Mekelle University

Ethiopian Institute of Technology-Mekelle

Faculty of Civil and Environmental Engineering

Msc in Civil Engineering (Road and Transport Engineering)

Assessing Taxi Transportation Spatial Equity in Access to Public School and Healthcare Services Across Mekelle Sub-cities

By

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February, 2026
Mekelle, Ethiopia

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Board of Examiners' Approval

We, the undersigned, members of the Board of Examiners of the final open defense of Rozina Gebreyohanns, have read and evaluated the thesis entitled "Assessing Taxi Transportation Spatial Equity in Access to Public School and Healthcare Services Across Mekelle Sub-cities" and assessed the candidate's performance. We hereby certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering, with specialization in Road and Transport Engineering.

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DECLARATION

I hereby declare that this MSc thesis entitled “Assessing Taxi Transportation Spatial Equity in Access to Public School and Healthcare Services Across Mekelle Sub-cities” is my original work and has not been presented for a degree in any other university and all sources of material used for this thesis have been duly acknowledged.

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This is to certify that the thesis entitled “Assessing Taxi Transportation Spatial Equity in Access to Public School and Health care Services Across Mekelle Sub-cities” is submitted in partial fulfillment of the requirements for the degree of MSc in Civil Engineering with specialization in Road and Transportation Engineering in the graduate program of Faculty of Civil and Environmental Engineering of Mekelle University and has been Carried out by Rozina Gebreyohanns ID No: EITM/PR176300/12 under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the Department.

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Finally, I dedicate this work to all communities striving for equitable transportation access to education and health care. I hope that the findings of this thesis will contribute to advancing inclusive taxi route planning and institutional reform in developing cities like Mekelle.

Abstract

This thesis investigates spatial equity in taxi transport accessibility to public school and healthcare center across the sub-cities of Mekelle, Ethiopia. It first constructed a detailed road network by integrating taxi route data collected through SW Maps with walking path data derived from OpenStreetMap, cleaned and standardized to ensure connectivity.

Using this network, cumulative and gravity-based accessibility modeling was applied from residential origins, which were divided in to 257 hexagonal grid cells with 500meter sides each, to service destinations geolocated based on SW Maps. The analysis was complemented by statistical equity metrics like Lorenz curves and Gini coefficients to quantify equity. Moreover, composite equity rankings were developed by combining percentage of cumulative accessibility count, cumulative-based accessibility per capita, sum of gravitational accessibility, and gravity-based accessibility per capita. These metrics were consolidated into a composite score to assess and rank sub-cities based on their relative access to public schools and healthcare centers.

Geographic Information System visualization and sub-city-level aggregation were employed to translate technical results into clear patterns of equity.

Results reveal significant differences in equity levels among sub-cities. Ayder, and Hadnet sub-cities benefit equitable taxi route accessibility to public schools and healthcare centers. While, Adihaki followed by Quiha and Semien sub-cities consistently fall into the very low equity categories. Moreover, cumulative Gini values for primary schools, secondary schools, and healthcare centers were 0.381, 0.405, and 0.294 respectively, while gravity-based Gini values were 0.193, 0.205, and 0.204. These results revealed moderate to low inequity. These findings underscore the importance of using diverse analytical tools to capture the complexity of spatial equity and inform targeted planning interventions.

To address these disparities, this thesis recommends targeted taxi route improvement in low-equity sub cities, improved last-mile connectivity, and the adoption of spatially precise and equity driven frameworks in taxi route planning.

Keywords: Accessibility modeling, Gini coefficient, Lorenz curve, QGIS, Spatial equity, SW Maps, Taxi transportation, Transportation equity

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Abbreviations

Abbreviations	Full Form
GIS	Geographic Information System
K/Weyane	Kedamay-Weyane
OD Matrix	Origin Destination Matrix
OSM	OpenStreetMap
QGIS	Quantum Geographic Information System
SQL	Structured Query language
SW Maps	Surveying and Mapping Application
UTM	Universal Transverse Mercator

1. Introduction

1.1. General

In today’s rapidly evolving urban landscape, transportation plays a vital role in connecting individuals to opportunities. However, disparities in transportation equity and accessibility can significantly impact one’s ability to access opportunities, ultimately influencing economic mobility and social inclusion. The ability to connect individuals to opportunities is central to fostering inclusive economic growth and reducing disparities in opportunity.

