaggregated according to Equation 1.

6.2 Optimized Trunk Route Set

The eight pickup areas were grouped into six candidate routes under the 35-seat capacity constraint (Section 4.3). The greedy construction heuristic and the OR-Tools CVRP solver converged on the same grouping and stop order, shown in Table 5.

Table 5 Optimized trunk route set, cross-validated by the OR-Tools CVRP solver.

Route	Stops (in order)	Demand (pax)	Distance (km)
Route 1	A1 → A4	26	85.8
Route 2	A2	25	46.0
Route 3	A3 → A5	35	46.2
Route 4	A6	22	36.5
Route 5	A7	28	32.1
Route 6	A8	35	6.4

6.3 Route Adjustment Comparison: Keep, Modify, Split, or Add a Bus

The four-option framework (Section 4.3) and the operating-cost model (Section 4.5) were applied to Route 1 (A1 + A4, 26 passengers, well under capacity; Table 6) and Route 3 (A3 + A5, 35 passengers, at full 35/35-seat capacity; Table 7), using peak-adjusted travel times from Table 4.

For Route 1, Keep and Modify are identical, since the current stop order is already the more efficient of the two orderings tested. Modify is the cheapest option at 74.2 EGP/passenger, roughly half the cost per passenger of either Split or Add bus, and comfortably feasible on one bus at baseline demand.

Table 6 Route 1 ($A1 + A4$, 26 passengers) comparison across options.

Option	Buses	Dist. (km)	Peak Time (min)	Cost (EGP/day)	Cost/Pax (EGP)
Option 1	1	85.8	96.9	1,929.6	74.2
Option 2	2	138.7	132.0	3,464.4	133.2
Option 3	2	171.6	193.8	3,859.2	148.4

Option 1: Keep / Modify (NU $\rightarrow$ A1 $\rightarrow$ A4) | Option 2: Split (2 dedicated routes) | Option 3: Add bus (2nd bus, same route).

Table 7 Route 3 ($A3 + A5$, 35 passengers) comparison across options.

Option	Buses	Dist. (km)	Peak Time (min)	Cost (EGP/day)	Cost/Pax (EGP)
Option 1	1	46.2	38.5	1,454.4	41.6
Option 2	2	86.8	69.5	2,841.6	81.2
Option 3	2	92.4	77.1*	2,908.8	83.1

Option 1: Keep / Modify (NU → A3 → A5) | Option 2: Split (2 dedicated routes) | Option 3: Add bus (2nd bus, same route).
*Add-bus peak time is a fleet total (two buses each completing the 38.5-minute route), not passenger wait time.

For Route 3, Modify remains the cheapest option per passenger at baseline demand (41.6 EGP/passenger), but Route 3 is already at full 35-seat capacity, so any demand growth requires a move to Split or Add bus (Section 6.4). Between those two, Split is markedly cheaper (81.2 vs. 83.1 EGP/passenger) because it avoids driving the full combined route twice; Add bus is a viable fallback where a second dedicated route cannot be operated, for example if a rented rather than owned bus is the only available second vehicle, in which case its daily cost would rise to approximately 4,500–5,500 EGP regardless of distance driven (Section 4.5), well above either owned-fleet option.

6.4 Sensitivity Analysis

Both routes were re-evaluated under a uniform +20% demand increase, a uniform −20% demand decrease, and twenty independent random perturbations in which each area's disaggregated demand was varied independently within ±20% (Section 4.3). Table 8 summarizes results.

Table 8 Sensitivity of Route 1 and Route 3 recommendations to ±20% demand perturbation, including the expanded 20-seed random analysis.

Scenario	**Route Pair**	**Feasible on 1 Bus**	**Recommendation**	**Avg. Demand**
Baseline	A1+A4	Yes	Modify	26.0
Baseline	A3+A5	Yes	Modify	35.0
+20% uniform	A1+A4	Yes	Modify	31.2
+20% uniform	A3+A5	No	Split or Add bus	42.0
−20% uniform	A1+A4	Yes	Modify	20.8
−20% uniform	A3+A5	Yes	Modify	28.0
Random ±20% (20 seeds)	A1+A4	20 of 20 (100%)	Modify in all seeds	25.8
Random ±20% (20 seeds)	A3+A5	11 of 20 (55%)	Modify in a majority of seeds	35.1

Route 1 (A1+A4) kept its Modify recommendation in every one of the 20 randomized scenarios, in addition to both uniform shifts, confirming that recommendation is robust to plausible demand uncertainty. Route 3 (A3+A5) is more sensitive under the expanded analysis: because it already sits at full 35-seat capacity at baseline, a majority of the 20 independent random draws kept it feasible on one bus, while the remainder pushed combined demand over capacity, requiring a move to Split or Add bus. The larger scenario set therefore sharpens, rather than changes, the original finding: a route's spare capacity at baseline demand is a strong predictor of how robust its Modify recommendation is to demand uncertainty.

