Smart Road Networks in Urban Freight Transport for Sustainable City Logistics

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Abstract: ***The burgeoning urbanization and population growth in African cities have precipitated a surge in freight transport demand, giving rise to challenges such as pollution, congestion, and environmental degradation. Addressing these issues, smart road networks (SRNs) have emerged as a progressive solution for sustainable urban freight transport. The present paper investigates the details of two research methods used for route optimization challenges. The first method is a multi-route planning system that employs a variety of algorithms to calculate the most optimal route. This system is capable of addressing complex route optimization challenges with near-optimal outcomes. The second is the continuous approximation model, which is used to calculate road network problems where customer locations differ on a daily basis. The study centers on the city of Lusaka in Zambia which has been considered as a case study to explore the potential of SRNs in fostering sustainable city logistics. Results have shown that by the implementation of SRNs would reduce delivery times by providing optimal routes for drivers. Furthermore, packages can be tracked in real time using vehicle-to-infrastructure technologies.***

Keywords: smart road networks, urban freight transport, sustainability, city logistics

1. Introduction

Twenty-first-century cities employ two primary strategies to enhance the quality of life, address modern social and human demands. The first as a tool for bettering cities is represented by the smart city paradigm (Anderson, 2020). The second strategy, which is centered on maintaining and replenishing the environment's resources and energy with unexplored health and environmental standards, is embodied in the sustainable city concept(Aina, 2017). A decade ago, the idea of "smart cities" first surfaced as one of the ways that globalization was embodied in informatics and contemporary technology, specifically represented by artificial intelligence. This approach used information and communication technology to support urban management systems and address issues brought on by the rapid rise in both social and economic growth as well as the emergence of significant environmental problems.

Urban freight transport plays a critical role in the cities' economy, ensuring the timely delivery of goods and services to businesses and households. However, the increasing urbanization and population growth in African cities have led to a significant increase in freight transport demand, resulting in congestion, pollution, and environmental degradation. To address these challenges, smart road networks (SRNs) have emerged as a promising solution for sustainable urban freight transport (Batty, 2013).

SRNs incorporate advanced technologies such as sensors, data analytics, and communication systems to optimize the flow of goods and improve the efficiency, safety, and sustainability of freight transport. The implementation of SRNs could facilitate real-time traffic management, route optimization, and freight tracking, which could reduce congestion, emissions, and delivery delays. Additionally, the adoption of electric vehicles and alternative fuels in the SRNs could further reduce emissions and promote sustainable transport.

Zambia, like many other African countries, is facing significant challenges in urban freight transport. Lusaka, which is Zambia's capital, is one of the rapidly growing cities facing these challenges. With a population of over 3 million people, Lusaka is a hub for various industries that rely on effective freight transport to sustain their operations (Macrotrends, 2024). However, the current transportation infrastructure in Lusaka is inadequate to meet the growing demand for freight transport, resulting in congestion, delays, and environmental pollution.

The research gap in intelligent road networks in urban freight transport for sustainable city logistics in Lusaka presents further exploration and development opportunities. While there is a growing emphasis on sustainability and integrating intelligent city technologies in urban freight logistics, specific gaps in research and implementation for Lusaka's context can be identified.

Despite all these carried out analysis, no specific data have been procured for the logistics in Lusaka (Zambia), while there is a growing emphasis on sustainability and integrating intelligent cities in freight logistics. Therefore, this paper has intent to investigate the potential of SRNs in Lusaka as a case study for sustainable city logistics. The study will assess the benefits and challenges of implementing SRNs in Lusaka and identify strategies to overcome the obstacles. The study will also explore the role of multiple stakeholders in the planning and implementation of SRNs and recommend policy interventions to promote sustainable urban freight transport. Overall, this research will contribute to the literature on sustainable urban freight transport and provide insights into the potential of SRNs to address the challenges of urban freight transport in Lusaka and other African cities.

The introductory section will provide a comprehensive description of the topic at hand. This will be followed by the problem setting which will outline the challenges faced in sustainable urban logistics and discuss the need for a well-designed SRN model. This section will also discuss the various factors that impact the efficiency of the urban logistics system. The next section will quantify the mathematical models associated with the SRNs model design for sustainable urban logistics. The paper will delve into the model's technical details and explain how it operates. It will also discuss the various parameters that are taken into consideration while designing the model. The following section will highlight a case study where the SRN model for sustainable urban logistics was implemented. It will detail the methodology employed, the data collected, and the results obtained. The case study results will be presented in the subsequent section. The paper will analyze the data collected and provide insights into the efficiency of the SRNs model. The results will be compared with those obtained from other models and discussed in detail.

