Pathways to Sustainable Transportation: Lessons from Lusaka's Paratransit Mapping and Emissions Modeling

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ABSTRACT

This paper addresses the need for sustainable transportation systems in rapidly urbanizing environments, focusing on Lusaka, Zambia's capital. The city primarily relies on paratransit or informal modes of transport, making it crucial to understand the challenges they pose and promote sustainable practices to mitigate the potential negative environmental and social externalities. Our research adopts a mixed-methods approach by combining qualitative stakeholder analysis with quantitative paratransit network mapping and route-level emissions modeling. Using the coupled infrastructure system framework, we analyze the social and institutional dynamics, identifying policy challenges and implementation opportunities in Lusaka's public transportation system. Key findings reveal the city's hub-and-spoke paratransit network with concentrated passenger activity in the central business district. CO2 emissions are highest around downtown terminals and along four main corridors, while PM10 emissions are particularly high on Great North and Kabanana Roads. Lusaka's transition to low-carbon transportation requires a nuanced approach balancing environmental protection, climate action, and the livelihoods of paratransit sector stakeholders. We recommend several operational improvements, such as route prioritization, peripheral network connectivity upgrades, and incentive-based policies for emission reduction. We also suggest institutional improvements, including establishing a Public Transportation Authority, developing a participatory framework, and enhancing monitoring and regulation processes. Overall, this study offers insights into improving paratransit systems in growing urban centers in low- and middle-income countries, particularly in sub-Saharan Africa, contributing to the broader discourse on sustainable urban mobility.

Keywords: Lusaka, Zambia, Sustainable transport, Paratransit, Emissions, Transport policy

INTRODUCTION

Sustainable public transportation plays a crucial role in avoiding lock-in to car-centric, high-emission development paths and contributes to low-carbon and equitable urban environments. Lusaka, the capital city of Zambia in Southern Africa, exemplifies the challenges faced by many emerging cities globally: it must accommodate rising transportation demand while mitigating negative socio-environmental impacts. Central to addressing this is understanding and improving the informal or paratransit services that dominate the city's public transport landscape.

This paper examines the challenges and opportunities in managing paratransit services and developing sustainable transportation frameworks in Lusaka, Zambia. We combine a qualitative analysis of the current state of stakeholders in paratransit service management and operations, with a quantitative examination of the paratransit network system and its related emissions. The goal is to outline a low-emission sustainable transport framework and propose viable policy solutions appropriate for Lusaka's context specifically, and more generally for cities in low- and middle-income countries where paratransit modes dominate.

Through a synthesis of empirical evidence based on on-the-ground data collection, academic debates, theoretical frameworks, and policy analysis, we explore the following key questions:

- How can paratransit mapping techniques be effectively implemented in Lusaka to better understand the operational patterns and dynamics of these services?
- What are the emission profiles of Lusaka's paratransit systems, and how can emission modeling techniques be utilized to quantify and analyze emissions for these services?
- How can the insights gained from the paratransit mapping be utilized to inform policy developed aimed at enhancing the sustainability of Lusaka's urban transportation system?

LITERATURE REVIEW

In many low- and middle-income countries, informal public transport or paratransit often provides affordable and flexible transportation for a large segment of the population, often serving as the sole mode of public transport, or complementing more "formal" systems, particularly in areas where formal transit is inadequate or absent *(1, 2)*.

Typically offered by individual owners operating a few buses under a lax governance structure, these small-scale operations enable efficient management and responsiveness to demand fluctuations *(3-5)*. The sector offers steady employment, especially for lower socio-economic groups, fostering economic survival and growth *(1, 6)*. The sector often represents a means of social emancipation, or of essential participation to society, and a form of indigenous entrepreneurship and creative adaptation *(1)*. However, paratransit's benefits are accompanied by non-trivial drawbacks. These include congestion, pollution, and decreased road safety, often accompanied by overcrowding of small vehicles and service unreliability *(2,3)*. The highly competitive nature of the business can also create tensions among operators and with law enforcement, particularly affecting the most vulnerable users *(3)*.

The regulation of paratransit systems spans a spectrum, from acceptance to prohibition, with variable degrees of stringency. The ongoing debate in literature centers on formalization, regulation, and laissez-faire approaches *(6-8)*. Engagement strategies with the paratransit sector range from fostering cooperation to enforcing compliance. Generally, it is accepted that recognizing and implementing targeted regulation of paratransit produces better outcomes than outright prohibition.

In urban Africa, paratransit services are an "organizing urban logic that cannot simply be banned," as they are embedded in social networks, power dynamics, and are integral to the infrastructure of African cities *(1)*. Any regulatory approach must consider local specificities and align with the "local needs, peculiarities and institutional capacity of a paratransit dependent city." *(8)*. Addressing the challenges of reform and governance requires understanding unique socio-cultural, political, and economic contexts, necessitating empirically grounded, policy-relevant research *(9)*.

Public transport in Lusaka

According to a 2022 World Bank study, which surveyed over 1,500 individuals from three different areas of Lusaka City, walking is the predominant mode of transportation in the city, accounting for 42% of all person-trips. Public buses, including minibuses, constitute the second most common mode at 31%, followed by private cars and taxis at 24%. Bicycles and school buses make up 2% and 1%, respectively *(10)*. Stakeholder interviews also reveal anecdotal evidence of a growing number of motorcycles in Lusaka, mostly used for light cargo, as Zambia does not officially permit passenger travel on motorcycles.

The current public transportation landscape in Lusaka is the result of historical changes propelled by economic and institutional factors. Prior to Zambia's independence in 1964, private companies like the Central African Services Company (CASC) dominated the transport sector. Post-independence until 1991, the government nationalized CASC and established the United Bus Company of Zambia (UBZ) to promote local ownership *(11)*. After 1991, the government implemented the Structural Adjustment Policy reforms and the Public Service Reform Programme, leading to the privatization of UBZ and other state-owned enterprises *(12)*. The economic liberalization policies of the early 1990s culminated in UBZ's closure in 1995 *(10)*. The government's decision to grant tax exemptions for minibus imports and liberalize public transport licensing resulted in a proliferation of private bus operators *(10,12)*.

Today, Lusaka's public transport system can be characterized by limited regulation and enforcement, despite existing bus registration and operating fee regulations *(13)*. Over 5,000 buses are registered, though this figure likely underestimates the actual number. Typically, a bus operator owns one or two buses, which are then leased to the drivers *(13)*. The service is on-demand and flexible, with network structure and service levels heavily dependent on individual drivers' decisions *(14)*. Buses usually depart from terminals only when they have reached a sufficient number of passengers, often resulting in long wait times for passengers (*10,14*). Drivers also have the autonomy to change routes based on perceived passenger demand, which leads to inconsistent service on some routes and inadequate on others.

While data on the average age of Lusaka's minibus fleet is not readily available, evidence suggests the city operates an aging fleet predominantly composed of smaller-capacity (e.g., 12-seaters) second-hand vehicles. This is driven by the affordability of financing through individual savings or small loans. Many vehicles were imported from Japan near the end of their operation life, with an expected local service duration of only 2-5 years *(10)*. Economic necessity compels operators to undertake extended daily trips to breakeven, resulting in increased vehicle kilometer traveled, fuel consumption, and emissions. Upgrading to newer or higher-capacity vehicles is financially challenging, given high interest rates and short loan terms for vehicle financing *(15)*. In 2017, the government's announcement of a planned ban on minibuses starting in 2019 raised concerns among owners and operators who feared increased poverty. As of 2022, the new government has not pursued this action, though discussions about modernizing public transport continue to be fraught with social implications *(15)*.

Despite the importance of public transport in Lusaka, comprehensive mapping of the city's transit remains incomplete. Previous attempts to map Lusaka's transport routes *(16)* were neither conductive for downstream analytics nor open-source, impeding evidence-based policy development. Moreover, while the aging fleet's contribution to urban air pollution and greenhouse gas emissions is recognized, the lack of route-level emissions modeling prevents precise identification of emission hotspots, hindering targeted interventions. To our knowledge, this is the first study to uniquely combine paratransit mapping, route-level emissions modeling, and comprehensive policy analysis based on stakeholder mapping and on-the-ground site visits, addressing critical gaps in understanding sustainability of Lusaka's public transport system.

METHODS

The research adopts four interrelated approaches for the study of Lusaka's public transport system: stakeholders mapping, paratransit mapping, emissions modeling, and Coupled Infrastructure System (CIS) analysis—deploying both qualitative and quantitative approaches, encompassing both institutional roles and technical analyses of transit operations.

Stakeholders Mapping

The stakeholders mapping aimed to identify and understand the different stakeholders involved in providing public transportation services in Lusaka, highlighting institutional and operational challenges and needs, and identifying the gaps between policy and implementation. This analysis was based on a review of transportation policy documents and a series of semi-structured interviews conducted in August 2023. Key public stakeholders' participants included the Road Transportation & Safety Agency (RTSA), the Ministry of Local Government and Rural Development (MLGRD), and the Lusaka City Council (LCC). Moreover, a consultation session was carried out with the Zambia Institute of Policy Analysis and Research (ZIPAR), a public research institution. From the private sector, consultations were held with the Public Passenger Transportation Drivers Association of Zambia (PPTDAZ), the Passengers, Pedestrians, and Cyclist Association (PP&CA), and Flash Buses, a private operator company.

Paratransit Mapping

The objective of public transport mapping was to identify paratransit routes and stops, to map paratransit activities in Lusaka, and perform network-level analyses to study passenger activity, vehicles flow, network efficiency, and GHG emissions.

