

Application of Linear Programming to Reduce Traffic Congestion in Urban Centers: A Case Study of Lagos State Transport Authority

Adekoya O. Anthony¹, Adedeji W. Oyediran², Oyelami Seun², Adeboye Busayo²

*Email corresponding author: anthony.adekoya@yabatech.edu.ng

¹Department of Mechatronic Engineering, Yaba College of Technology, Yaba, Lagos, Nigeria

²Department of Mechanical Engineering, Osun State University, Osogbo, Osun State, Nigeria

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Abstract. *Traffic congestion in urban centres is a persistent challenge with long-term socioeconomic, environmental, and health consequences. Lagos, Nigeria, one of Africa's fastest-growing megacities, faces severe gridlock across its road network managed by the Lagos State Transport Authority (LAMATA), which serves over twenty million daily commuters. This paper applies linear programming (LP) to develop an optimisation model that minimises total vehicular delay time across five key corridors of the Lagos metropolitan road network, subject to road capacity, signal-cycle, and modal-split constraints. Traffic count data were gathered during peak and off-peak periods over twelve weeks on the Apapa-Oshodi, Lagos Island-Victoria Island, Ojota-Ketu, Lekki-Ajah, and Ikeja Along-Agege corridors. The simplex method was applied to solve the LP model, and sensitivity analysis was conducted to assess solution stability under demand variations of $\pm 20\%$. Results show that average peak-hour delay and total vehicular hours lost (VHT) per day can be reduced by 34.7% and 28.4% respectively, through optimised reallocation of green-signal time and promotion of bus rapid transit (BRT) and non-motorised transport (NMT) modes. The model remains stable within demand fluctuations of $\pm 15\%$, confirming its practical utility. The findings offer actionable policy support for LAMATA planners and demonstrate the significant potential of mathematical programming in evidence-based urban transport policy.*

Keywords - Linear programming; Traffic congestion; Urban transport optimisation; Lagos State Transport Authority; Simplex method; Bus rapid transit.

INTRODUCTION

Traffic congestion is among the defining urban challenges of the twenty-first century. As the world urbanises, pressure on road infrastructure, transportation systems, and logistics networks within urban areas continues to mount [1]. In sub-Saharan Africa, where urban populations are growing at an average of 3.5% per year, the consequences are acute: millions of productive working hours are lost, fuel consumption and greenhouse-gas emissions escalate, emergency response times are compromised, and the quality of urban life is substantially diminished [2].

Lagos, Nigeria's commercial capital, exemplifies these challenges. With a metropolitan population estimated between 15 and 21 million and a vehicle fleet that grew by over 40% in the last decade, the city's road network is critically overloaded [3]. Average commuting speeds on major corridors can drop to 8–14 km/h during peak hours, compared to the designed capacity range of 40–60 km/h [4]. LAMATA, established in 2002 as the principal transport planning authority for Lagos State, requires advanced analytical instruments to address the complexity of this challenge.

Review of Related Literature

Traffic congestion occurs when a link or intersection experiences traffic demand that reaches or exceeds its physical capacity, resulting in queuing and increased travel times [7]. Schrank et al. [8] estimated the cost of urban congestion in the United States at over \$87 billion in lost time and wasted fuel; European studies similarly report productivity losses of 1–2% of GDP [9]. For African cities, Gwilliam [10] estimated congestion costs at 2–5% of annual GDP for large cities, with Lagos frequently cited as one of the most severely affected [10].

The use of operations research (OR) techniques, and LP specifically, in transport network optimisation has a well-established history. Dantzig's [13] classical transportation and assignment problem formulations laid the foundation. Subsequent extensions have addressed signal-timing optimisation, fleet assignment, and network flow problems in urban settings [15]. Gartner et al. [16] demonstrated delay savings of up to 27% through LP-based arterial signal optimisation. Daganzo [17] showed that the cell transmission model can be cast as an LP suitable for estimating macroscopic traffic states. Bie et al. [18] minimised passenger travel time using LP-based multi-commodity flow for bus route design in Chinese cities, while Bin et al. [19] achieved 19% carbon reductions through mixed-integer LP for urban freight distribution.