2. Problem Setting

The increasing urbanization of cities in Africa has led to a rise in demand for freight transport, resulting in traffic congestion, pollution, and environmental degradation. To address these challenges, Smart Road Networks (SRNs) have emerged as a promising solution for sustainable urban freight transport (Holguín, 2019). This literature review provides an overview of the key concepts related to SRNs, urban freight transport, and sustainable city logistics and discusses their relevance to the case study of Lusaka.

2.1 Smart Road Networks (SRNs) overview

SRNs are innovative approaches to road infrastructure that integrate advanced technologies, such as sensors, communication systems, and data analytics. They enable real-time monitoring and management of traffic flow and road conditions. In addition to that, SRNs offer numerous benefits for urban freight transport, including improved safety, efficiency, and sustainability (Alexey, 2019). For example, SRNs can facilitate real-time traffic management, route optimization, and freight tracking, which can reduce congestion, emissions, and delivery delays. Additionally, adopting electric vehicles and alternative fuels in SRNs can further reduce emissions and promote sustainable transport (Abubakar, 2018).

Smart roads refer to integrating various technologies such as intelligent traffic signs, streetlights, and autonomous vehicles that utilize these roads. This integration is supported by systems such as IoT sensor networks, communication networks, big data, and artificial intelligence applications. These systems work together to create smart roads that are safer, more efficient, and sustainable (Gargi, 2018).

SRNs play a crucial role in promoting sustainable city logistics and improving urban freight transportation (Caragliu, 2020). These networks leverage advanced technologies and data-driven approaches to optimize the movement of goods within cities, reduce congestion, enhance efficiency, and minimize environmental impacts (Tariq, 2020).

2.1.1 Benefits of Smart Road Networks in Urban Freight Transportation:

Smart road networks enable real-time monitoring and management of traffic flow, allowing for efficient routing and scheduling of freight vehicles (He & Haasis, 2020). By utilizing intelligent transportation systems (ITS), Smart Road Networks help alleviate traffic congestion, leading to smoother freight movement and reduced travel times (Comi, Schiraldi, & Buttarazzi, 2018).

Intelligent road networks incorporate traffic cameras and sensors to improve road safety by detecting and preventing accidents (Lee & Yoon, 2021). Through better capacity management and optimization of freight transport, intelligent road networks contribute to reduced fuel consumption and environmental impacts (Nathanail, Gogas, & Adamos, 2016). Smart Road networks can be integrated with other innovative city initiatives, such as urban planning and environmental sustainability, to create a holistic and interconnected urban freight transportation system (Silva, Khan, & Han, 2018).

2.1.2 Smart Road Network Technologies:

- **Intelligent Transportation Systems (ITS):** ITS technologies, such as traffic monitoring systems, dynamic message signs, and vehicle-to-infrastructure communication, enable real-time traffic management and improve the efficiency of freight transportation.
- **Digital Cameras and License Plate Recognition:** Digital cameras equipped with license plate recognition capabilities can be used for congestion charging mechanisms, which help reduce traffic congestion and improve air quality in urban areas.
- **Data Analytics and Predictive Modeling:** Smart Road networks leverage data analytics and predictive modeling to optimize freight routes, predict traffic patterns, and make informed decisions for efficient freight transportation.

2.2 Urban Freight Transport

Urban freight transport refers to the movement of goods within cities and is a critical component of urban economies. However, urban freight transport is also a significant source of traffic congestion, emissions, and noise pollution (Huang, 2020). To address these challenges, there is a growing interest in developing sustainable urban freight transport solutions that prioritize environmental and social considerations (Bektaş, 2016). Several approaches to sustainable urban freight transport have been proposed in the literature, including using low-emission vehicles, consolidating deliveries, and optimizing delivery routes.

2.2.1 Freight Transportation in Logistics and its Impacts in Urban Cities

The role of transportation in logistics is critical in supply chain management; as a result, transportation serves as a connector between several stages that involve the transformation of raw resources into valuable goods for consumers and products that have outlived their life cycle to the point of disposal (Adamos, 2017). Transportation occurs when the required steps and sub-stages in a logistics system of product distribution are planned to minimize cost and maximize service for clients, which forms the notion of business logistics (Srinivasan, 2011).