The mapping process was conducted in two stages: pilot and full-scale. This two-stage approach is standard practice for mapping public transport routes, as the pilot phase allows researchers to evaluate network peculiarities and validate routes for full-scale deployment. The process began with a training session for the surveyors on the relevance of paratransit mapping in African cities, as well as technical, logistical, and safety instructions. The three-day pilot phase identified 88 routes and conducted 14 validated onboard surveys, 4 validated frequency surveys, and section counts. The full-scale mapping lasted about 5 weeks, primarily carried out during morning peak hours (8:00-11:00). This data collection involved a total of 417 onboard surveys as well as 216 hours of observed frequency data across 67 routes. Moreover, 60 hours of section count surveys were conducted at 15 different locations, with each survey session lasting about 20 minutes.

The final output of the data processing comprises a reduced set of trips and stops representing Lusaka's transit network. This data was transformed from GIS format into the General Transit Feed Specification (GTFS), the standard format for public transport schedules and associated geographic information. Since onboard survey data include timestamped GPS track points, stop locations, and fares, vehicle speeds were aggregated by time interval into an output layer of commercial speeds. For trips with itinerary deviations across onboard surveys, a representative GPS trace was selected based on its proximity to the average of all collected traces.

Each trip was then associated with every stop it spatially passes in the digitized stops dataset. Stop times were estimated using the commercial speeds layer after spatially joining stops and trips geometries. Finally, route headways per route were estimated using section counts and frequency surveys data of number of vehicles on selected road segments.

Paratransit and Emission Modeling

Our model adopted the gtfs2emis bottom-up approach *(17)*, utilizing two primary inputs: the constructed GTFS feed (using collected public transit data), and the public service vehicle (PSV) fleet characteristics dataset from RTSA, including vehicle profiles (model year, euro stage, fuel type) and their share in the total fleet.

The GTFS is first converted to a "transportation model" of synthetic GPS traces, including every segment traversed by any trip throughout the day, with the distance and speed calculated from the GTFS. Next, emissions per trip segment are estimated by multiplying its length by the corresponding emission factor, which is the emitted mass of a pollutant per kilometer traveled at a specific speed, by vehicle weight and fuel type.

The gtfs2emis R package incorporates emission factors from two models: CETESB (The Environmental Company of Sao Paulo), which includes non-speed-dependent factors for minibus taxis, and EMEP (European Monitoring and Evaluation Programme), which offers speed-dependent factors. The package uses a hybrid model, first by applying emission factors from CETESB, then scaling them by EMEP factors. While the standard gtfs2emis implementation calculates emission factors as a weighted sum from the whole fleet and samples a vehicle profile by *segment*, our approach sampled a vehicle profile per *trip*. For each synthetic trip, we assigned a vehicle profile and corresponding emission factor through weighted sampling from the RTSA-provided fleet characteristics dataset. For final emissions estimates, we performed 100 experiments. The model outputs then produce spatial and temporal emissions estimations for CO_2 and PM10.

The Coupled Infrastructure System (CIS) framework

Our study employs the Coupled Infrastructure System (CIS) framework *(18)* to understand the relationships between users, providers, regulations, the built environment, and natural resources in the Lusaka context. The CIS framework combines different aspects of a shared resource ecosystem and frames the system as a configuration of different infrastructure classes, comprising technical, natural, and social infrastructure *(19)*. Although designed as a robust and replicable methodology for case study analysis *(18)*, we use the framework here as a *descriptive* device. We use it to expand the typical technical perspective of transportation planning and consider Lusaka's transportation ecosystem as a set of "dynamically interacting infrastructure classes," where governance emerges within this complex system, shaped and impacted by the linkages between its different components and resulting feedback loops *(20)*. Figure 1 illustrates the general CIS framework, showing interactions between infrastructure classes. "Resource Users," "Infrastructure Providers," and "Public Infrastructure" (hard or soft) interact within a political feedback loop. The framework articulates the relationships between "Resource Users," "Infrastructure Providers," and the natural ecosystem ("Natural Infrastructure") in an operational feedback loop, where changes in one component may impact or be influenced by others.

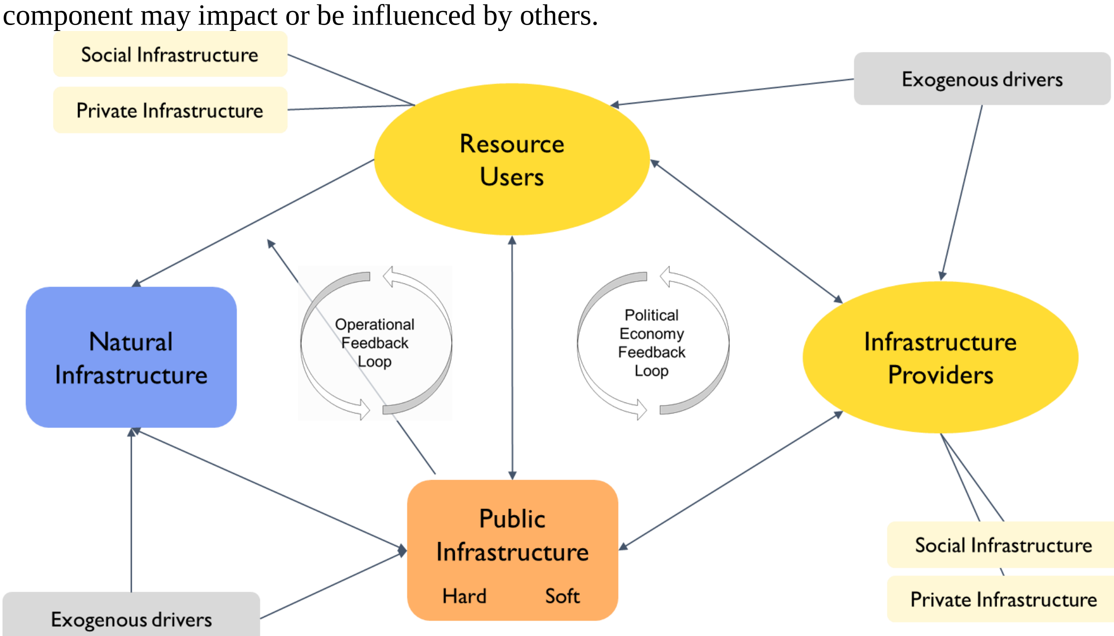


Figure 1: The Coupled Infrastructure System conceptual framework (Anderies et al., 2004)

RESULTS

Key Stakeholder Groups

In this section, stakeholders are categorized according to their governmental role into six groups: National Agencies, Ministries, Local Authorities, Research Institutions, Civil Society Organizations and Co-operatives, and Transportation Operators (Table 1). Each stakeholder has a complex organizational structure, and only the relevant departments to the provision of transportation are reviewed and discussed.

Governmental level		Organization and Roles	Acronym	Date of consultation
Public Sector	National Agencies	Road Transportation & Safety Agency	RTSA	08/08/2023
		Road Development Agency	RDA	
		National Road Fund Agency	NRFA	
		Zambia Environmental Management Authority	ZEMA	
	Ministries	The Ministry of Transportation and Logistics	MoTL	
		The Ministry of Works and Supply	MoWAS	
		Ministry of Finance and National Planning	MoFNP	
		Ministry of Green Economy and Environment	MoGEE	
		Ministry of Infrastructure, Housing and Urban Development	MIHUD	
		Ministry of Local Government and Rural Development	MLGRD	10/08/2023
	Local Authorities	Lusaka City Council	LCC	10/08/2023
		Traffic Police		
	Research Institutions	Zambia Institute of Policy Analysis and Research	ZIPAR	11/08/2023
Private Sector	Civil Society Organizations and Cooperatives	Public Passenger Transportation Drivers Association of Zambia	PPTDAZ	08/08/2023
		Commuters' Right Association of Zambia	CRAZ	
		Bus and Taxi Owners Association of Zambia	BTOAZ	
		Public Passenger Transport Multipurpose Cooperative	PPTMPC	
		Passengers, Pedestrians, and Cyclist Association	PP&CA	10/08/2023
		Talk Road Safety Foundation	TRSF	
	Operators	Individual operators		
		Companies (e.g., Flash Buses) ● Operates a fleet of about 270 buses ● Owns and manage the Millennium Bus Station		09/08/2023
		Associations		

Table 1: Mobility public and private stakeholders identified, affiliation, and dates of consultation.

The Road Transportation & Safety Agency (RTSA) is the primary national agency that regulates road transportation. It handles vehicle licensing, safety standards, education, enforcement, and accident research. The Road Development Agency (RDA) maintains public roads and establishes construction safety standards. Both are supported by the National Road Fund Agency (NRFA). The Zambia Environmental Management Authority (ZEMA) incorporates environmental issues into national planning, focusing on sustainable resource management and pollution control. The Lusaka City Council (LCC) is the main authority in Lusaka's urban area. Its key departments manage transportation and sustainability policies and collaborate with national agencies like RTSA and RDA. Figure 2 further details the division of implementation and policy-making roles among different bodies. In practice, stakeholder consultations revealed fragmented and overlapping management of transportation operations. While the Local Government Act mandates local authorities to establish and maintain public transport services *(21)* including public service vehicle (PSV) registration, issuance of operating licenses and permits, and route assignment—RTSA largely performs these functions. This overlap highlights the need for clearer delineation of responsibilities between local and national authorities.