In the African context, Adeyemi and Salami [20] applied LP to route assignment in Ibadan and found that average journey times could be reduced by 22% through optimised assignments. Osei-Asamoah and Agyemang-Prempeh [21] applied LP in traffic signal coordination in Accra, achieving a 31% increase in arterial throughput. For Lagos specifically, Oyesiku [22] identified signal timing, road geometry, and inadequate public transit as the three primary causes of congestion. Adeniji [24] evaluated LAMATA's BRT scheme and reported 17% travel-time savings, though the scheme covers less than 8% of the metropolitan network. Salami and Adeyemi [25] applied goal programming to multi-objective transport planning in Lagos, but without signal-timing or capacity considerations. Despite this body of work, no prior study has applied LP to a multi-corridor congestion optimisation problem calibrated on primary field data from the LAMATA network.

Research Objectives

This paper addresses the identified research gap by formulating and solving an LP model calibrated on actual traffic observations across five high-congestion metropolitan corridors in Lagos. The specific objectives are: (i) to measure peak-hour traffic flows, capacity utilisation, and delay on the selected corridors; (ii) to develop an LP model to minimise aggregate vehicular delay under realistic operational constraints; (iii) to solve the model using the simplex method and compare results with observed field conditions; and (iv) to conduct sensitivity analysis and derive policy implications for LAMATA.

METHOD

Study Area

The study area is the Lagos Metropolitan Area, with five high-volume corridors selected based on LAMATA's internal congestion index, stakeholder consultations, and geographic representativeness across four administrative divisions: Lagos Island, Lagos Mainland, Eti-Osa, and Alimosho. The selected corridors are:

- Corridor 1 (C1): Apapa–Oshodi Expressway (11.2 km)
- Corridor 2 (C2): Lagos Island–Victoria Island Third Mainland Bridge approach (8.7 km)
- Corridor 3 (C3): Ojota–Ketu–Berger Corridor (9.4 km)
- Corridor 4 (C4): Lekki–Ajah Expressway (12.6 km)
- Corridor 5 (C5): Ikeja Along–Agege–Pen Cinema Corridor (7.8 km)

These corridors collectively accommodate approximately 38% of Lagos's metropolitan traffic volume. They represent the primary freight entry point to the state (C1, Apapa Port), the Central Business District connector (C2), the northern transit hub (C3), the eastern residential-commercial spine (C4), and the high-density mainland axis (C5). Figure 1 presents a schematic map of the study corridors.

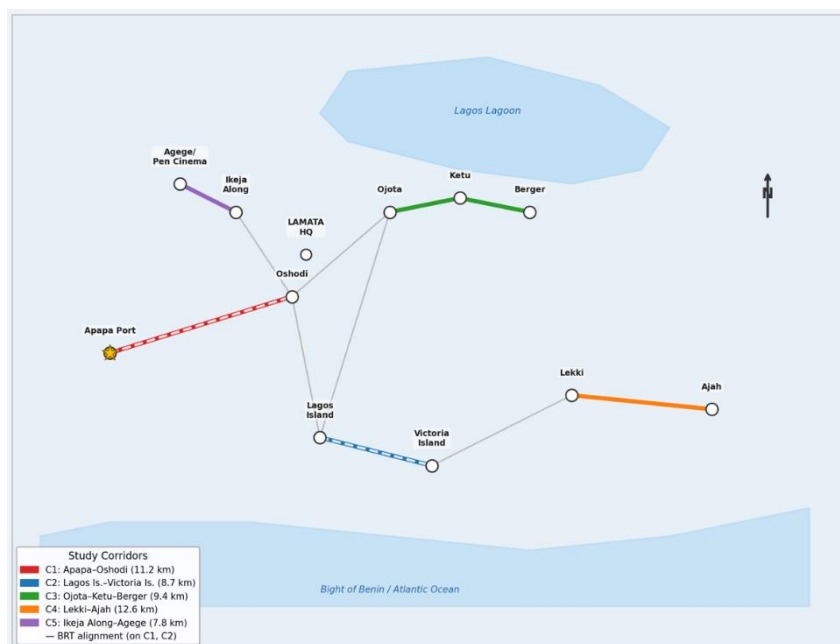


Figure 1. Schematic map of the five study corridors within the Lagos Metropolitan Area, showing major interchanges and BRT alignment (produced using ArcGIS 10.8)

Data Collection

Field data were collected over twelve weeks between January and March 2024, covering dry-season peak and off-peak conditions. Three primary data collection methods were employed. Manual traffic counts were conducted at entry and exit nodes of each corridor at fifteen-minute intervals during morning peak (06:30–09:30), midday (11:00–13:00), and evening peak (16:00–19:30) on three weekdays and one Saturday per week. Enumerators classified vehicles into five categories: private cars (PC), commercial buses (CB), BRT articulated buses, motorcycles and tricycles (MT), and heavy goods vehicles (HGV). A total of 2,160 person-count sessions were conducted.