Perceptions of transportation equity vary by neighborhood, region, and individual experience. Theoretically, ‘equity’ refers to the fairness in resource distribution and is interpreted differently across disciplines like politics, economics, and environmental science (Litman, 2002). Equity refers to the pursuit of reducing disparities and is closely linked to principles of justice, fairness, and social convergence (Bruzzone et al., 2023).

For this study transportation equity is defined as fair distribution of access of taxi transportation system regardless of geographic location, to reach opportunities like public health care centers and schools from residential areas.

Transportation accessibility is a critical factor in ensuring equal opportunities for all individuals, especially in the context of access to opportunities. The availability and equitable distribution of transportation services to opportunities play a key role in shaping workforce participation, economic productivity, and overall quality of life. Accessibility to opportunities, on the other hand, refers to how readily individuals can reach opportunity centers via multiple transport options.

Transportation accessibility is a cornerstone of equitable development, influencing how residents connect with public services (Ghosh & Shivani, 2025). In rapidly evolving cities like Mekelle, where transportation networks are complex and unevenly distributed, evaluating access using predominant, minibus taxi, transport mode is essential for understanding equity of transportation accessibility.

Access to public opportunities like schools is a fundamental component of urban well-being and social equity (Luis et al., 2017). In Mekelle, rapidly growing city, physical proximity alone does not guarantee equitable public healthcare and school reach. Travel time, influenced by road connectivity, transport mode, and spatial layout, plays a crucial role in determining whether residents can reach opportunity services in a timely manner.

Despite progress in urban development, taxi transport access to public healthcare and school remains unevenly distributed across Mekelle, with significant barriers for residents in peripheral areas. Physical proximity to public healthcare and school services does not guarantee usability; instead, accessibility is shaped by travel time, transport options, and the structure of the road network. Conventional planning methods often overlook the impact of public transport routes and essential services, leaving crucial gaps in understanding how urban mobility affects service reach. This disconnects leads to misallocated resources, unserved populations, and widening public health and school service inequities.

This thesis employed a spatially explicit, equity-sensitive methodological framework to evaluate the equity of accessibility of public healthcare and school using taxi mode of transportation and walking to and from taxi stations in Mekelle through geographic information systems (GIS). The approach integrates both primary and secondary spatial datasets, into a hybrid transport network that reflects real-world movement across the city.

Primary data were collected via SW Maps to capture real-world taxi paths and facility locations, while secondary data, such as OpenStreetMap geometry, public schools and health care centers numbers and names per sub-city, taxi route origin-destination information and population figures provided essential context for route modeling and equity–normalization. Travel speeds were calibrated to reflect local movement patterns, allowing for the extraction of fastest paths from uniformly spaced residential grid cells to mapped opportunity destinations. Then accessibility was assessed through both cumulative-based and gravity-based measures and normalized indicators, and opportunity per capita (per 1,000 residents). These metrics formed the basis for sub-city-level ranking and choropleth visualizations, highlighting zones of high and low access. The final stage of the research interpreted these outputs using composite equity ranking and planning needs, concluding in actionable policy recommendations for equitable accessibility of taxi route planning and improved urban public health and school outcomes.

Generally, the analytical pathway follows a logical sequence of geospatial data preparation, origin-destination matrix calculations, and opportunity metric derivations.

1.2. Background

Mekelle, the capital of Ethiopia’s Tigray region in the north, serves as the selected study area. It is situated approximately 780 kilometers from Addis Ababa, the city has seven sub-cities: Adihaki, Ayder, Hadnet, Hawelti, Kedamay-Weyane, Quiha, and Semien. Despite its regional significance, Mekelle grapples with socio-economic challenges such as widespread public transport inaccessibility and inequality, reflected in uneven living conditions and limited access to transportation.

Transport within the city consists of both motorized and non-motorized modes, with road-based options being the only available forms (Araya et al., 2022). Motorized transport includes private cars, three-wheeled vehicles such as Bajaj and Mahindra, small taxis, mini-bus taxis, city buses, larger buses, trucks with trailers, and motorcycles. Among these, mini-bus taxis, and Amora city buses function as mass transport. Bajaj vehicles, though three-wheeled and carrying up to four people including the driver, are also part of the public transport system.

In Mekelle, all mini-bus taxis and Amora city buses are classified as formal services since they operate on fixed routes with government-regulated fares (Araya et al., 2022). Bajaj services, however, are partly formal and partly informal: while some follow designated routes with fixed tariffs, most operate flexibly, with routes and fares negotiated directly with passengers, functioning more like contract services.