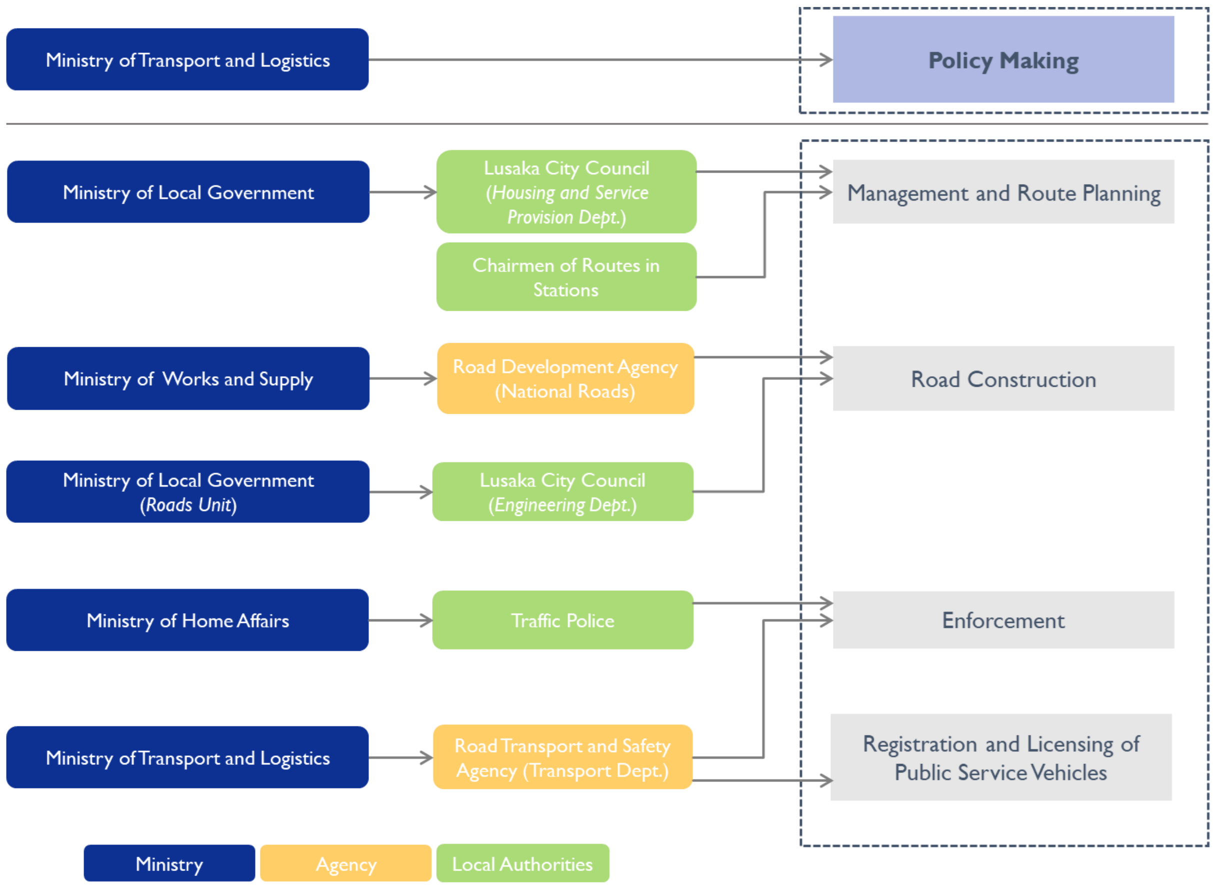


Figure 2: Roles of the different stakeholders and affiliation to the ministries

Civil society organizations and cooperatives (Table 1) play a role in communicating between government entities and the private sector. The Associations regularly participate in meetings with RTSA to address transportation issues like fuel fee adjustments and their impact on fares. Key organizations include the Public Passenger Transportation Drivers Association of Zambia, which facilitates communication on insurance, pension schemes, and loans for drivers; the Commuters' Right Association of Zambia, which represents commuters' interest in fare discussions; the Bus and Taxi Owners Association of Zambia, which advocates for minibus drivers and their business development; the Passengers, Pedestrians and Cyclists Association, which focuses on safety awareness and community engagement; and the Talk Road Safety Foundation, which promotes road safety awareness. Despite potential for cooperation, Lusaka's transport associations operate in silos due to their differing memberships and mandates. This fragmented approach potentially limits their collective effectiveness in addressing sector-wide challenges and engaging with the government stakeholders as a unified front.

In addition to individual bus owners, the interviews reveal the existence of private companies that typically own fleets of around 180-260 buses and are responsible for driver employment, servicing, and insurance. While the current public transport system in Lusaka relies mostly on competitive practices that often prioritize long operating hours over service quality, safety and environment, any transition to sustainable and decarbonized transport, potentially involving upgrades, reforms, or phase-out of minibuses would necessitate holistic measures to engage and empower Lusaka's affected "informal" sector.

Paratransit Mapping Results

Passenger Activity

The Lusaka network map (Figure 3) illustrates routes and stops, distinguishing between official "bus stations" and "virtual stops." Virtual stops were identified during the paratransit mapping process where passengers were observed boarding and alighting. Given the semi-formal nature of the paratransit services, the inclusion of virtual stops provides a more comprehensive picture of the public transport network. Figure 4 visualizes passenger demands through onboarding and alighting patterns. Boarding activity concentrates near or at designated stations, while alighting is more widely distributed throughout the network, suggesting minibuses primarily serve as "local" rather than express services. Demand patterns generally indicate exceptionally high paratransit activity in Lusaka's city center, with terminal usage disproportionately higher than other locations. The radial structure of road and transit networks contributes to increased traffic in the center. Consequently, passengers traveling between different parts of the city often must transfer at one of the central terminals, further intensifying city center congestion.