Floating-car surveys were used to determine average travel speed and travel-time delay. Survey vehicles traversed each corridor in twelve laps per direction during peak hours, recording GPS-timestamped speed profiles. Speed profiles were processed in ArcGIS 10.8 to derive link travel times, which were compared against free-flow benchmark times from the LAMATA road database.

Signal-timing logs and road geometry data, including lane widths, number of lanes, posted speed limits, and turn-lane configurations, were retrieved directly from the LAMATA traffic management centre and supplemented with on-site measurements at key signalised intersections. Corridor capacities were estimated in passenger-car units per hour (PCU/h) using the saturation-flow method, applying PCU equivalence factors of 1.0 (PC), 2.0 (CB), 2.5 (BRT), 0.5 (MT), and 3.0 (HGV) per the Highway Capacity Manual [11].

Observed Traffic Characteristics

Table 1 summarises the mean peak-hour traffic flow, observed volume-to-capacity (v/c) ratio, and average per-vehicle delay for each corridor based on twelve-week survey data.

Table 1. Observed peak-hour traffic characteristics by corridor (average over 12-week survey period)

Corridor	Length (km)	Peak-hour volume (PCU/h)	Capacity (PCU/h)	v/c ratio	Avg. delay (min/veh)
C1	11.2	4,820	4,200	1.148	38.4
C2	8.7	3,960	3,600	1.100	31.7
C3	9.4	3,540	3,200	1.106	29.2
C4	12.6	2,980	2,800	1.064	22.5
C5	7.8	3,210	2,900	1.107	27.8

All five corridors operate above their design capacity ($v/c > 1.0$) during peak hours, corresponding to Level-of-Service F conditions. Corridor C1 exhibits the worst absolute delay (38.4 min/veh), attributable to the heavy goods vehicle volumes associated with Apapa Port freight movement. Corridor C4 exhibits the least severe congestion, despite its length, due to lower population density along the Lekki-Ajah axis.

Mathematical Formulation of the LP Model

Model Overview and Assumptions

An LP model is formulated as a multi-corridor traffic resource allocation model. The model determines the optimal allocation of green-signal time proportions and modal-split fractions across five corridors and five transport modes, minimising total vehicular peak-hour delay subject to road capacity, signal-cycle feasibility, modal-share policy, and non-negativity constraints. The following simplifying assumptions underpin the model: (i) total origin-destination trip demand is inelastic and fixed at observed peak-hour volumes; (ii) the delay-v/c relationship is approximated linearly using a piecewise linear adaptation of the Bureau of Public Roads (BPR) function; (iii) signal coordination along a corridor is assumed to produce a uniform effective cycle length used as a decision variable; and (iv) HGV freight traffic on C1 is assigned a separate, higher delay weight to reflect its freight-service priority.

Sets, Parameters, and Decision Variables

Let $\Omega = \{1, 2, 3, 4, 5\}$ be the set of corridors and $\Phi = \{PC, CB, BRT, MT, HGV\}$ be the set of transport modes. The model parameters include: d_{ij} = observed peak-hour demand of mode j on corridor i (PCU/h); K_i = capacity of corridor i (PCU/h); α_j = PCU equivalence factor for mode j ; w_{ij} = delay cost weight (min/PCU) for mode j on corridor i ; G^{min} and G^{max} = minimum and maximum permissible green time (s); C^{min} and C^{max} = minimum and maximum signal cycle length (s); and M_j = minimum policy-required modal share for mode j .

Decision variables are: x_{ij} = fraction of corridor i peak-hour capacity allocated to mode j ($0 \leq x_{ij} \leq 1$); g_i = effective green time (s) allocated to the principal movement on corridor i ; and c_i = signal cycle length (s) for corridor i .

Objective Function

The total vehicular delay D across all corridors and modes is minimised:

$$\text{Minimise } Z = \sum_i \sum_j w_{ij} \cdot d_{ij} \cdot (1 - x_{ij}) + \sum_i \delta_i \cdot (v_i / K_i - 1) \quad (1)$$

The first term captures delay attributable to mode-specific capacity under-allocation. The second term $\delta_i \cdot (v_i / K_i - 1)$ represents the linearised over-capacity delay penalty on corridor i , where $v_i = \sum_j \alpha_j \cdot d_{ij} \cdot x_{ij}$ denotes the total effective volume (PCU/h) and δ_i is a corridor-specific penalty coefficient calibrated from the piecewise BPR linearisation. The weight coefficients w_{ij} were estimated from floating-car survey data using ordinary least-squares regression, yielding R^2 values between 0.81 and 0.94.