6.5 Total Network Cost and Potential Avoided Cost

Applying the operating-cost model (Section 4.5) across the full six-route trunk network gives an estimate of total daily operating cost, and of the potential avoided cost from choosing the recommended action on Routes 1 and 3 rather than defaulting to Split whenever a combined route could instead be modified. Under the recommended configuration, Modify for Routes 1 and 3 and Keep for Routes 2, 4, 5, and 6, total daily network cost is approximately **8,436 EGP**. Under a hypothetical alternative configuration where Routes 1 and 3 are always Split into dedicated routes, total daily network cost rises to approximately **11,358 EGP**. The recommended configuration therefore represents a potential avoided cost of approximately **2,922 EGP per day**, a **25.7%** reduction relative to that hypothetical always-split scenario.

Assuming approximately 22 operating days per month and an approximately 180-day academic year, this translates to approximately **64,300 EGP per month** and approximately **526,000 EGP per academic year** in avoided cost, relative to a hypothetical network that defaults to splitting every route once it grows past its original grouping. Total network operating cost under the recommended configuration itself is estimated at approximately **185,600 EGP per month** and approximately **1,518,000 EGP per academic year**. These figures use the operating-cost assumptions in Section 4.5 and the route distances in Table 5, and should be treated as planning-level estimates rather than an audited budget.

7 Discussion

The results in Section 6 are consistent with, and extend, the campus-DRT literature reviewed in Section 2. Alahmadi and Alzahrani [10] found that a hybrid fixed-route-and-DRT configuration outperformed either mode alone at Al-Baha University; the present study arrives at a structurally similar conclusion within the fixed-route layer alone, showing that a single combined route (Modify) can match a split configuration (Split) on demand served while costing roughly half as much per passenger under the representative operating-cost assumptions, so long as spare capacity remains. Expanding the route-adjustment decision from two options to four did not change which option is cheapest at baseline demand for either route, but it did materially change the size of the gap between options: the cost gap between Modify and Split (roughly 1.8× per passenger for both routes) is smaller than the raw distance-based km-per-passenger gap reported in earlier analysis of this dataset, because the fixed daily cost

per bus (900 EGP) is a smaller share of total cost than distance-only comparisons imply. Applied across the full network, this gap is large enough to matter operationally: roughly 526,000 EGP per academic year in potential avoided cost separates the recommended configuration from a hypothetical always-Split policy (Section 6.5).

The expanded, twenty-seed sensitivity analysis also revealed a more nuanced picture for Route 3 than the original three-seed test: a 55% feasibility rate under randomized ±20% demand indicates that Route 3 should be treated as a near-term candidate for proactive capacity planning, for example by pre-arranging access to a rented second bus, rather than as a route that can be safely left in its current combined configuration indefinitely. Applying a measured Cairo peak-congestion adjustment (42.7%; TomTom [25]) rather than free-flow travel times also meaningfully changes the absolute travel-time figures used to communicate expected commute times to students, even though it does not change the underlying distance-based route grouping or the cost-based Keep/Modify/Split/Add-bus recommendation, since neither depends on travel time as the primary criterion.

The New Cairo feeder proof-of-concept provides complementary qualitative evidence rather than a network-scale cost estimate. On a real SUMO road network, the DBSCAN-clustered, dynamically routed feeder serves substantially more students and produces lower walking-distance burden than the illustrative fixed-stop baseline in the simulated pilot zone. This result supports the physical and algorithmic feasibility of the hybrid design, but it should be read as feasibility evidence for one pilot zone, not as a validated forecast for the full network.

Several limitations remain. First, demand figures are scenario-based estimates derived from a 95-response survey, of which 33 responses fell within the eight flagged pickup areas and 62 were outside scope (Section 4.1); the per-area disaggregation of the two combined-route pairs (Equation 1) is a secondary estimate based on raw respondent counts within each pair, not an independently collected area-level demand figure, and should be revisited once real ridership or GPS-derived demand data are available. Second, the operating-cost model is representative and assumption-based rather than audited, and assumes a single one-way morning trip per route per day; actual institutional fuel, maintenance, depreciation, payroll, and scheduling data could change the cost comparison. Third, the 42.7% congestion adjustment applied in Section 4 is a citywide average from a public traffic index rather than a corridor-specific measurement of the exact roads used by each route, and may understate or overstate delay on any individual corridor. Fourth, agreement between the greedy heuristic and the OR-Tools solver is convergent evidence of a strong local optimum, not a formal proof of global optimality. Fifth, the feeder proof-of-concept covers only one pilot zone with an illustrative fixed-stop baseline and synthesized demand, and should not be generalized to the other seven areas without further simulation and deployment data.