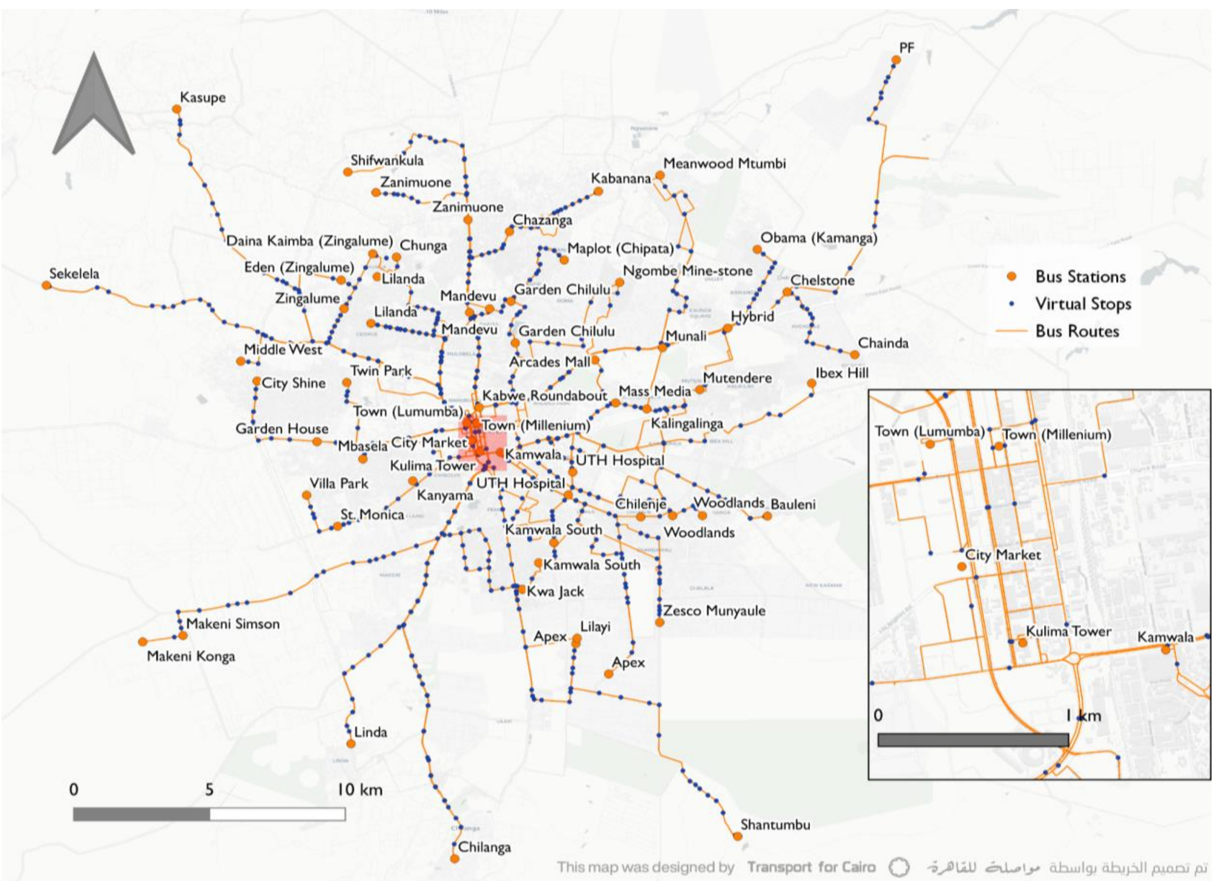


Figure 3: A geographic map of Lusaka paratransit network

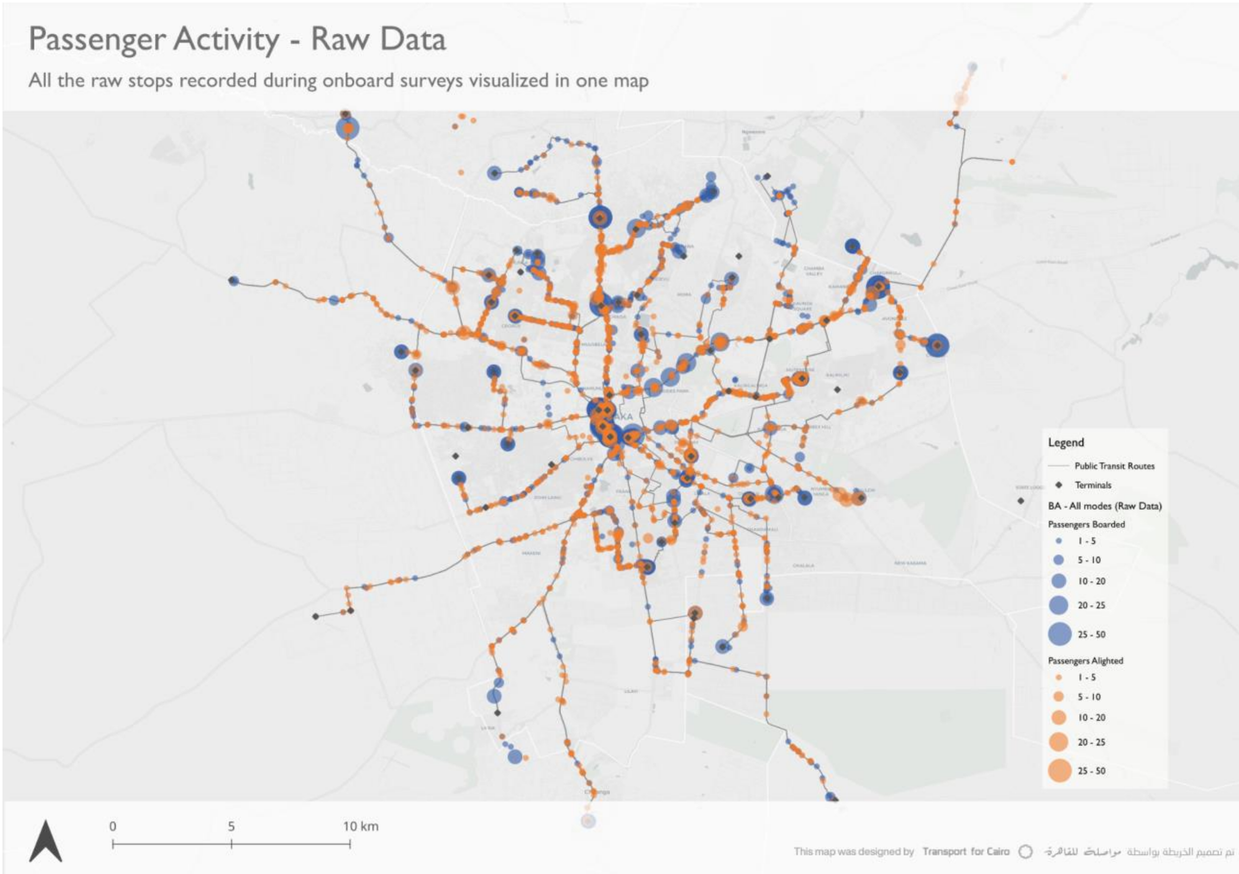


Figure 4: Map of passenger boarding and alighting

Commercial Speed Profiles and Passenger Flows

Spatial aggregation of onboard survey data yields several network-level datasets, specifically commercial speeds (Figure 5), and passenger flows (Figure 6).

Commercial speeds, estimated from GPS traces, reveal that average speed on most roads' ranges between 20 and 30 km/hr (Figure 5). Notably, while speeds in the city center are low, the peripheral areas of Lusaka—where many trips originate or terminate—exhibit the lowest commercial speed profiles (0-10 km/hr). This pattern reflects drivers' need to continuously pick up passengers or pause for potential passengers along these routes, in contrast to the more efficient loading from designated terminals in the downtown area. The combination of demand data (Figure 4) and commercial speed profiles (Figure 5) can suggest potential locations for new terminals, which could improve overall network efficiency.

Passenger flow per network link (Figure 6) is estimated by calculating vehicle occupancy from onboard survey data, then multiplying it by a factor derived from estimated trip headways for a given time period. As expected, the resulting analysis confirms Lusaka's radial road network structure, with a central hub in the downtown area. The analysis also reveals that the northern section of the network is characterized by three arterial roads: Great East, Great North, and Lumumba roads.

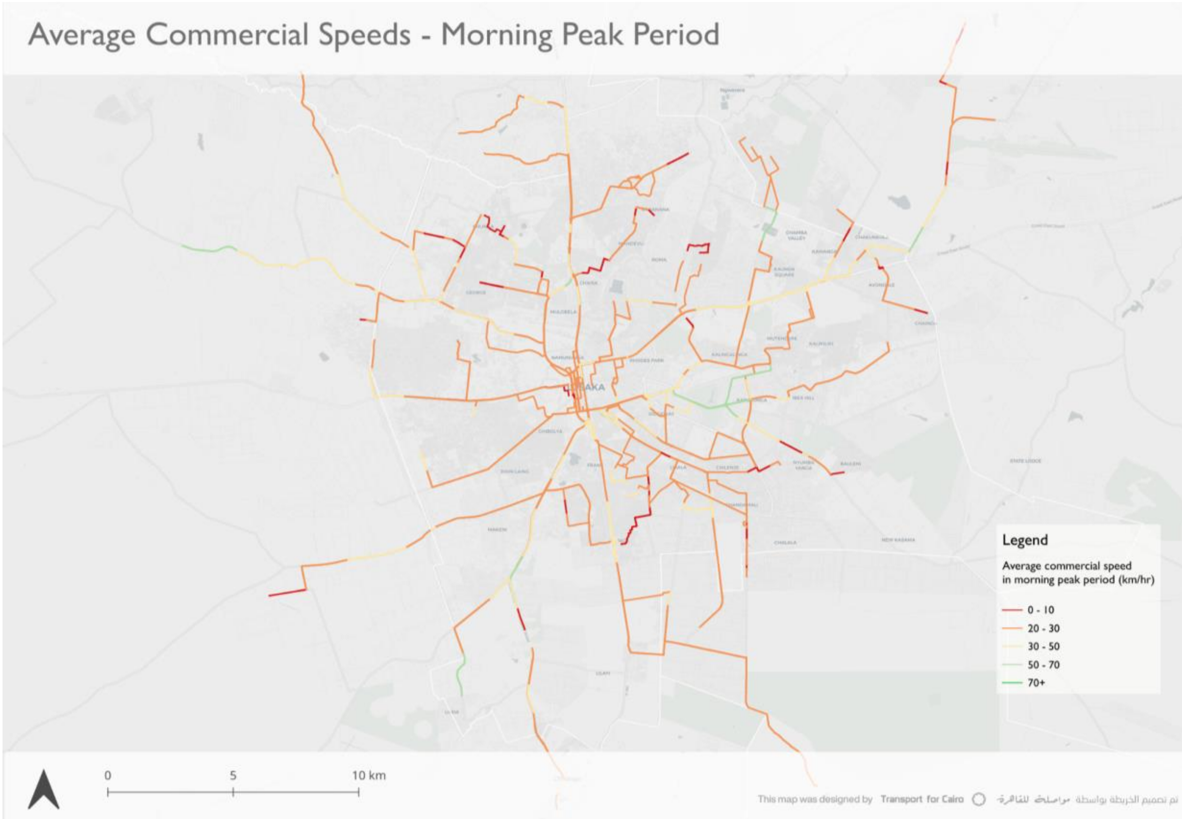


Figure 5: Average paratransit commercial speeds in morning peak period.

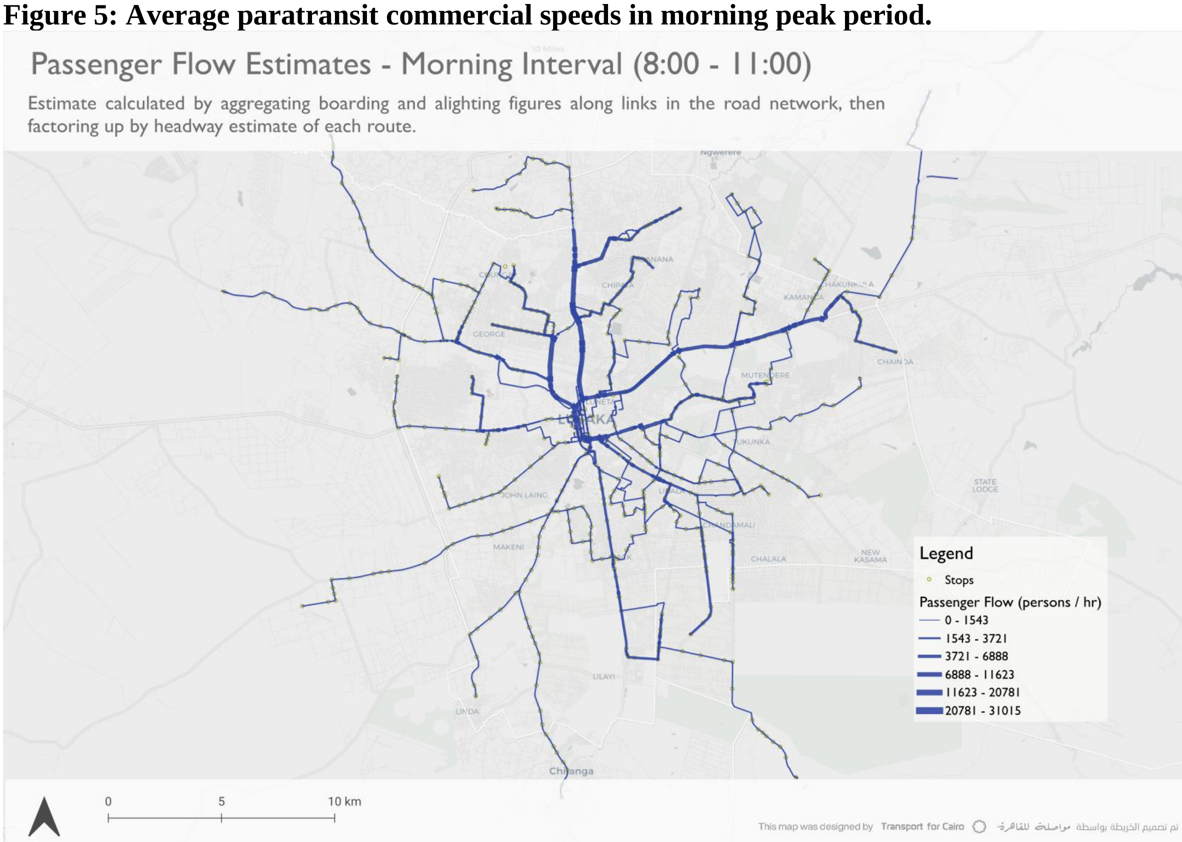


Figure 6: Passenger flow estimates during morning peak period.