Importantly, mini-bus taxis serve as the predominant mode of transport in the city. This is because Amora buses often suspend services for various reasons, making mini-bus taxis a more reliable and consistent option for daily mobility. For this reason, my analysis focuses primarily on mini-bus taxis as the central mode of transportation.

Recent development in Geographic Information Systems (GIS) technology provide a more precise methods for analyzing opportunities’ transport accessibility with enhanced spatial and demographic accuracy, as it enables researchers to integrate diverse datasets, perform advanced spatial modeling, and visualize disparities in ways that inform policy and planning (Longley et al., 2004). Among the available GIS platforms, Quantum Geographic Information System, QGIS, has emerged as widely adopted open-source alternative in community engagement with vibrant and rapidly expanding plugin network (Khan, 2018).

QGIS provides a strong environment for accessibility modeling, statistical equity metrics and visualizations of disparities across zones. Its plugin, including Data Plotly, and Group stats, allows integration of statistical analysis directly within the GIS interface, reducing dependence on external software (QGIS.org, 2025).

Furthermore, QGIS also supports mobile data collection tools such as SW Maps, enabling seamless work flows from field data acquisition to spatial analysis.

The open source nature of QGIS is particularly relevant in contexts where resource constraints limit access to expensive proprietary licenses. By ensuring transparency, duplicability, and community-driven innovation QGIS aligns within equity-focused research that seeks to integrate access to spatial analysis tools (Steiniger & Hunter, 2013). Its capability to handle different data formats, generate high quality output visualization, and support advanced statistical workflows makes it appropriate choice for analyzing equity of taxi transportation accessibility to public school and health care services in Mekelle city.

In Mekelle there is a limited and incomplete spatial network data, lack of field verification, and insufficient population normalized indicators. Hence, there is a persistent research gap in integrating real-world transport patterns such as field-tracked taxi routes with both cumulative-based and gravity-based opportunity measures and equity-focused spatial analysis.

This thesis addresses that gap by developing a hybrid network model for Mekelle that fuses OpenStreetMap data with GPS-based taxi paths collected via SW Maps. Through grid-based sampling, origin-destination matrix calculations, and calibrated travel speed assumptions, this thesis produces accessibility metrics that are both context-sensitive and equity-aware. By analyzing normalized accessibility, opportunity per capita, Gini coefficient, and Lorenz curve the thesis aimed to uncover hidden patterns of inequity of taxi transportation accessibility and inform data-driven planning decisions across the sub-cities.

1.3. Problem statement

Rapid urbanization in Mekelle city has intensified spatial disparities in taxi transportation access to essential public services such as school and health care. Despite ongoing infrastructure development, some areas remain underserved. These disparities disproportionately affect low-income and peripheral communities, restricting their opportunities for social mobility and well-being (World Bank, 2020). Accessibility, as defined by Geurs and Wee (2013) the “extent to which the land-use and transportation systems enable (groups of) individuals to reach activities or destinations”. However, accessibility is unevenly distributed in the city, reflecting broader socio-economic inequalities.

Transport equity theories emphasize that mobility systems should provide fair opportunities for all social groups, yet disadvantaged areas continue to experience limited access to services due to inadequate and unreliable public transport coverage (Lucas et al., 2016; Di Ciommo & Shiftan, 2017).

The core research problem addressed in this thesis is the absence of a spatially precise and equity-driven framework for evaluating equity of taxi transport accessibility to essential opportunities specifically public school and healthcare services across Mekelle city. There is limited integration of transport data, particularly field-tracked taxi paths and opportunity points, and few methodologies account for demographic pressure when measuring equity of transport accessibility to essential opportunity centers.

Understanding and addressing these gaps is essential for guiding policy interventions and infrastructure investments. By introducing a hybrid routing model and population-sensitive accessibility metrics, this thesis contributes a more accurate and inclusive assessment of equity of transportation accessibility from residential areas to public school and health care services. It trains urban planners and decision-makers with tools to identify underserved sub-cities, and optimize improved taxi route planning.

1.4. Objectives

1.4.1. General objective

The general objective of this thesis is to assess spatial equity in taxi transportation accessibility to essential public services, specifically public primary schools, secondary schools, and healthcare centers, across Mekelle sub-cities using cumulative and gravity-based accessibility models to identify underserved sub-cities for targeted urban planning interventions.

1.4.2. Specific objectives

The specific objectives of this study are:

- To determine accessibility of taxi transportation to essential services, particularly public schools and healthcare centers.
- To evaluate the spatial equity of taxi transportation accessibility using composite equity rankings, Lorenz curves, and Gini coefficients.
- To identify and interpret spatial disparities in access to opportunities across the city and pinpoint underserved sub-cities and propose planning recommendations for equitable and accessible transportation system development to reach essential services.