Freight transportation arose from the necessity to provide essential consumer items to urban and suburban regions and for the reverse flow of worn goods in terms of clean garbage. This is done so that citizens might have access to commodities produced by enterprises worldwide wherever and whenever they are needed (Lindholm, The Impact of Urban Freight Transport: A Definition of Sustainability from an Actor's Perspective, 2008). As a result, while urban freight transportation is critical to serving inhabitants' demands, it also adds significantly to the non-sustainable consequences on the environment, economy, and society. The structure of freight transport growth in Europe has changed in numerous ways over the years due to the shift from rail to truck transport and the expansion of the logistics range. The leading causes of this development are the increased demand for transportation brought about by logistics, particularly with the rise in flexible production and distribution structures and the most recent infrastructure improvements (Irannezhad, 2020).

Urban areas worldwide are growing and developing quickly as a result of increased economic activity and the demand for more consumer goods and services, all of which must be transported from production sites to the desired locations (Abrahamsson, 2011). This has led to a significant increase in the demand for both private and commercial vehicles, with over a billion cars in operation in 2010 compared to nearly 130 million registrations worldwide in the 1960s.

The amount of time it takes for private and commercial vehicles to travel is increased by road congestion. Additionally, cars, trucks, and buses release air pollutants, primarily carbon dioxide, which contributes to global climate change, according to the Union of Concerned Scientists (2018). When breathed, the odorless, colorless, and toxic gas known as CO_2 can prevent oxygen from reaching a living thing's heart, brain, and other critical organs (Thompson, 2020).

Smart Road Networks are key to sustainable city logistics and urban freight transportation. By leveraging advanced technologies and data-driven approaches, these networks enable efficient, safe, and environmentally friendly movement of goods within cities. Integrating Smart Road Networks with other innovative city initiatives can enhance urban areas' sustainability and livability.

The literature review has provided an overview of the key concepts related to smart road networks, urban freight transport, and sustainable city logistics. The review has highlighted the potential benefits of SRNs for sustainable urban freight transport and the challenges facing implementing sustainable solutions in Lusaka. The next chapter will present the research methodology used to investigate the potential of SRNs in Lusaka.

2.3 Sustainable City Logistics

Sustainable city logistics refers to integrating sustainable transport solutions into urban freight transport systems. Sustainable city logistics aims to reduce urban freight transport's environmental and social impacts while maintaining the economic benefits. Sustainable city logistics involves the development of integrated transport systems, the promotion of low-emission vehicles, and the optimization of delivery routes. Adopting sustainable city logistics can lead to numerous benefits, such as reduced transport costs, improved air quality, and enhanced livability and accessibility in urban areas(Taniguchi, 2014).

2.3.1 Transforming a Metropolitan Cityinto a Sustainable Urban City

Transforming a metropolitan city into a sustainable one involves a multifaceted approach that considers various aspects of urban development, including environmental, social, economic, and technological factors. The following are some critical steps and strategies that can contribute to the transformation:

1) **Sustainable Urban Planning:** Adopt sustainable urban planning practices that prioritize compact and mixed land use, efficient transportation systems, and the preservation of green spaces. This includes designing walkable and bike-friendly neighborhoods, promoting public transit, and integrating green infrastructure such as parks and urban gardens.
2) **Energy Efficiency and Renewable Energy:** Implement energy-efficient measures in buildings and infrastructure, including using energy-efficient appliances, insulation, and smart grid technologies. Promote the adoption of renewable energy sources such as solar and wind power to reduce reliance on fossil fuels and lower carbon emissions.
3) **Sustainable Transportation:** Promote sustainable transportation options such as walking, cycling, and public transit to reduce reliance on private vehicles. Develop infrastructure for electric cars and support car-sharing and bike-sharing programs. Implement intelligent transportation systems to optimize traffic flow and reduce congestion.
4) **Collaboration and Partnerships:** Foster collaboration among various stakeholders, including government agencies, businesses, community organizations, and academic institutions. Collaborate with international organizations and networks such as the United Nations Sustainable Development Goals and C40 Cities to share best practices and learn from successful sustainable urban initiatives.
5) **Monitoring and Evaluation:** Establish mechanisms to monitor and evaluate the progress of sustainability initiatives. Set targets and indicators to track the city's performance in energy consumption, waste reduction, air quality, and social equity. Regularly assess the effectiveness of implemented strategies and make adjustments as needed.

By implementing these strategies and engaging in a holistic approach to sustainable urban development, Lusaka can transform into a sustainable metropolitan city that prioritizes environmental stewardship, social well-being, and economic prosperity.