Network Accessibility and Efficiency

Access, defined as "the potential for interaction," commonly accounts for existing transport networks and land use *(22)*. Our study estimates the cumulative share of Lusaka's population reachable within a 60-minute paratransit journey. We use the city's population distribution as a proxy for destinations like jobs, which are harder to quantify in low- and middle-income countries. Using GTFS and road network data obtained from paratransit mapping process, we create 60-minute isochrones on an [H3 hexagon grid](#) (resolution 8), with trip origins at each hexagon's center. The uniform grid allows aggregation of both the population within each hexagon and the percentage of population accessible from it (Figure 7). The average access in Lusaka is only about 5%, though in some cases it reaches up to 62%.

We also compared paratransit network efficiency by calculating travel distances for a set of origin-destination (OD) pairs. The comparison used two mode combinations: (a) paratransit and walking, and (b) private cars. Five locations were selected: four points in Lusaka's periphery with relatively high population density, and one downtown. As seen in Figure 8, the distance traveled on paratransit routes is consistently higher than by private vehicle routes for the same OD pairs, with one exception. The inefficiency of paratransit routes is more pronounced when traveling between peripheral locations (e.g., Mutendere to Kabanana). This can be attributed to the paratransit network's radial structure and the complex transfers required in the city center.

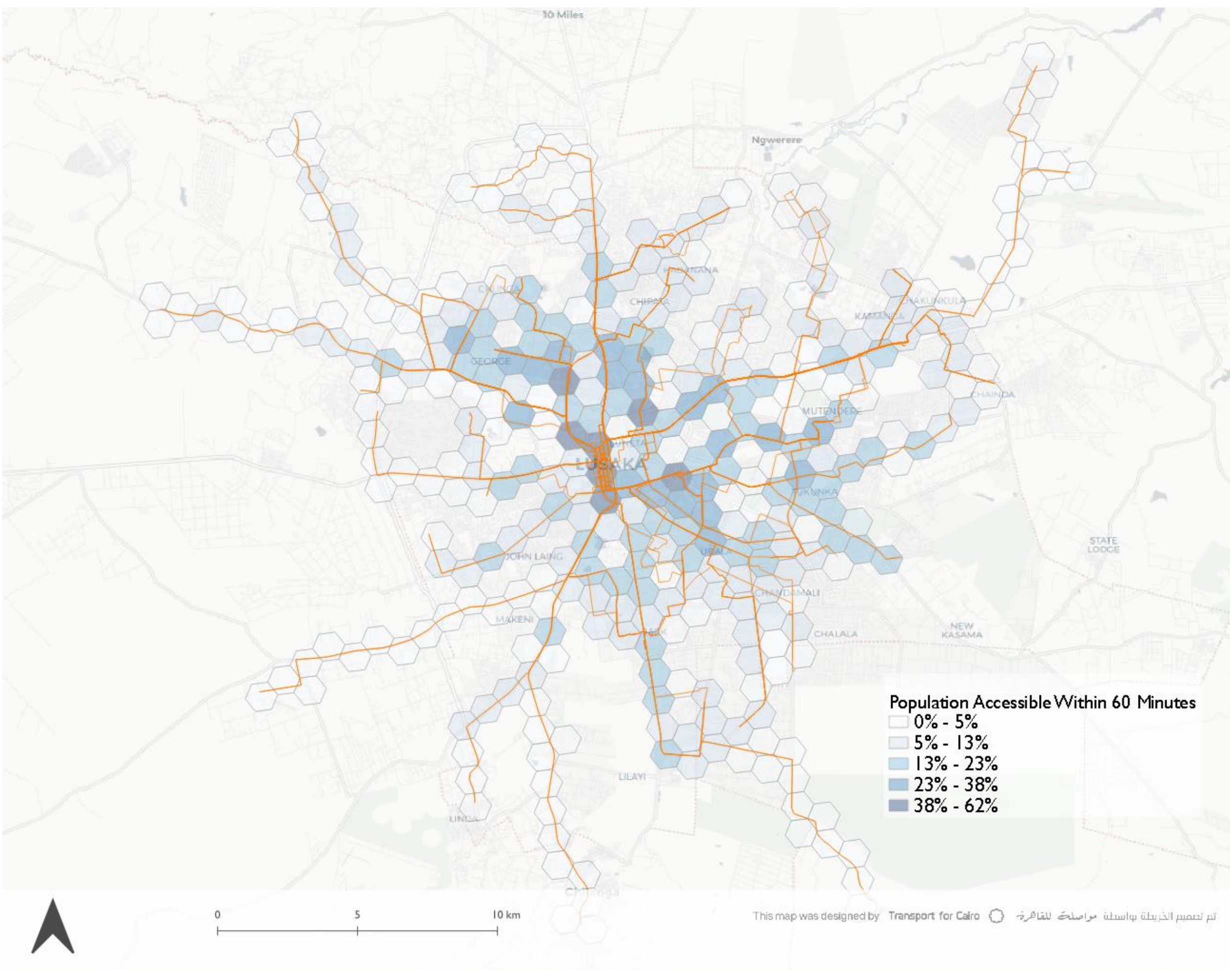
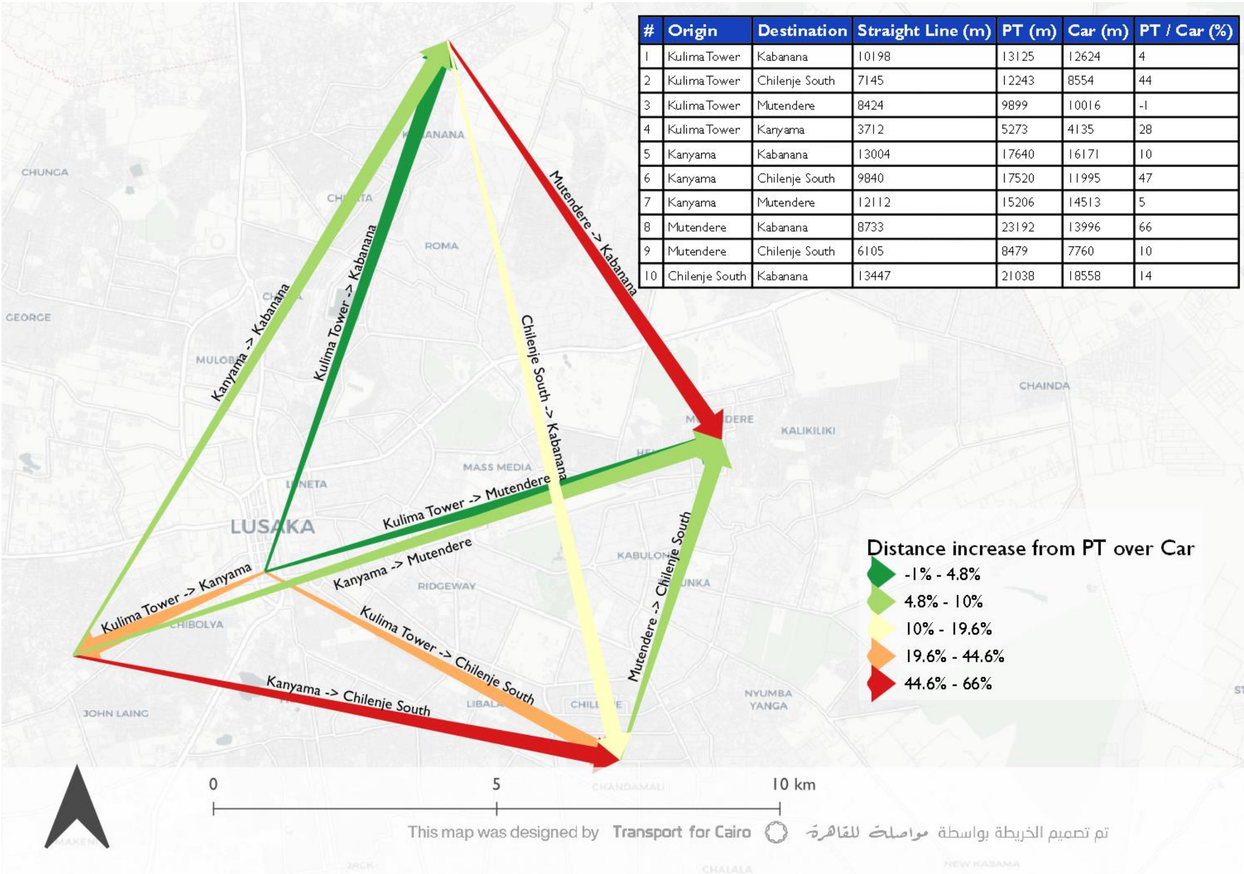


Figure 7: Accessible Population within 60 minutes using Paratransit and Walking



#	Origin	Destination	Straight Line (m)	PT (m)	Car (m)	PT / Car (%)
1	Kulima Tower	Kabanana	10198	13125	12624	4
2	Kulima Tower	Chilenje South	7145	12243	8554	44
3	Kulima Tower	Mutendere	8424	9899	10016	-1
4	Kulima Tower	Kanyama	3712	5273	4135	28
5	Kanyama	Kabanana	13004	17640	16171	10
6	Kanyama	Chilenje South	9840	17520	11995	47
7	Kanyama	Mutendere	12112	15206	14513	5
8	Mutendere	Kabanana	8733	23192	13996	66
9	Mutendere	Chilenje South	6105	8479	7760	10
10	Chilenje South	Kabanana	13447	21038	18558	14

Figure 8: Paratransit vs Private Car travel distance comparison

Emissions Results

Lusaka's paratransit fleet, comprising 5,064 registered vehicles, is estimated to perform an average of 5.6 trips daily, totaling 29,970 trips between 8am and 7pm along 68 routes. These citywide operations are estimated to generate 225.17 metric tons of daily CO2 emissions, translating to approximately 82,000 tons annually. This figure aligns reasonably with a 2022 World Bank study that estimated 61,000 annually based on 3,000 minibuses *(10)*. Our study further provides the spatial distribution of estimated daily CO2 emissions along public transport routes in Lusaka City (Figure 9). The results show a predictable concentration in downtown areas, where 90% of routes originate. Beyond the city center, significant emissions are distributed along four main corridors: Lumumba Road, Great North Road, Great East Road, and Chilimbulu Road.