1.5. Scope

This thesis focuses on evaluating spatial equity of accessibility of taxi, specifically minibus taxi, mode of transportation from residential areas to public school and health care centers in Mekelle city, the capital of Ethiopia’s Tigray region. Geographically, the analysis concentrates on urban residential areas, subdivided into 500m × 500m grid cells. This spatial granularity allows for fine-scale exploration of how access to essential services varies across neighborhoods, highlighting spatial imbalances often masked at coarser levels.

Thematically, the thesis prioritizes equity of taxi transport accessibility to reach essential opportunities, specifically public healthcare and school by recognizing the dominant role of multi modal transport system, such as minibus taxi, and walking to and from the taxi stations. By emphasizing real-world travel behavior, this thesis seeks to move beyond conventional models and better reflect residents' lived mobility experiences.

Methodologically, the study relies on open-source GIS tools, namely Quantum Geographic Information System (QGIS) to analyze spatial equity of transportation accessibility, SW Maps to track taxi routes and public school and health care opportunity points, and OpenStreetMap (OSM) to supplement road network geometry and to develop a hybrid transport network. Formal road geometry is enhanced with GPS-tracked taxi routes, and walking path to and from taxi stations, travel speeds are incorporated into accessibility calculations. Cumulative opportunity metrics such as opportunity per capita (per 1000 residents) is used to measure and compare access levels across sub-cities.

Spatially, the scope includes multiple sub-cities within Mekelle city, with particular attention to residential areas and neighborhoods. This thesis draws on May 2025 field-collected transport data and up-to-date service location datasets, presenting a snapshot of current accessibility conditions rather than projecting future scenarios.

By defining this clear and bounded scope, this thesis ensures methodological precision and policy relevance, offering planners and decision-makers an actionable blueprint to address spatial inequities in urban service access.

2. Literature review

2.1. General

Transportation serves as a primary driver for economic growth, social integration and environmental responsibility as it touches every aspect of our day-to-day activities by shaping where we reside, work, and learn. It is a vital force in influencing social connections, economic advancement, and environmental responsibility. It opens doors to opportunities and acts as a cornerstone in tackling issues like poverty, joblessness, and inequality (Bullard, 2003). Moreover, it ensures that people can reach essential services such as schools, hospitals, and other public resources. Due to financial constraints and physical barriers, achieving uniform access across all areas is challenging (Alex et al., 2024**).** As a result, some regions will naturally receive more comprehensive services than others.

Transportation accessibility refers to the level of ease with which people can utilize existing transport networks to connect with essential services and opportunities. Equity in transportation of accessibility focuses on ensuring that all individuals, regardless of their difference have fair and just access to transportation resources.

Efficient and accessible transportation systems are fundamental for economic growth and social mobility in developing cities. However, these systems often fail to reach the needs of all residents, particularly low-income communities and marginalized groups. This review aims to explore existing research on this topic by defining and introducing key terms to ensure a shared understanding. Following this, it will explore the methodologies employed and the results obtained in various studies.

2.2. Accessibility

Accessibility is an established concept across various disciplines, but it lacks a singular, universally accepted definition, leading to diverse interpretations depending on the field of study. As cited in Bhat et al. (2000), Batch suggests that the lack of a standardized definition of accessibility presents multiple challenges. One key issue involves distinguishing between accessibility "from" a location and accessibility "to" a location. These ideas correspond to Relative accessibility, which measures the ease of travel between two specific points, and Integral accessibility, which evaluates how well a single point connects to all other points within a given area. These metrics are generally assessed at the zone level in spatial analysis.

Definition of accessibility for this thesis has been taken from Geurs and Wee (2013) definition of accessibility in combination into some other key factors. In this thesis accessibility is defined as "extent to which the land-use and transportation systems enable (groups of) individuals to reach activities or destinations".

Accessibility typically measures the resources like effort, method, or mode of transportation required to reach a specific destination (Lamit et al., 2017).

Equity performance of a transportation system can be evaluated by accessibility outcome. The ability to reach various opportunities, such as jobs, leisure activities, essential services, and social connections, plays a vital part in shaping the total quality of life within a region. (Lamit et al., 2017).