3. SRN Model design

3.1 Freight Scheduling and Routing

A well-developed multi-route planning system comprises three essential components: (1) an urban freight transport network, (2) a routing engine, and (3) a set of route queries (Mrazovic, Eser, Ferhatosmanoglu, Larriba-Pey, & Matskin, 2018). The transport network serves as the foundational physical traffic network, encompassing loading areas and the connecting roads. This network is aptly formalized through a directed graph D (L, P), where the set of nodes, L= $\{l_1, ..., l_N\}$ represents loading areas, and the set of edges, P= $\{p_{ij} \mid l_i, l_j \in L\}$ denotes the shortest paths connecting them. Additionally, each node $l_i \in$ L is assigned a specific vehicle capacity, represented by v_i, and each edge $p_{ij} \in$ P is endowed with a corresponding travel cost, denoted as q_{ij}.

The dedicated graph database stores the urban freight transport network model, serving as a crucial resource for the routing engine. This routing engine is the central and pivotal component, embodying our solutions for addressing complex route optimization challenges with near-optimal outcomes. The engine takes a specified set of route queries, denoted as R = $\{r_1, ..., r_N\}$, each corresponding to delivery vehicles represented by V = $\{v_1,, ..., v_N\}$. Each individual query, r_k, includes parameters such as the initial location, l_s^k, of the vehicle r_k, the delivery start time s_t, a set of delivery locations (i.e., loading areas) to be visited along the planned route $\breve{G}_k$, and the estimated delivery durations, $\breve{g}_i^k$, for each loading area v_i within $\breve{G}_k$.

The route query, r_k, for vehicle v_k is defined by its initial position, $l_s^k \in$ L, delivery start time, s_t^k, a set of predetermined delivery locations, $\breve{G}_k \subseteq$ L, and the estimated delivery durations $\{\breve{g}_i^k \mid l_i \in \breve{G}_k\}$. The concurrent route queries, R = $\{r_1, ..., r_N\}$, have delivery location sets $\breve{G}_k$ for each $r_k \in$ R, and these sets can intersect. Due to limited capacity, loading areas can only accommodate a restricted number of vehicles simultaneously. The selection of a route for a particular vehicle can significantly impact the duration of routes scheduled for other vehicles operating within the same system. As a result, it is essential to consider the interdependent nature of such decisions and their potential effects on the system's overall performance. By taking a comprehensive approach to route planning, it is possible to optimize the efficiency of individual vehicles and the entire system as a whole. In practical terms, if a delivery area reaches its total capacity, other vehicles must wait in a queue based on a first-come-first-served policy before being accommodated in the congested area. Thus, the primary objective is to construct an optimal set of routes, denoted as $\tilde{O} = \{\tilde{o}_1, ..., \tilde{o}_N\}$ (one for each query $r_k \in$ R), aiming to minimize the total time cost in the transport system collectively This cost is expressed as the sum of the durations of all routes, $\tilde{o}_k \in \tilde{O}$.

The duration of a single route $\tilde{o}_k$ is computed as the sum of the travel times along $\tilde{o}_k$, delivery duration$t_i^k \forall l_i \in \breve{G}_k$, and waiting times $t_i^k \forall l_i \in \breve{G}_k$. Therefore, the cost is expressed in the equation 1.

$$cost\,(\tilde{o}_k) = \sum_{l_i \in \breve{G}_k} \left(w_k + t_k + \sum_{l_i \in \breve{G}_k} x_{ij}^k q_{ij} \right) \quad (1)$$

where$x_{ij}^k \in \{0, 1\}$ is a decision variable defined to be equal to 1 if edge p_{ij} is traversed in route $\tilde{o}_k$, and equal to 0, otherwise.

Remember that for a specific route $\tilde{o}_k$, the travel costs q_{ij} ,and estimated delivery durations $\breve{g}_i^k \forall l_i \in \breve{G}_k$ are known from the graph model *D (L, P)* and route query r_k, respectively. On the other hand, the queue waiting time t_i^k at each loading area $l_i \in \breve{G}_k$ needs to be explicitly computed. However, such computation is not straightforward since it depends on other routes in the system, while the delivery durations differ from route to route. Therefore, in the next section we propose an efficient algorithm to compute the total waiting time.