Figure 10 displays PM10 emissions weighted by resident population (left) and by boarding activity (right). The analysis reveals that the areas with high PM10 emissions and high population density are concentrated in the northern quarter of the city. Notable hotspots outside the city center include the areas around Chelstone, Zanimuone and UTH Hospital stations. These townships and neighborhoods are surrounded by corridors with high paratransit service flow, particularly Great North and Kabanana Roads, each serving nine routes.

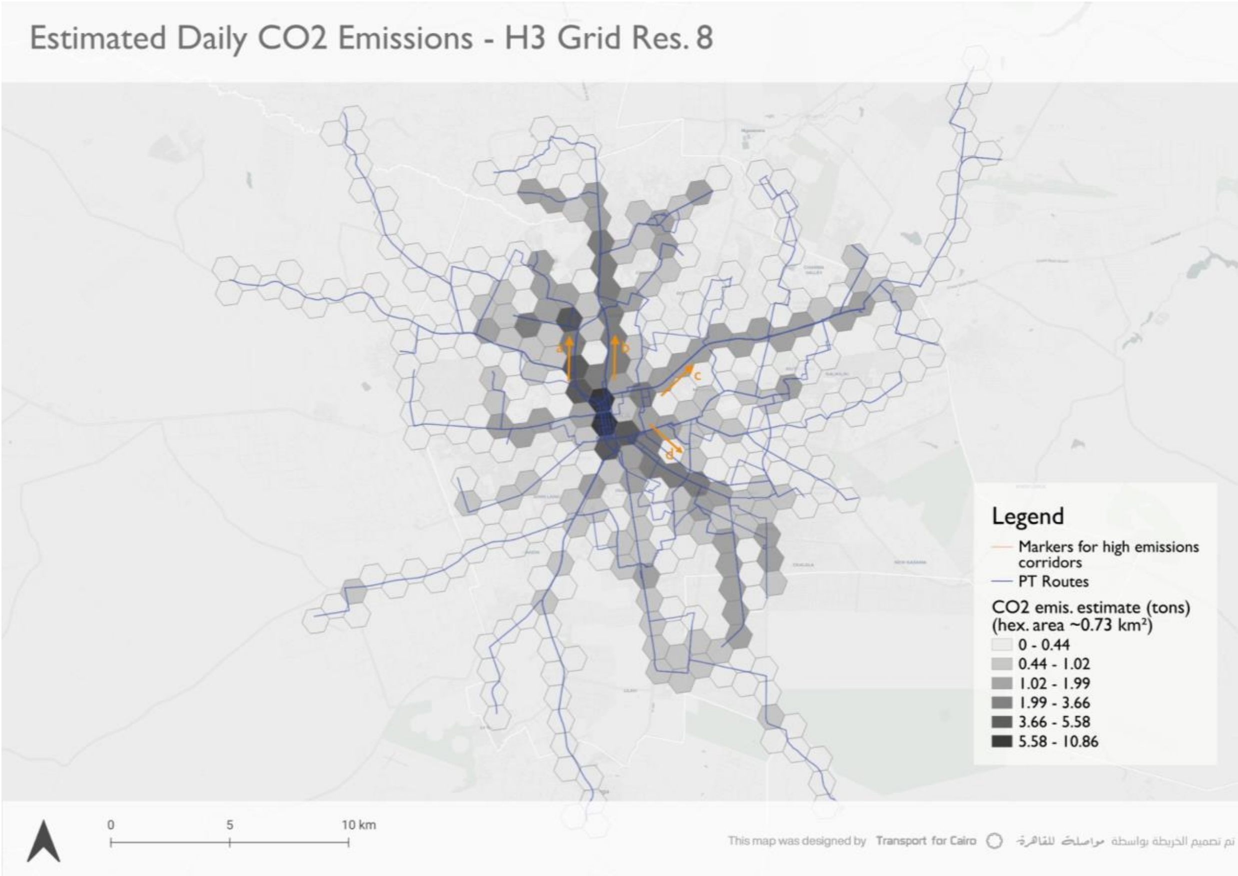


Figure 9: Estimated Daily CO2 Emissions - H3 Grid Resolution 8

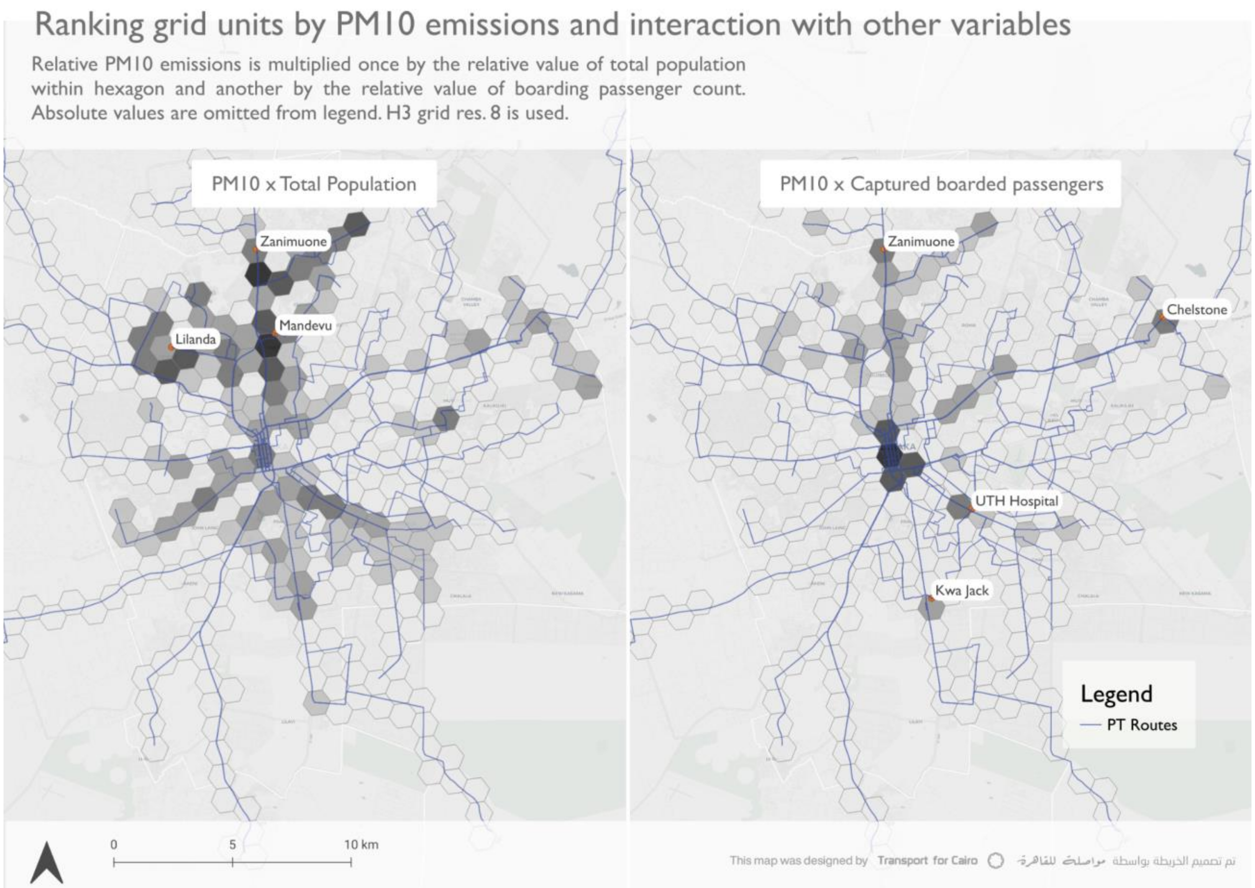


Figure 10: Interaction of PM10 levels with population and passenger activity

DISCUSSIONS

Figure 11 illustrates the CIS framework components in Lusaka's context. "Resource Users" encompass all transportation users, from drivers to pedestrians and minibus operators. "Infrastructure Providers" are divided into two categories: (1) public providers, which include local government (Lusaka City Council and its departments), and National Agencies involved in transportation infrastructure provision; and (2) private providers, comprising paratransit service providers for both individual public service vehicles (PSV) and companies. "Public Infrastructure" comprises: (1) hard infrastructure (road, highways, sidewalks, stations) and (2) soft infrastructure (policies, regulations, fare structures, fuel costs, and registration requirements, as well as organizations active in the mobility ecosystem, such as ZIPAR, providers and drivers' associations). "Natural infrastructure" refers to the air quality, land use and climate conditions of the local ecosystem.