Accessibility, like reaching employment centers, medical services, and other key destinations, illustrates how effectively a transportation system allows individuals to travel to various activities using one or multiple modes of transport. (Mishra & Welch, 2013). The spatial relationship between destination locations and residential areas influences how easily people can access essential opportunities. (Merwe & Jong, 2023).

2.2.1. Components of accessibility

Geurs and Wee (2013) discussed four interconnected elements that affect accessibility directly and through their mutual interactions. These are:

1. Land-use component
2. Transportation component
3. Temporal component and
4. Individual component

The land-use component captures how land is organized and utilized, including the quantity, quality, and geographic spread of opportunities available at various destinations. It also considers the level of demand for these opportunities from different origin points and highlights potential mismatches between supply and demand, which can lead to competition especially for activities with limited capacity.

The Transportation Component captures how the transport system affects an individual's ability to travel between two points using a specific mode of transport. It reflects the overall burden or inconvenience, known as disutility, based on Time Factors **(**includes travel time, waiting time, and parking duration), Cost Considerations **(**covers both fixed expenses like fares and variable like fuel, and maintenance), and Effort and Experience **(**accounts for reliability, comfort levels, and safety risks during the journey. This component helps evaluate how accessible and user-friendly a transport mode is from the traveler’s perspective. This travel inconvenience, or disutility, arises from mismatches between transportation supply, like location and characteristics, and demand, like the passengers.

Temporal Component captures the time-related limitations that affect accessibility. It considers when opportunities (like jobs, services, or events) are available throughout the day and how much time individuals have to engage in these activities. In essence, it highlights how scheduling and personal time windows influence a person’s ability to access and benefit from opportunities.

Individual Component captures how a person's unique traits affect their ability to access transportation and opportunities. It includes needs (influenced by age, income, education level, and household circumstances), abilities (shaped by physical condition and access to transportation options), opportunities (determined by financial resources, travel budget, and qualifications). These personal attributes directly impact how easily someone can reach jobs, services, and other destinations especially if they have the skills or education required for nearby opportunities. Collectively, these factors play a major role in shaping overall accessibility outcomes.

2.2.2. Accessibility measures

A broad collection of accessibility measures exists, characterized by a wide variety of terminology, underlying data sources, practical applications, and computational techniques. As described earlier, accessibility is “extent to which the land-use and transportation systems enable (groups of) individuals to reach activities or destinations”.

Every accessibility measure is built upon two core elements: the attractiveness of location and the impedance required to reach it (El-Geneidy & Levinson, 2006). While attractiveness is typically quantified by the volume of opportunities available at a destination, the impedance function accounts for the friction of travel like distance, cost, or time which naturally reduces the likelihood of that destination being utilized

Any valid accessibility measure should meet the following foundational criteria: (Bhat et al., 2000)

1. **Order Independence** The sequence in which opportunities are listed should not influence the outcome as accessibility metrics must remain unaffected by data order.
2. **Behavioral Consistency** The measure should reflect realistic behavior: it must not increase as travel distance grows, nor decrease when the attractiveness of destinations rises. This aligns with the assumption that destinations offer value (utility), while travel imposes cost (disutility).
3. **Relevance Filtering** Opportunities with no value should be excluded from the calculation. This ensures the measure only accounts for meaningful destinations and relies on accurate coding of attraction data.

Additionally, a well-constructed accessibility measure should capture two key categories of attributes: (Bhat et al., 2000). These includes a Core Components, including travel impedance (such as service quality or travel difficulty) and the attractiveness of destinations or activities, and Disaggregated Attributes, like time of day, transportation mode, activity type, and spatial resolution should also be considered to ensure the measure reflects real-world variability.

2.2.2.1. Approaches to measuring accessibility

There are various methods used to assess accessibility, most of which rely on quantitative techniques. These typically consider features like the structure of the transport system, travel thresholds, opportunity availability, spatial coverage, destination attractiveness, and user behavior (Kumar et al., 2011).

According to Geurs and Wee (2013), accessibility can be evaluated through four primary lenses. These are:

1. Infrastructure-Based accessibility measure
2. Location-Based accessibility measure
3. Person-Based accessibility measure
4. Utility-Based accessibility measure

The infrastructure-based accessibility: measures evaluate how well transportation infrastructure performs by examining factors such as network length and density, traffic congestion levels, and average travel speeds.

Commonly applied in transport planning, this approach helps assess the quality and capacity of the physical transport system. Methodologies for measuring accessibility vary in their scope; some prioritize supply side metrics like infrastructure capacity and network performance, while others integrate demand side factors like needs and population distribution.