Given an urban freight transport network *D(L,P)* and a fleet of vehicles $V = \{v_1, ..., v_N\}$ with the corresponding set of route queries $R = \{r_1, ..., r_N\}$, the goal of the proposed problem is to determine the set of N routes $\tilde{O} = \{\tilde{o}_1, ..., \tilde{o}_N\}$ that collectively minimize the total time cost, while visiting all of the planned nodes $l_i \in \breve{G}_k \forall r_k, \in R$. We further formalize it as follows

$$f\,(\tilde{O}) = \sum_{\tilde{o}_k \in \tilde{O}} cost(\tilde{o}_k) \quad (2)$$

$$= \sum_{\tilde{o}_k \in \tilde{O}} \sum_{l_i \in \breve{G}_k} \left(\breve{g}_i^k + t_i^k + \sum_{l_i \in \breve{G}_k} x_{ij}^k c_{ij} \right) \quad (3)$$

where x_{ij}^k *is a decision variable introduced in Definition 2.3, and each route* $\tilde{o}_k \in \tilde{O}$ *visits all of the planned nodes* $l_i \in \breve{G}_k$ *starting at node* l_s^k *and time* s_t^k.

```
In [1]: from datetime import datetime, timedelta

        #Time taken to deliver a parcel

        #Variables
        Start_Off_Time = '2023-12-30 07:00'

        #Convert string to datetime object
        SoT = datetime.strptime(Start_Off_Time, '%Y-%m-%d %H:%M')

        #Constraints
        travel_time_per_vehicle = timedelta(minutes=40)
        loading_duration = timedelta(minutes=20)
        parking_time = timedelta(minutes=15)
        package_delivery_time = timedelta(minutes=5)

        #Arrival time
        arival_time = SoT + loading_duration + travel_time_per_vehicle + parking_time + package_delivery_time
        print(arival_time)

        2023-12-30 08:20:00
```

Figure 1: Tracking Code

An algorithm such as the one depicted in Figure 1 above, can track arrivals and departures at or from loading areas. In the algorithm, each such event is modelled as a tuple containing the type of the event (arrival or departure), the corresponding node and route, and the scheduled time. For example, tuple (*Arrival*, $\tilde{o}_k$, l_i, $\grave{a}_i^{\ k}$) represents arrival at node l_i in route $\tilde{o}_k$ scheduled at time $\grave{a}_i^{\ k}$. Similarly, tuple (*Departure*, $\tilde{o}_k$, l_i, $\acute{y}_i^{\ k}$) represents departure from node l_i in route $\tilde{o}_k$ scheduled at time $\acute{y}_i^{\ k}$. Notice that we use a different notation for a scheduled arrival time ($\grave{a}_i^{\ k}$) and departure timeis ($\acute{y}_i^{\ k}$). This is because these times are correlated, meaning that one can be computed as a result of the other by knowing the estimated waiting time, delivery duration, and travel cost.

Since vehicles depart from loading areas after finishing their deliveries, departure time$\acute{y}_i^{\ k}$ can be computed from arrival time$t_i^{\ k}$ by adding waiting time$t_i^{\ k}$ and delivery duration$\breve{g}_i^{\ k}$. Formally, the …… is expressed in equation 4

$$\acute{y}_i^{\ k} = \grave{a}_i^{\ k} + t_i^{\ k} + \breve{g}_i^{\ k} \quad (4)$$

On the other hand, the arrival time $\grave{a}_i^{\ k}$ can be computed from departure time $\acute{y}_i^{\ k}$ from l_i's predecessor l_j, by adding travel cost q_{ji}, i.e.,

$$\grave{a}_i^{\ k} = \acute{y}_i^{\ k} + t_i^{\ k} + q_{ji} \quad (5)$$

3.2 Continuous Approximation Model

By putting in place a calculated road network problem where customer locations differ daily, we need to approximate customer locations by using distribution functions that will allow us to get CA-based models that enable us to estimate trip distance and cost. We can use this model to determine which transportation strategy a logistic service provider will use to serve a specific service region in the distribution area (Fontaine, Minner, & Schiffer, 2023). We study a service region in the Euclidean space Q in which different demand classes $d \in D$ are subdivided, each characterized by a specific parcel volume k_i. To calculate the number of parcels in a region *N (Q)*, we utilize the point-based parcel density$\delta_i(x)$ of the number of parcels for each demand class l and point $x \in Q$, which results from each demand class's distribution; formally

$$N(Q) = \sum_{d \in D} \left(⍰_{Q x \in Q} \delta_i(x) dx \right)$$

We proceed with the assumption that the demand distributions of distinct classes are independent. Consistent with the overarching CA paradigm, we maintain this assumption that $\delta_i(x)$ is nearly constant in a region large enough to exploit a vehicle's capacity. "We have considered an array of transportation modes m∈*M*. The decision variable $f_{ml}(x)$ describes the portion of parcels at point x of demand class l, distributed via transportation mode m. Then, the mode-specific parcel density in point x for mode m is

$$\Delta_m(x) = \sum_{l \in L} \delta_1(x) f_{ml}(x) \quad (6)$$

and the mode-specific parcel volume density is

$$\Delta_m(x) = \sum_{l \in L} k_1 \delta_1(x) f_{ml}(x) \quad (7)$$

We define $n_m(x)$ as the number of stops of a route and $v_m(x)$ as the shipment volume of a stop at a point x. Let $r(x)$ denote the distance between the depot and point x in kilometers.