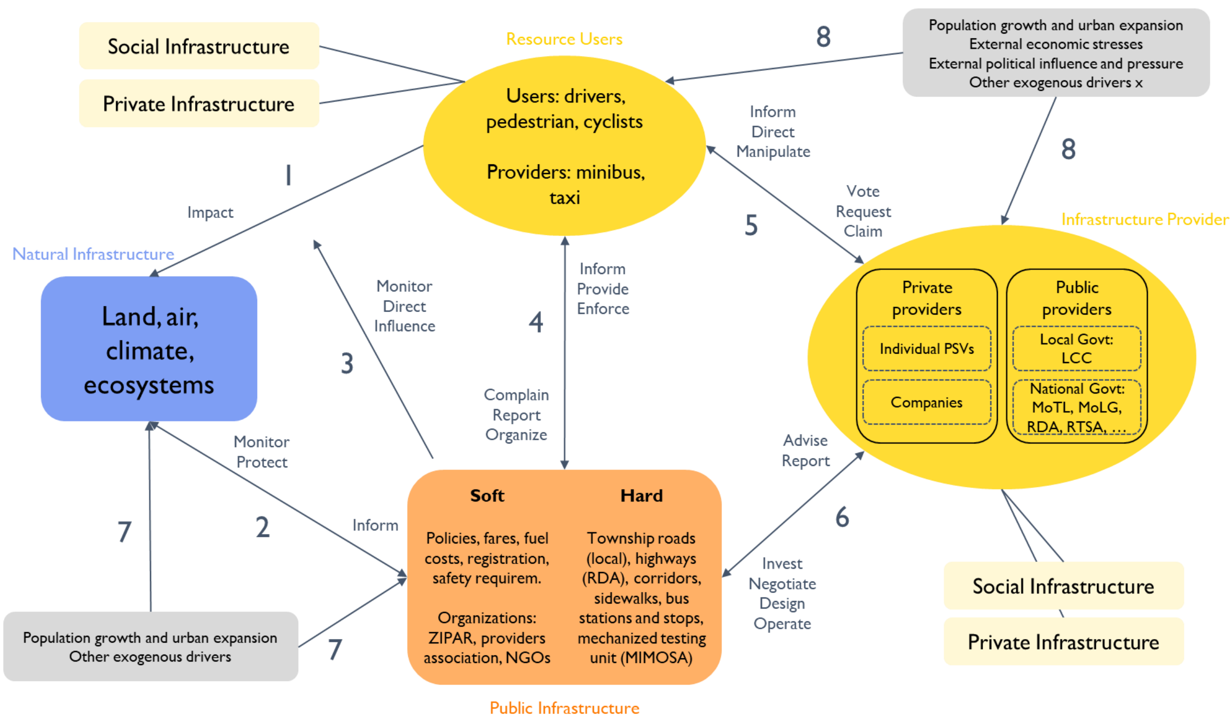


Figure 11: The CIS framework and the City of Lusaka mobility ecosystem

Political economy feedback loop

Figure 12 illustrates the Political Economy Feedback Loop in the City of Lusaka. The Lusaka City Council (LCC) has the mandate "to establish and maintain a public transport service" *(21)*, including route allocation and fare regulation. Current legislation requires LCC to establish a public transportation authority (PTA), which could improve transport service planning and harmonize routes, schedules, and fare system. However, LCC's efforts to centralize through a PTA have faced strong resistance from operators, likely due to concerns about possible loss of autonomy. Consultations also highlighted a lack of clarity among different stakeholders regarding LCC's in establishing the PTA, as well as on the operational and institutional mandate that PTA would assume. These challenges are compounded by LCC's lack of financial resources, technical capacity, and enforcement power. Strengthening LCC's institutional and technical capacity and clearly delineating responsibilities are essential for effective governance, improved stakeholder engagement and successful implementation of reforms.

Recognizing institutional and operational power [Links 5 and 6] is critical when promoting policy change, as local interest groups can significantly influence outcomes. Any transitions, such as through the establishment of a PTA, must balance the advantages of demand-driven paratransit services with the need for better regulation and planning, while also considering the socioeconomic implications for those currently operating in the informal sector [Links 4 and 6].

The local authority's role should involve articulating user needs to ensure their perspectives are valued and accounted for in paratransit operations. The policy agenda setting to engage with operators and manage paratransit providers [Link 6] would benefit from including local needs representation in policy formulation [Link 5]. Implementing passenger information systems based on paratransit mapping data and engaging local communities through passengers' associations could be impactful interventions for LCC [Link 5].

The review of paratransit operations and associated emissions suggests introducing new regulations, such as shifting from a zone-based to a route-based vehicle registration approach, thereby allowing public authorities to regain some control over route planning [Link 6]. However, this may conflict with driver and operator associations' profit-maximizing interests, particularly since they set routes autonomously. Exploring underlying dynamics would help identify who can institute and enforce regulations, and what interventions public institutions can implement to negotiate with stakeholders and define an effective policy framework [Link 6].

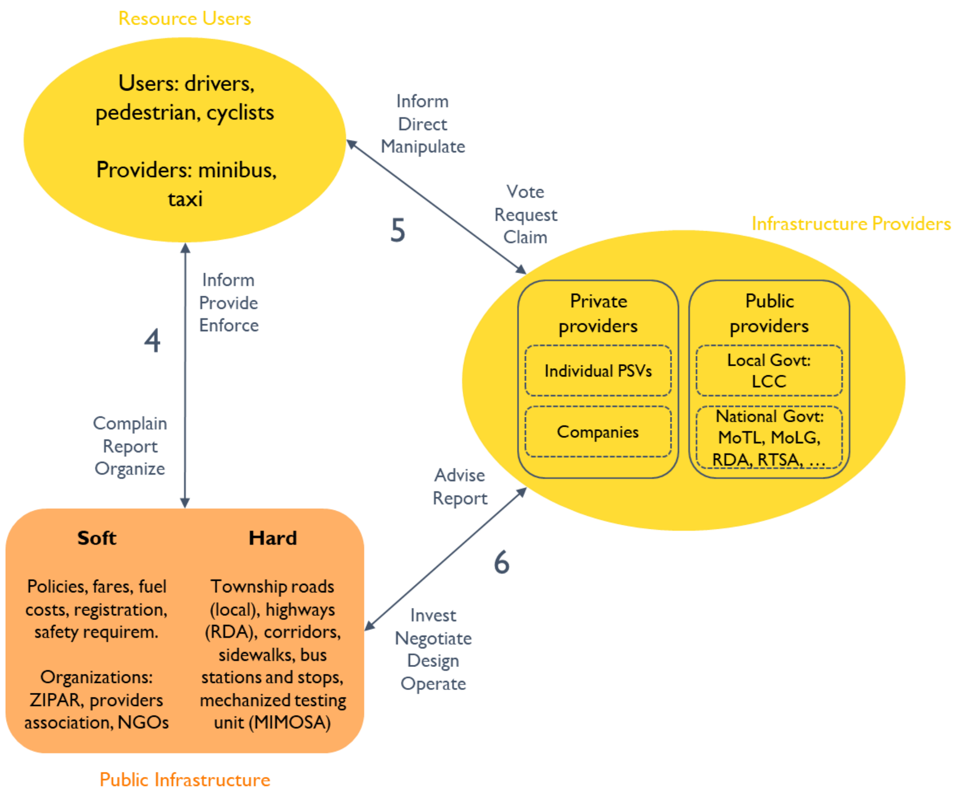


Figure 12: The political economy feedback loop: Users – Infrastructure – Providers

Operational feedback loop

In the CIS framework, the Operational Feedback Loop (Figure 13) focuses on the relationships between infrastructures, both hard and soft, the users of the system, both mobility users and providers, and the natural resources.

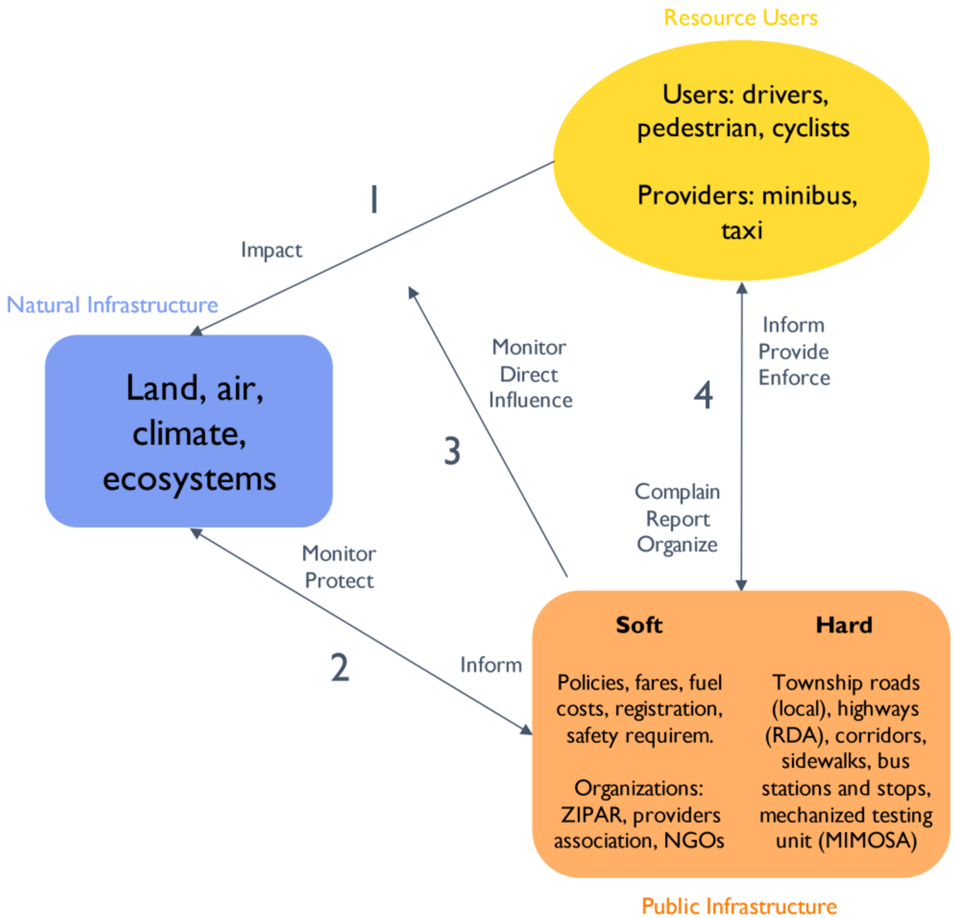


Figure 13: The operational feedback loop: Users – Infrastructure – Natural resources

Paratransit operations

The main operational challenge identified is the congestion in the central business district, which causes slowdowns, increases emissions, and limits accessibility. Users endure long waiting times at trip origins and during transfers at central bus terminals. Policies should focus on enhancing operations management in central stations, such as: developing flow metering and improving timing to remove bottlenecks; upgrading stations infrastructures; providing training and capacity building programs for bus operators and station managers, especially as station management is delegated to operators [Link 4].