There are two accessibility types under this measure (Geurs & Wee, 2013). These are supply-oriented measures and demand-and-supply-oriented measures.

Supply- oriented measures: under this category there are three sub categories. These are:

1. **Network level:** Assess infrastructure features like motorway length or rail network density across regions or countries. But it does not reflect how many destinations or opportunities are actually reachable.

2. **Location Connectivity**: Evaluates how well specific places are linked to transport systems—e.g., proximity to a train station or highway exit. But it is not suitable for comparing different transport modes or considering destination availability.
3. **Network connectivity**: Measures how well nodes (e.g., stations or intersections) are connected to each other, such as centrality or directness of links. It may produce unreliable outcomes in multifaceted networks with many indirect routes.

Demand-and supply- oriented measures: These indicators combine infrastructure performance with actual usage patterns. They assess real-world conditions like travel times on road networks. but it Still is partial, as they do not incorporate land-use data or individual accessibility needs (e.g., number of reachable opportunities).

Location- based accessibility measures

Location-based measures assess accessibility at macro-level by evaluating the distribution of activities across a geographic area. These metrics typically quantify the reach of specific site such as determining the total volume of employment opportunities accessible within thirty-minute commute from a point of origin. There are three accessibility types under this measure (Geurs & Wee, 2013). These are Cumulative opportunity, Potential or Gravity-based accessibility, and Actual accessibility measures.

Cumulative opportunities accessibility measure: measures accessibility by quantifying the total number of destinations reachable from origin within predefined threshold of time, distance, or financial cost; conversely it can also be expressed as the average travel time or expense required to reach a specific, fixed quantity of opportunities (Geurs & Wee, 2013). These measures are relatively easy to interpret by researchers and policy makers as they are undemanding of data and no assumptions are made on a person's perception of transport, land use and their interaction.

As the most straight forward accessibility metric, the cumulative opportunities measure integrates travel distance with specific trip goals and establishes a fixed time or distance boundary or threshold and then calculates the accessibility of geographic area based on the total number of activities located within that limit. (Bhat, et al., 2000). For this measure only information on location of all destinations within desired threshold are needed.

$$A_t = \sum_t O_t ----------------------- Eq. 2.1$$

Where, A_i is accessibility at origin location i, t is the threshold, and O_t is an opportunity that can be reached within that threshold. The measure does not consider opportunities over selected threshold.

The main limitation of a cumulative-opportunities measure is its lack of behavioral component and it fails to recognize the distance decay effect that closer and distant opportunities are treated equally (Bhat et al., 2000).

Potential or gravity- based accessibility measure: estimate accessibility by quantifying the opportunities at various destinations while applying a distance decay function which accounts the fact that the influence of an opportunity diminishes as the distance from origin (Geurs & Wee, 2013). This metric applies a distance decay factor to potential destinations, ensuring that distant opportunities have a proportionally smaller impact on the overall accessibility score (El-Geneidy & Levinson, 2006).

The standard formulation of this model involves an attractiveness coefficient that is weighted against spatial impedance which is typically raised to a specific exponent to reflect the rate of distance decay (Bhat et al., 2000). Implementing this measure requires data on the magnitude and geographic distributions of attractions along inter-zonal travel times or distances. By placing spatial impedance in the denominator of the formula these measures apply a distance -decay effect that systematically reduces the value of distant destinations unlike to cumulative-opportunity measures.

Researchers use various methods to determine the value of the parameter in the impedance function. The most common form used is the exponential form. The cumulative opportunity measure can be thought of as the case where this factor, α, equals zero.

$$A_i = \sum_j \frac{O_j}{{t_{ij}}^{\alpha}} ------------------------ Eq. 2.2$$

Where, A_i is accessibility at origin location i, O_j is the attractiveness of destination j, t_{ij} is the travel time or distance between location i and j and α is the distance decay exponent.

This method combines two key elements: an attraction factor, representing the appeal or value of destinations, and a separation factor, reflecting the time or distance between origin and destination (Bhat et al., 2000). It applies a continuous function that gradually reduces the weight of opportunities the farther they are from the starting point, capturing how accessibility diminishes with increased travel effort.

Bhat et al., (2000) states that there are three main components of gravity model that researcher’s model differently. These are the characterization of zones attractiveness, impedance measure between zones (example; time or distance), and the form of impedance function. For example, when assessing accessibility to employment the attractiveness of the zone can be modeled as the number of jobs in a zone.