We now define all necessary cost parameters and incorporate investment cost, if applicable, within the general operational cost factor. For each mode of transportation, we take into account the mode-specific upper-echelon costs $\dot{c}_m$ per km

$$\dot{c}_m = \frac{w^S + w_m^{\ L}}{w_m^{\ L}} \quad (8)$$

with w^s being the driver's salary per hour, $w_m^{\ L}$ being each vehicle's operating cost per hour, and $w_m^{\ L}$ being each vehicle's upper echelon average travel speed. Similarly, costs for lower echelon routing are

$$c_m = \frac{w^s + w_m^{\ D}}{v_m^{\ D}} \quad (9)$$

based on a mode-specific operating cost per hour $w_m^{\ D}$, and a mode specific lower-echelon average travel speed $v_m^{\ D}$. To simplify the presentation, we assume that the driver wage is equal for both levels and various modes of transportation, but this assumption can be relaxed. Costs of stopping τ_m such as parking and serving the customer, depend on the driver's cost w_s and the average time $t_m{}^S$ that the driver needs to search for parking with transport mode m and delivering the parcel can be equated as

$$\tau_m = w_s t_m^S \quad (10)$$

We can state the approximated costs per delivery stop $z_m(x)$ for transportation mode m at point x as

$$z_m(x) = \frac{2r(x)\dot{C}m}{nm(x)vm(x)} + \frac{cmk(1m(x))^{-\frac{1}{2}} + \tau m + \tilde{\tau} mvm(x)}{vm(x)} \quad (11)$$

where k denotes a common CA routing constant. The first quotient defines the full-truck-load upper-echelon costs. This represents the costs for driving a conventional truck into a service region. The second quotient comprises the operational costs. The first term states mode-specific lower-echelon costs based on its distance approximation. The optimization model determines the optimal distribution of transportation modes for service region Q. The second term refers to stopping costs while the third term represents volume-based handling costs. The vehicle capacity for each transportation mode is c_m.

$$\min \int_{x\in M} \left(\sum_{m\in M} \Lambda_m(x)\, z_m(x) \right) \quad (12a)$$

$$\text{s.t. } n_m(x)\, v_m(x) \le c_m \quad \forall m \in M,\ x \in Q \quad (12b)$$

$$v_m(x) = \frac{\Lambda_m(x)}{\Delta_m(x)} \quad \forall m \in M,\ x \in Q \quad (12c)$$

$$\sum_{m\in M} f_{ml}(x) = 1 \quad \forall l \in L,\ x \in Q \quad (12d)$$

$$f_{ml}(x) \ge 0 \quad \forall l \in L,\ m \in M,\ x \in Q \quad (12e)$$

$$n_m(x) \ge 0 \quad \forall m \in M,\ x \in Q \quad (12f)$$

Objective (12a) minimizes overall cost, which results from the modal split. Constraints (12b) secure vehicle capacity constraints for each mode. Eq. (12c) defines the average volume in a region $v_m(x)$ as the quotient of demand and volume distribution. Constraints (12d) ensure that the demand of a region is covered, either by one or multiple transportation modes. Constraints (12e) and (12f) state the domains of the decision variables. With Q being the size of the service region, we formulate the cost function similar to Fontaine, et al.,(Smart and sustainable city logistics: Design, consolidation, and regulation, 2023). As the location related parameter $\delta_1(x)$ is nearly constant in a region that is still large enough to exploit a vehicle's capacity, we approximate the cost function and all location-related parameters by specific parameters based on the continuous approximation model (12). Here, we assume that constraints (12b) are binding and, consequently, all vehicles are fully utilized. Because of this, $n_m v_m$ can be replaced with c_m in *(a)*. Then, constraints (13c) allow to replace Λ_m / v_m with Δ_m in (12b). Using the definitions of Λ_m and Δ_m, we derive the final cost function (13).