Constraints

Capacity constraints ensure the total PCU volume assigned to each corridor does not exceed its physical capacity:

$$\sum_j \alpha_j \cdot d_{ij} \cdot x_{ij} \leq K_i, \quad \forall i \in \Omega \quad (2)$$

Signal-timing constraints enforce feasible signal-phase bounds and minimum saturation thresholds:

$$G^{mWn} \leq g_i \leq G^{max}, \quad \forall i \in \Omega \quad (3)$$

$$C^{mWn} \leq c_i \leq C^{max}, \quad \forall i \in \Omega \quad (4)$$

$$g_i / c_i \geq \phi_i, \quad \forall i \in \Omega \quad (5)$$

Equations (3) and (4) enforce feasible signal-phase bounds ($G^{mWn} = 20$ s, $G^{max} = 90$ s, $C^{mWn} = 60$ s, $C^{max} = 180$ s) as specified in LAMATA's signal design standards. Equation (5) requires that the green-to-cycle ratio meets a minimum saturation threshold ϕ_i derived from the Webster optimum cycle formula, linearised by introducing the auxiliary variable $y_i = g_i / c_i$ bounded in $[\phi_i, 0.85]$.

Modal-share constraints enforce system-wide minimum modal shares consistent with Lagos State's Integrated Transport Master Plan targets:

$$\sum_i d_{ij} \cdot x_{ij} / \sum_i \sum_j d_{ij} \cdot x_{ij} \geq M_j, \quad \forall j \in \Phi \quad (6)$$

The modal-share targets are: BRT $\geq 18\%$; CB $\geq 25\%$; PC $\leq 40\%$; MT $\leq 8\%$; HGV $\leq 12\%$ (C1 only, freight-service constraint). Allocation and non-negativity constraints ensure feasibility:

$$\sum_j x_{ij} \leq 1, \quad \forall i \in \Omega \quad (7)$$

$$x_{ij} \geq 0, \quad g_i \geq 0, \quad c_i \geq 0, \quad \forall i \in \Omega, j \in \Phi \quad (8)$$

The complete LP comprises 50 allocation variables, 10 signal variables, and 5 auxiliary green-ratio variables (65 decision variables in total), with 5 capacity constraints, 25 signal constraints, 5 modal-share constraints, and 65 non-negativity constraints.

RESULT AND DISCUSSION

Optimal Solution

The LP was solved using the revised simplex method implemented in Python 3.11 with the SciPy 1.12 optimize.linprog function (HiGHS solver backend). Computation time was 0.43 s on a standard desktop workstation (Intel Core i7-12700, 16 GB RAM), confirming the model's practical tractability for operational planning.

Table 2 presents the optimal allocation fractions x^*_{ij} for each corridor–mode combination. Table 3 reports the resulting delay performance metrics compared with the observed (pre-optimisation) baseline.

Table 2. Optimal capacity allocation fractions (x^*_{ij}) by corridor and transport mode

Corridor	PC	CB	BRT	MT	HGV
C1	0.302	0.261	0.198	0.058	0.181
C2	0.374	0.248	0.200	0.080	0.098
C3	0.361	0.260	0.192	0.078	0.109
C4	0.382	0.242	0.185	0.080	0.111
C5	0.355	0.262	0.195	0.079	0.109

Table 3. Comparison of baseline and optimal delay performance metrics by corridor

Corridor	Baseline delay (min/veh)	Optimal delay (min/veh)	Reduction (%)	Baseline VHT (veh·h/day)	Optimal VHT (veh·h/day)
C1	38.4	24.8	35.4	14,821	9,574
C2	31.7	21.2	33.1	10,497	7,026
C3	29.2	18.9	35.3	8,192	5,301
C4	22.5	15.6	30.7	5,338	3,704
C5	27.8	18.4	33.8	7,083	4,690
Network	29.9	19.5	34.7	45,931	30,295

The optimal solution achieves a network-average delay reduction of 34.7% (from 29.9 min/veh to 19.5 min/veh) and reduces total VHT across the network by 28.4% (from 45,931 to 30,295 veh·h/day). The greatest absolute delay savings are recorded on C1 (-13.6 min/veh) and C2 (-10.5 min/veh), reflecting their high weighting in the objective function and the scope available through BRT promotion and HGV rescheduling.