The paratransit mapping analysis (Figure 4) reveals demand hubs in peripheral areas, which suggests that improving peripheral connectivity could reduce central hub overcrowding. This can be supported by the creation of designated bus terminals in peripheral areas, which would increase the efficiency of the network by aggregating both paratransit services demand and offer. In fact, drivers and passengers alike would be encouraged to converge into terminals to provide and access services, reducing the need for frequent boarding stops along peripheral routes.

These measures should be complemented by interventions to promote better connectivity on peripheral roads. This challenge relates to the provision and maintenance of public infrastructure, such as roads and sidewalks, bridges, etc., and land use dynamics [Link 4]. The low quality of sidewalk infrastructure, particularly in peripheral areas (detected during site visits and the consultations), may discourage users from choosing alternative modes like walking or cycling. The CIS framework emphasizes a better understanding of user experience and factors affecting user behavior is crucial to estimate the potential impact of infrastructure projects—including exploration of what and how users complain, report issues, or provide feedback to improve system performance [Link 4].

Measures to increase the competitiveness of transit services necessarily pass through increased efficiency, as well as safety and reliability of services. The existence of unreliable low frequency bus routes, as well as the long detours that some routes often take, might be factors that negatively impact the demand for paratransit. A data collection system, where providers are required or incentivized to provide information on their operations, would facilitate the coordination of services from the central local authority, and allow the provision of timely and accurate information to passengers.

Given the importance of private providers in the operation of paratransit services, obtaining consensus across stakeholders is critical. Public authorities should channel operational efforts of the different providers (individual PSVs and companies) to inform users and ensure more transparency in the system. This can be achieved by setting up working groups that involve stakeholders, including drivers and providers' associations, as well as passenger organizations [Link 4].

Emissions

The emissions modeling results show CO2 and PM10 emissions are mostly concentrated in specific city areas (downtown and four main corridors). The findings suggest route prioritization strategies for high-capacity buses on relevant corridors, based on frequency, demand density, and pollution levels. Currently, minibus operators and drivers self-manage paratransit operations, and interventions could hinder their profit-maximization strategies [Link 4]. For example, replacing 12-seater buses with 24-sector ones and aggregating routes would require extensive negotiation with the minibus operators and drivers. While emission reduction strategies targeting corridors could be impactful, they require significant enforcement efforts due to potential conflicts with local operators' interests.

An alternative policy intervention is designing dedicated rights-of-way on corridors that would prioritize paratransit over private vehicles. However, modal shift is notoriously difficult and there is little guarantee that certain policies would produce significant behavioral changes for users and providers. Targeted investigations should be carried out to explore behavioral changes derived from specific interventions [Link 3]. Demand management interventions on the main corridors could also influence how user behavior impacts emissions [Links 1 and 3]. For instance, establishing designated bus terminals in peripheral areas could concentrate demand, reducing frequent stops, thereby reducing emissions.

Several measures could improve system sustainability through pricing incentives [Link 2 and 3]. These include increasing gas tax or vehicle sales tax based on fuel efficiency levels and expected vehicle life. Updating vehicle registration procedures to promote systemwide emissions standards could significantly impact paratransit providers' emissions [Link 1]. However, since current operations rely on aging, poorly maintained vehicles to keep costs low, financing and upgrading to higher-quality vehicles significantly increases operational costs, which most small-scale operators cannot sustain. There is a need to overcome financial barriers for fleet modernization and service improvement, through a thorough understanding of the business models used by operators, as well as potential new ones that could be adopted.

Finally, to reduce the environmental impact of transportation, monitoring activities need to be implemented, both in terms of emissions monitoring and user behavior. Local authorities should establish policies regulating data collection requirements for emission levels throughout the transportation network. At the local level, practices should be set up to streamline the integration of this data into the policymaking process [Link 2].

Sustainable transportation framework

Analysis of Lusaka's current policy framework reveals a disconnect between transportation and environmental policies, particularly at the intersection of local and national levels. To address this, a more functional framework should provide flexibility and self-learning capacity, encouraging diverse stakeholders to provide feedback and participate in sustainable policy formulation while fostering public awareness about relevant policy issues.

At the local level, public agencies would benefit from clearly formulating balanced sustainability objectives and goals that consider local needs and contextual factors, such as the dynamics of the paratransit sector. More specific measures for the policymakers could include incorporating environmental assessment in the Road Fitness Licenses, expanding mechanized testing units, and requiring regular evaluations of all registered vehicles. However, aligning local environmental impact assessment needs with national regulation established by the RTSA presents challenges, given the fragmented transportation planning scenario.

A uniform policy to promote paratransit fleet improvements and create stronger connections between local and national environmental agencies is advisable. For example, local requirements for emission reductions in new vehicles could be supported by national legislation on import taxes incentivizing more environmentally friendly vehicles. Such regulations require national-level implementation, involving agencies like Zambia Environmental Management Authority.

For sustainable management of paratransit services, developing a coherent set of indicators and observing their interactions within the system is crucial. Collecting and analyzing paratransit emissions data matched with local service demand can support this effort. Local authorities should avoid over-relying on externally defined metrics. Identifying appropriate factors to measure the impact of sustainable transportation policies requires nuanced understanding, such as user experiences with paratransit services, paratransit route characteristics, and the interplay of politics, interests, and power among paratransit providers and decision makers.

CONCLUSION

As rapid urbanization intensifies vehicular traffic globally, the need for sustainable practices becomes increasingly urgent. Lusaka, Zambia's capital, exemplifies the challenges faced by many growing cities in low- and middle-income countries, where "informal" or paratransit services dominate public transportation. This paper first reviewed relevant academic debates in paratransit services and sustainable transportation frameworks. We then mapped and analyzed stakeholders in Lusaka's public transport management, examining their roles and challenges from both institutional and operational perspectives. This qualitative analysis was combined with a quantitative examination of the paratransit network and its route-level emissions. Using the coupled infrastructure system approach, we analyzed the complex ecosystem of actors and infrastructure classes shaping the overall policy framework.

Key findings from paratransit mapping and emission modeling analyses are summarized:

- Lusaka's paratransit network follows a hub-and-spoke model, with many transfers occurring downtown, increasing city center congestion.
- Boarding activity concentrates at central business district terminals, while aligning is more distributed.
- While city center speeds are low, Lusaka's outer areas—origins and destinations for many trips—have the lowest commercial speeds (0-10 km/hr), possibly due to the lack of designated terminals.
- Paratransit accessibility is limited compared to private vehicles, especially in peripheral areas.
- CO_2 emissions concentrate around downtown terminals and along four main corridors: Lumumba Road, Great North Road, Great East Road, and Chilimbulu Road.
- Great North and Kabanana Roads exhibit high PM_{10} emissions and high demand, suggesting targeted emission reduction strategies could be effective.

Based on these findings, we propose the following policy recommendations.

Operational improvements:

1. **Route prioritization and traffic management:** Promote high-capacity buses on key corridors and design dedicated lanes to reduce route overlap and emissions in congested areas. It is crucial to ensure cooperation from paratransit operators and relevant stakeholders to efficiently implement and enforce prioritization.
2. **Peripheral network connectivity:** Upgrade sidewalk infrastructure and create designated peripheral bus terminals to efficiently aggregate demand and reduce emissions. These interventions require investments in adequate infrastructure and facilities. There may be potential resistance from existing paratransit operators.
3. **Incentive-based policies:** Introduce pricing incentives based on efficiency and emissions to promote fleet upgrades and discourage polluting vehicles. Potential measures can include graduated gas taxes or vehicle sales taxes based on fuel efficiency and emissions. Public authorities would need to ensure that pricing policies are fair and equitable, mitigating potential negative impact on operators and vulnerable populations.

Institutional Improvements:

1. **Public Transportation Authority (PTA) establishment:** Implement the creation of the PTA as prescribed by regulation *(23)*. This authority would be responsible for planning and regulation of the transportation system, including paratransit services. However, there is the need to clarify the role and mandate of the PTA, addressing stakeholder concerns and ensuring alignment. In this context, the capacity of the Lusaka City Council to manage and plan transportation services and carry out institutional reforms needs to be strengthened.
2. **Participatory policy framework:** Encourage stakeholders' engagement, capacity building, and cooperation through structured negotiating forums with operator and passenger associations. A self-learning policy framework could encourage feedback and participation, ensuring users' perspectives are considered in managing paratransit operations. Formal involvement of drivers'

associations and companies in policy formulation through structured negotiating forums might also be necessary.

3. **Enhanced monitoring and regulation:** Implement standardized data collection and analysis processes for paratransit activities, emissions, and travel behavior. The information collected can be disseminated via passenger information systems, such as paratransit maps, to increase transparency and accessibility of paratransit services. Again, the alignment of stakeholders' interests needs to be achieved to minimize resistance to data collection and sharing, ensuring data accuracy, reliability, and relevance for policy interventions.

Zambia's transition to a sustainable and climate-resilient transportation demands a nuanced approach balancing multiple priorities. It must address the urgent need for environmental protection and climate action while safeguarding the livelihoods of those within the paratransit sector—from daily users to drivers and operators. Moving forward, policymakers and transportation stakeholders must prioritize holistic and inclusive strategies, to create an equitable, efficient, and adaptable transportation system that can meet future challenges. By doing so, Lusaka can set an example for sustainable urban mobility in rapidly growing African cities.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: research paper conception and design: Buffoni and Tun; data collection: Melegy and Abdulaziz; analysis and interpretation of results: Melegy, Abdulaziz, Buffoni, and Tun; draft manuscript preparation: Buffoni, Tun, and Msoni. All authors reviewed the results and approved the final version of the manuscript.

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