$$\sum_{m\in M} \Lambda_m z_m = \sum_{m\in M} \Lambda_m \left(\frac{2r\dot{C}_m}{n_m v_m} + \frac{c_m k(\Delta_m)^{-\frac{1}{2}} + \tau_m + \tilde{\tau}_m v_m}{v_m} \right) \quad (13)$$

$$= \sum_{m\in M} \Lambda_m \frac{2r\dot{C}_m}{c_m} + \sum_{m\in M} \Lambda_m \left(\frac{c_m k(\Delta_m)^{-\frac{1}{2}} + \tau_m + \tilde{\tau}_m v_m}{v_m} \right) \quad (14)$$

$$= \sum_{m\in M} \Lambda_m \frac{2r\dot{C}_m}{c_m} + \sum_{m\in M} \Lambda_m c_m k(\Delta_m)^{\frac{1}{2}} + \sum_{m\in M} \Delta_m \tau_m + \sum_{m\in M} \Lambda_m \tilde{\tau}_m \quad (15)$$

$$= \sum_{m\in M} \Lambda_m \left(\frac{2r\dot{C}_m}{c_m} + \tau_m \right) + \sum_{m\in M} c_m k(\Delta_m)^{\frac{1}{2}} + \sum_{m\in M} \Delta_m \tau_m \quad (16)$$

$$= \sum_{m\in M} \sum_{l\in L} \delta_1 k_1 f_{ml} \left(\frac{2r\dot{C}_m}{c_m} + \tau_m \right) + \sum_{m\in M} c_m k(\Delta_m)^{\frac{1}{2}} + \sum_{m\in M} \sum_{m\in M} \delta_1 f_{ml} \tau_m \quad (17)$$

$$= \sum_{m\in M} \sum_{l\in L} \left(\delta_1 k_1 \left(\frac{2r\dot{C}_m}{c_m} + \tau_m \right) + \delta_1 \tau_m \right) f_{ml} + \sum_{m\in M} c_m k(\Delta_m)^{\frac{1}{2}} \quad (18)$$

4. Case Study

The present case study investigates the experiences of stakeholders concerning the road network and the introduction of Smart Road Networks (SRN) in Lusaka, Zambia. By leveraging surveys and interviews, the study aims to gain valuable insights into demographic factors, including gender and occupation. Subsequently, stakeholders provide their viewpoints on the present road network in Lusaka, reflecting on the challenges faced with vehicle usage and business operations' timeliness. The study then examines stakeholders' perceptions of traffic congestion and their attitudes towards the incorporation of Smart Road Networks (SRN) for freight service delivery.

Throughout the course of the study, stakeholders express a range of opinions on the Lusaka Road network, with many offerings of firsthand accounts of challenges faced, particularly in regards to traffic congestion. The study also assesses the attitudes towards implementing Smart Road Networks for freight services, focusing on ease of use and the potential enhancement of effectiveness. Stakeholders' preferred routes, transportation modes, vehicle capacity, parcel load, and trip durations further paint a detailed picture of the challenges and opportunities faced by stakeholders in urban freight transport. The findings of the study provide a foundation for urban planners and logistics professionals, offering practical implications for the integration of Smart Road Networks to streamline and enhance freight service delivery in Lusaka.

5. Results

210 people participated in the survey, comprising of 177 males and 33 females. The majority of the participants were light truck drivers (36.7%), followed by motorbike riders (31.4%) and cargo truck drivers (19.5%). This is shown in Figure 2 below. When asked about the road network, 57.6% of participants rated it as fair, while 22.9% considered it good and 19.5% thought it was bad.

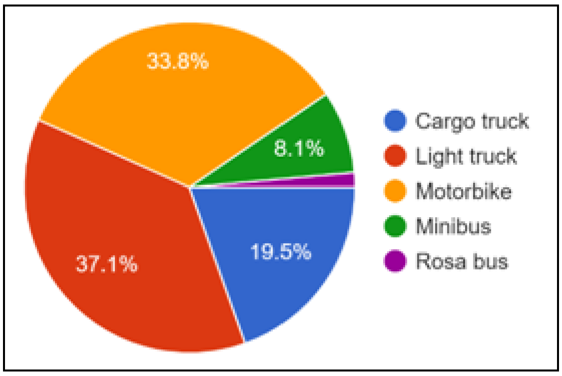

Figure 1: Transport Mode

52.6% of the respondents faced challenges with their vehicles due to the road network, while 41% rarely faced any challenges. 5.2% of the participants did not face any challenges. In terms of conducting business in a timely manner, 53.3% of the respondents sometimes conducted their business in a timely manner, while 23.8% responded positively, and 22.9% did not.

The survey revealed that 94 road users believed the current road network was moderately congested. More than half of the respondents believed that Smart Road Networks were easy to use. When asked whether utilizing Smart Road Networks would enhance their effectiveness in freight service delivery, 55.3% of the participants agreed.