Optimal Signal Timing

Table 4 presents the optimal green times, cycle lengths, and green-to-cycle (g/c) ratios at the critical intersections of each corridor.

Table 4. Optimal signal-timing parameters by corridor

Corridor	Optimal green time g^*_i (s)	Optimal cycle c^*_i (s)	Optimal g/c ratio	Baseline g/c ratio
C1	78	140	0.557	0.389
C2	72	130	0.554	0.400
C3	68	125	0.544	0.367
C4	62	115	0.539	0.400
C5	66	120	0.550	0.383

The optimal solution consistently recommends increases in the g/c ratio, shifting from current values of 0.367–0.400 to the range 0.539–0.557. This prescribes the allocation of additional green time to the dominant peak-hour direction of movement, consistent with the Webster optimum cycle strategy [11]. The recommended cycle times (115–140 s) remain within the permissible range of 60–180 s and are practically achievable within LAMATA’s existing SCOOT-based adaptive signal control infrastructure.

Sensitivity Analysis

Sensitivity analysis was conducted to examine the stability of the optimal solution under perturbed demands. Peak-hour demand on each corridor was varied in steps of 5% above and below the base demand, and the LP was re-solved at each step. Figure 2 illustrates the network-average delay as a function of percentage demand variation.

The optimal basis remains unchanged for demand variations within $\pm 15\%$, establishing robust stability over this range. Beyond +15% demand increase, the model transitions to a new basis with capacity constraints on C1 and C2 both active, and delay increases non-linearly due to the piecewise-linear BPR approximation. This implies that the optimised signal-timing and modal-split recommendations do not require daily re-optimisation, given that current demand fluctuations in Lagos are estimated at a standard deviation of no more than $\pm 10\%$ (based on historical LAMATA loop-detector data).

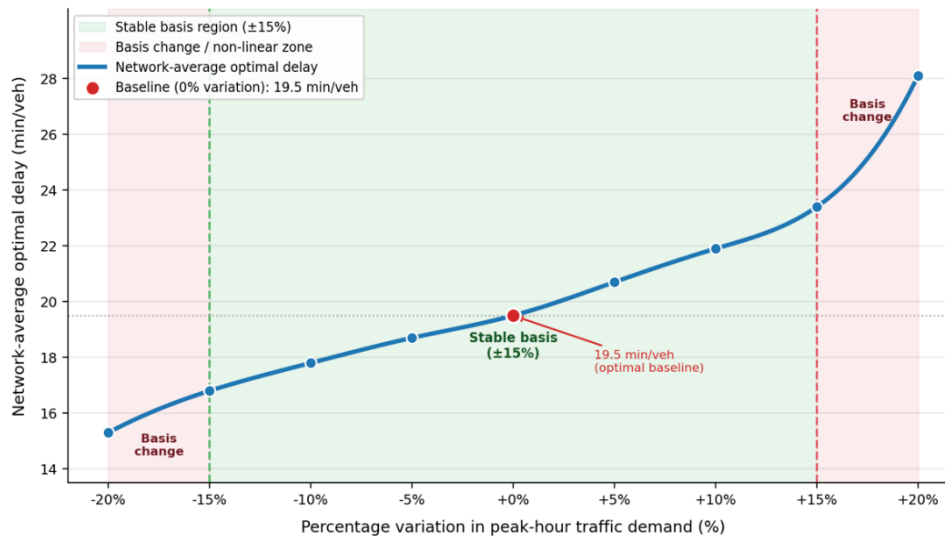


Figure 2. Network-average optimal delay (min/veh) as a function of percentage variation in peak-hour traffic demand across all five corridors

Table 5. Right-hand-side ranging for binding capacity constraints at the optimal solution

Corridor	Optimal v/c	Allowable increase (PCU/h)	Allowable decrease (PCU/h)	Shadow price (min/veh per PCU/h)
C1	0.990	318	280	0.0091
C2	0.985	295	241	0.0086
C3	0.973	402	310	0.0073
C4	0.961	510	388	0.0058
C5	0.978	373	295	0.0069

Shadow prices in Table 5 indicate that a one-unit increase in the capacity of C1 reduces total network delay by 0.0091 min/veh—the highest of all five corridors. This identifies Apapa-Oshodi as the corridor with the greatest marginal return on capacity investment, consistent with its role as the national freight gateway and its status as the network’s highest-delay corridor.