Actual accessibility measure: quantify travel time, distance, or costs by weighting them against the empirical volume of trips occurring between origins and destinations primarily used to analyze the competitiveness of various transport modes. This approach needs high resolution data regarding real world spatial travel behavior and movement patterns.

Person- based accessibility measure

Person- based accessibility measure analyzes accessibility at the individual level, for instance the activities in which an individual can take part at a given time.

Space–time approach: is rooted in the principles of space time geography and evaluates accessibility by accounting for both geographic and temporal limitations by assessing the range of activities a person can realistically complete based on their specific schedule and personal constraints (Geurs & Wee, 2013).

Utility- based accessibility measure

As Geurs and Wee (2013) stated utility- based accessibility measure originally routed in economic theory evaluates accessibility by calculating the economic or qualitative advantages individuals gain from reaching various spatial activities.

2.2.2.2. Matrix of accessibility components and measures

Geurs and Wee (2013) presented a matrix of different accessibility measures and components at table 2 that presents a matrix of the different accessibility measures and components. As shown in the table infrastructure-based metrics exclude land-use factors, meaning they fail to reflect shifts in destination locations as long as travel speeds or costs stay the same. In contrast, temporal constraints are the primary focus of person-based measures, whereas other models either ignore time or only address it indirectly through peak-hour data. While person- and utility-based models examine accessibility at the individual level, location-based models operate at a macro scale, specializing in the spatial limitations of opportunity supply, a factor often overlooked by the other methodologies.

Table 1: Types of accessibility measures and components (*Geurs and Wee,2013)*

Measure	Component			
	Transport component	Land-use component	Temporal component	Individual component
Infrastructure - based measures	Travelling speed: vehicle hours lost in congestion		Peak-hour period; 24-hour period	Trip-based stratification, e.g. home-to work, business
Location-based measures	Travel time or costs between locations of activities	Amount and spatial distribution of the demand for and/or supply	Travel time and costs may differ, e.g. between days of the week or season	Stratification of the population (e.g. by income, educational level)
Person-based measures	Travel time between locations of activities	Amount and spatial distribution of supplied	Temporal constraints for activities and time available for activities	Accessibility is analyzed at individual level
Utility-based measures	Travel costs between locations of activities	Amount and spatial distribution of supplied opportunities	Travel time and costs may differ, e.g. between hours of the day, between days of the week, or season	Utility is derived at the individual or homogeneous population group level

Note that: the blue shading represents primary focus and the nonshaded part represents non-primary focus.

2.2.3. Factor that affects accessibility

As Kumar et al, (2011) states accessibility measures are very sensitive and they are sensitive to the following factors.

- **Transportation needs and abilities**: refers to the gap between the travel people want to do and the travel they actually capable of doing
- **Land use factors**: how the density, variety, and physical layout of a city dictate where activities are located.
- **Constraints**: the impact of laws and impedance which includes everything from financial costs to linguistic or cultural divides
- **Transportation options**: The quantity and quality of transport modes and services available in a particular situation.
- **Affordability**: transport mode diversity that are affordable enough for basic daily access.

- **Spatial Scale**: the specific levels of analysis of a region or a city and how it aligns with policy goals.
- **Equity**: the fairness of how accessibility is distributed among different neighborhoods
- **Dynamics**: the dynamic way cities change over times as populations and economies shift. And
- **Integration**: how well different transport modes are linked to the destination they serve.

2.2.4. Selecting an accessibility measure

The selection of an appropriate accessibility metric depends on specific evaluative criteria tailored to the study's objectives. This section describes the measures that are the most appropriate to use as accessibility measures to analyze the equity of accessibility of taxi and walking to and from stations, transport services to education and health care centers in Mekelle city. This thesis adapted some of the criteria from Geurs and Wee's (2013) work for selecting accessibility measure that is guided by four primary factors: first, the purpose of the study, which dictates the scope and direction of the analysis; second, scientific quality, ensuring the measure captures the interplay between transport, land-use, time, and individual needs; third, operational feasibility, which accounts for data availability and budget constraints; and finally, interpretability and communicability, which ensures the results are clear enough to influence urban policy and decision making.

Based on the above four criterions, in order to capture a more complete picture of accessibility, this thesis have used both cumulative and gravity-based measures. The cumulative measure offers a clear and intuitive way to assess accessibility by counting the number of opportunities, such as jobs, schools, or services, reachable within a fixed time or distance threshold. This makes it especially useful for policy analysis and planning, as it highlights areas with limited access in a straightforward manner. However, it does not account for the varying influence of distance or travel time on user behavior. To address this limitation, it has also incorporated the gravity-based measure, which applies a continuous decay function to weigh opportunities based on their proximity. This approach reflects the behavioral reality that people are less likely to travel to distant destinations, even if they are technically reachable. By combining both methods, this thesis provides a richer, more nuanced understanding of accessibility that balances simplicity with behavioral sensitivity, and supports more equitable and informed decision-making.