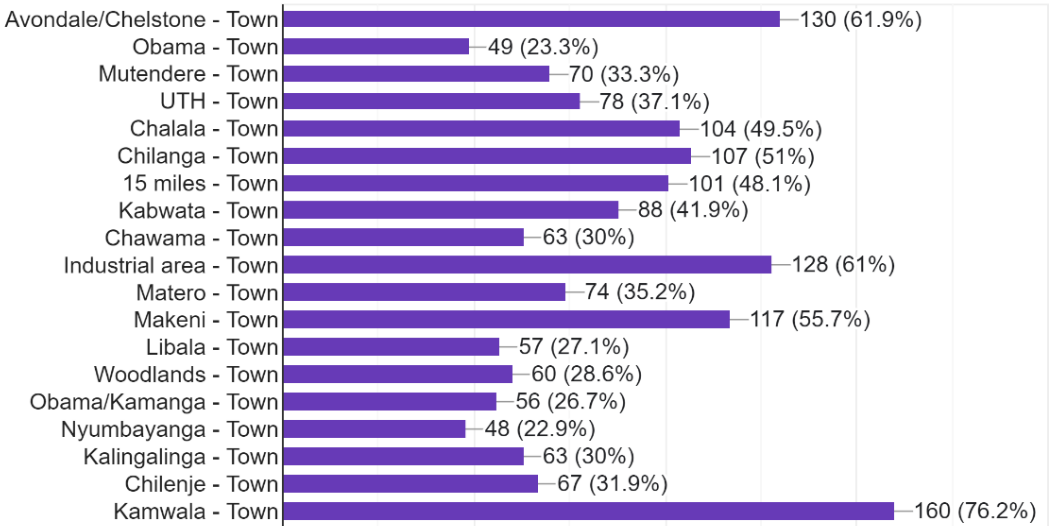

Figure 3: Frequently Used Routes

113 respondents had a positive attitude towards Smart Road Networks if implemented. As shown in the Figure 3 above, logistics operations in Lusaka were concentrated in the Kamwala-Town area, and each transporter mostly took 1-5 parcels per trip. Additionally, light trucks were the preferred transportation mode in the city, with a carry capacity of up to 5 tons. Finally, most trips took about an hour for a daily delivery to be made.

6. Conclusion and Outlook

This paper analyses the benefits of smart road networks as a model to overcome urban freight challenges and ensure that sustainable city logistics is achieved. A case study in the city of Lusaka in Zambia is considered, and the following conclusions can be drawn.

To start with, more than half of the surveyed individuals experienced challenges with using the current road network infrastructure. This is also evident in the duration the packages take to reach customers. As indicated in the results, the majority (29.9%) of the trips take an hour to reach their indented destinations. The implementation of smart road networks would reduce delivery times by providing optimal routes that drivers can take. Furthermore, packages can be tracked in real time by accessing the precise location that a particular vehicle positions itself on the road. This would also aid in estimating the delivery time of a particular parcel in any given trip.

Moreover, as urban freight transport plays a critical role in the global economy, the issue of congestion on roads can lead to several problems like delays, increased costs, and lost opportunities. To tackle this challenge, a new and innovative approach has been introduced that offers a theoretical solution. The novel problem-solving approach is based on the Smart Road Networks (SRNs) model, which can help resolve the congestion problems in urban freight transport networks effectively. By combining the strengths of these two research methods, businesses can optimize their routes, save time and money, and increase customer satisfaction.

The proposed solution involves providing drivers with access to estimated delivery times via the SRNs model. By doing so, drivers can optimize their routes, avoid congestion, and complete their designated routes more efficiently. This can lead to more timely deliveries, which would ultimately benefit both the company and its customers.

The proposed solution is most effective in dense urban environments where multiple routes are being queried concurrently. The SRNs model can optimize the routes of multiple drivers simultaneously, leading to reduced congestion, lower costs, and more efficient freight transport. Therefore, this approach can be an effective solution for addressing the challenges of congestion in urban freight transport networks.

Sustainability??

In conclusion, integrating smart road networks into urban freight transportation is a viable way to support sustainable logistics. These networks have the potential to improve efficiency of logistics in urban areas, reduce environmental impact, and expedite delivery operations by utilizing state-of-the-art technologies. In order to guarantee smooth operation of and optimal benefits, successful integration of smart road networks necessitates cooperation among stakeholders, infrastructure development and the creation of supportive policies. Smart road networks offer an appealing means of achieving environmentally friendly, economically, and sustainable logistics practices in urban freight transport. In order to fully utilize smart road networks for sustainable logistics, more investigation, cooperation and funding will be required.

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