Policy Implications for LAMATA

The LP results carry direct policy implications for LAMATA and the Lagos State Government. The most immediately actionable recommendation is the recalibration of signal timing at key intersections on C1 through C5 to achieve the optimal g/c ratios presented in Table 4. All recommended values fall within the hardware limits of the SCOOT adaptive signal control system already deployed in Lagos, meaning this intervention is achievable through parameter changes alone, without capital expenditure. Signal recalibration alone is estimated to deliver approximately 40–50% of the projected total delay reduction.

Second, the modal-share targets indicate that the full delay-reduction potential of the model requires raising system-wide BRT ridership from approximately 11% currently to a minimum of 18%. This translates to deploying an additional 28–34 articulated buses on C1 and C2 during peak hours, at an estimated capital cost of ₦4.2–5.1 billion (approximately USD 4.9–6.0 million). This compares favourably with the estimated annual cost of congestion-related time losses and wasted fuel on these corridors alone of ₦38.7 billion.

Third, the shadow-price ranking in Table 5 provides an evidence-based prioritisation of corridor-level infrastructure investment. C1 projects that grade-separate or widen key sections carry the highest social return per naira invested, followed by C2 and C3. This ranking can directly inform LAMATA’s capital investment programme for the 2025–2030 planning horizon.

Comparison with Prior Literature

The 34.7% improvement in peak-hour delay achieved by the present LP model compares favourably with the 27% reduction reported by Gartner et al. [16] for arterial signal optimisation and the 22% reduction in journey time found by Adeyemi and Salami [20] for network route assignment in Ibadan. The higher magnitude of improvement in the present work reflects the model's simultaneous optimisation of signal timing and modal split, and the greater scope for improvement afforded by the severe over-saturation of the Lagos corridors.

The shadow-price pattern, with the highest values on the freight-sensitive C1 and the lowest on the comparatively uncongested C4, is consistent with the economic theory of congestion pricing: marginal social cost is highest in the most stressed parts of the network. This supports the argument advanced by Daganzo [17] and others for corridor-differentiated congestion charges as a complementary demand management tool.

Limitations

Several limitations of this study should be acknowledged. The demand-fixity assumption means that the model does not capture induced-demand effects that could offset some of the gains from improved signal timing over the medium term. Modelling elastic demand would require a non-linear equilibrium programme, which constitutes a natural extension of the present LP framework. The piecewise linearisation of the BPR function introduces approximation error at very high v/c ratios (> 1.2), observed on C1 during special-event days; predictions under such extreme conditions should be interpreted with caution. The twelve-week survey period does not fully capture seasonal variation including public holidays, flooding events, and major construction activities. Future applications should incorporate real-time loop-detector or GPS-probe data feeds to enable dynamic re-optimisation.

CONCLUSION

This paper has demonstrated the application of linear programming to optimise traffic management across five key congested corridors of the Lagos metropolitan road network, using primary field data collected in collaboration with LAMATA. The key conclusions are as follows.

A 65-variable, 100-constraint LP model was formulated and solved in under one second, confirming the computational tractability of the method for operational transport planning. The optimal solution reduces network-average peak-hour delay by 34.7% (from 29.9 to 19.5 min/veh) and total vehicular hours lost per day by 28.4% (from 45,931 to 30,295 veh·h/day), through coordinated increases in green-to-cycle ratios (to 0.539–0.557) and a modal shift towards BRT (target: 18% system-wide). Sensitivity analysis confirms that the optimal basis is stable for demand variations within $\pm 15\%$, establishing robustness suitable for daily operational deployment. Shadow-price analysis identifies the Apapa-Oshodi corridor as the highest-priority candidate for infrastructure investment.

The study makes three contributions to the literature: (i) it presents the first multi-corridor LP model for Lagos calibrated on primary field data; (ii) it generates practical signal-timing recommendations compatible with LAMATA's existing SCOOT infrastructure; and (iii) it provides an evidence-based ranking of corridor-specific investments for the 2025–2030 capital programme.

Future research should extend the model to incorporate stochastic demand, elastic mode choice, and multi-period network dynamics. Integration with real-time sensor data streams, using online adaptive optimisation, would further enhance the system's responsiveness to non-recurrent congestion events such as incidents and adverse weather conditions.

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