8 Conclusion and Future Work

This paper presented a survey-based optimization case study of Nile University's fixed-route shuttle network, Using survey responses to construct scenario-based demand estimates disaggregated to the individual pickup-area level, real Greater

Cairo road-network distances adjusted for measured peak-hour congestion, a four-option Keep/Modify/Split/Add-bus route-adjustment framework evaluated with a representative, assumption-based operating-cost model, and an expanded twenty-seed sensitivity analysis. Applying the recommended configuration across the full six-route trunk network represents a potential avoided cost of approximately 2,922 EGP per day, or roughly 526,000 EGP per academic year, relative to a hypothetical always-Split scenario. Results also show that a route's spare capacity at baseline demand is a strong predictor of how robust its Modify recommendation is to demand uncertainty. The fixed-route trunk network is the paper's empirically validated contribution; the feeder layer is a proof-of-concept only and is not a network-wide validation.

A demand-responsive feeder layer for lower-density peripheral zones remains a natural extension of the trunk network presented here. Such a layer would aggregate scattered pickup requests into shared Virtual Pickup Points using a network-distance-constrained DBSCAN variant, following the demand-aggregation precedent established for campus and Mobility-as-a-Service settings [12–14] and the walking-incentive finding of Stiglic et al. [15], with feeder vehicles synchronized to trunk departures using a Dial-a-Ride-with-Time-Windows formulation [21–23]. The proof-of-concept implementation of the DRT feeder layer for New Cairo (Section 5) confirms the physical feasibility of our hybrid system on the real Cairo road network. Full empirical validation at scale, including baseline comparisons and parameter sensitivity analysis, remains future work.

Future work is prioritized as follows:

- Replace the scenario-based, pair-level-disaggregated demand data used in this paper with real ridership or GPS-derived demand data collected at the individual pickup-area level.
- Replace the representative, assumption-based operating-cost parameters (Section 4.5) with the university's actual fuel, maintenance, depreciation, payroll, and scheduling figures, including whether return or afternoon trips should be costed in addition to the one-way morning trips modeled here.
- Obtain corridor-specific, rather than citywide, congestion measurements to refine the peak-adjusted travel times in Section 4.
- Verify formally whether the OR-Tools CVRP solution is provably distance-optimal for this dataset.
- Given Route 3's sensitivity to demand uncertainty (Section 6.4), pre-plan a rented-bus contingency or a Split decision ahead of the next enrollment cycle.
- Extend the New Cairo feeder proof-of-concept to the remaining seven pickup areas, replace its illustrative fixed-route baseline and synthesized demand with real stop locations and ridership data, and formally integrate its trunk-stop exchange point with the trunk network's departure schedule using a DARPTW formulation.
- Pilot the resulting system with a subset of routes and iterate based on real usage and rider feedback.

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Data Availability

The data supporting the findings of this study are available from Nile University, Egypt, but restrictions apply to the availability of these data, which were used under institutional restrictions for the current study and are therefore not publicly available. The data are, however, available upon reasonable request and with the permission of Nile University, Egypt.

Competing Interests

The authors declare no competing interests.

Author Contributions

M.N. conceived the project idea; designed and implemented a website supporting the proposed methodology, with the resulting system and findings to be reported in future work; assisted with the SUMO-based DRT feeder simulation; and contributed to manuscript writing. M.M. led the survey design and data collection, conducted the CVRP construction and route-adjustment analysis, implemented the OR-Tools CVRP solver cross-validation, developed the operating-cost model and sensitivity analysis, and wrote the manuscript. H.A.S. designed and implemented the SUMO-based DRT feeder simulation, conducted the Monte Carlo robustness analysis, and contributed to manuscript writing. H.M. served as the supervising professor and provided overall supervision and guidance throughout the research. All authors reviewed and approved the final manuscript.

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A Appendix

Appendix A. Project Repository

The full Nile Ride codebase (platform, clustering, and routing scripts) is maintained in a private repository. Access may be made available upon reasonable request to the corresponding author.

Appendix B. Survey Instrument

Demand for this study was collected through a 95-response survey with conditional branching by respondent type (student vs. staff/faculty) and residence, covering current commute mode, distance to the nearest existing bus stop, typical commute time and monthly cost, satisfaction with current transportation, and willingness to walk up to 10 minutes to a shared pickup point. Responses were collected between June 30 and August 16, 2026, and flagged eight residential clusters with unmet shuttle demand, which became the pickup areas used throughout the route optimization and route-adjustment analysis (Sections 4.3 and 6).