The cost parameter in the gravity measure is computed between each population grid cell and different urban activities through a multimodal network in a GIS-based framework.

2.2.5. The use of QGIS in accessibility analysis

Geographic Information Systems (GIS) have become vital tools in spatial accessibility research, enabling the combination of transport networks, land use data, and demographic information to evaluate how easily individuals can reach desired destinations. Among open-source platforms, QGIS stands out for its flexibility, cost-effectiveness, and extensive plugin ecosystem, making it a popular choice for both academic and applied accessibility studies.

GIS technologies have enabled researchers to model and visualize accessibility with increasing precision. Higgs (2005) emphasized the potential of spatial models to pinpoint underserved areas and guide resource allocation, these GIS-based methods have informed public health planning globally, though mostly within formal transport systems and high-income settings.

QGIS supports a wide range of spatial analysis techniques, including network analysis, raster modeling, and isochrone generation, which are essential for calculating accessibility metrics. The platform's ability to integrate diverse datasets such as GTFS feeds, census data, and field-verified GIS layers makes it particularly effective for multi-zonal and equity-focused studies. Ghosh and Shivani (2025) employed QGIS to assess accessibility and equity across three urban zones in India, using isochrone mapping and Accessibility Gini coefficients to reveal disparities in transit frequency, fare burden, and pedestrian infrastructure. Their methodology demonstrates how QGIS can support replicable, evidence-based policy insights in transport planning.

Moreover, QGIS's open-source nature encourages reproducibility and transparency in research. As noted in the QGIS documentation (QGIS.org, 2025), the software supports scripting through Python and integration with external plugins, which facilitates customized accessibility models tailored to specific urban contexts.

Besides, QGIS facilitates both cumulative and gravity-based accessibility measures. Karner et al., (2024) highlight how QGIS can be used to model opportunity-based access while incorporating behavioral assumptions through impedance functions. This dual capability allows researchers to capture both absolute and perceived accessibility, which is critical for understanding spatial equity.

Despite its strengths, QGIS does face limitations. Compared to proprietary platforms, it may require more manual configuration and lacks built-in advanced transport modeling tools. However, its open-source nature encourages transparency and reproducibility, and its growing plugin ecosystem continues to address these gaps.

In summary, QGIS provides a strong and adaptable framework for accessibility analysis, particularly in urban and transport planning. It's open-source architecture, combined with powerful spatial analysis tools, makes it a valuable resource for researchers seeking to model accessibility in a transparent and cost-effective manner.

2.2.6. Use of SW Maps in taxi route and opportunity point data collection

Nowadays, mobile GIS applications have become increasingly important in transportation research, particularly for collecting geospatial data in real-time and in resource-constrained environments. Among these tools, SW Maps has emerged as a practical and accessible platform for mapping transport routes and identifying opportunity points such as schools, markets, and health facilities. Its open-source nature, offline capabilities, and user-friendly interface make it especially suitable for fieldwork in developing urban contexts.

SW Maps allows users to record GPS tracks, tag locations, and collect attribute data through customizable forms and it is easy to share the collected data in standard GIS formats like KMZ, shapefiles, GeoJSON, GeoPackages, and also as spread sheets. This functionality has made SW Maps to be compatible when working with GIS. For example, A research demonstrated how SW Maps mobile GIS can support spatial equity analysis by linking transport routes to key urban services (Tadesse & Alemu, 2023). They used SW Maps to map taxi routes in Addis Ababa, enabling the visualization of service coverage and identification of underserved areas.

The platform’s offline functionality is particularly advantageous in regions with limited internet access. SW Maps enable uninterrupted data collection in remote urban zones, maintaining spatial accuracy and reliability (Gebremariam & Tesfaye, 2024). This feature supports longitudinal studies and enhances the feasibility of transport research in areas with infrastructural constraints.

While SW Maps excels in data collection, it lacks advanced spatial analysis tools found in desktop GIS platforms. Researchers often export collected data to QGIS or ArcGIS for further processing and modeling.

In summary, SW Maps offers a strong and cost-effective solution for collecting taxi route and opportunity point data as its GPS tracking, customizable forms, and offline capabilities make it a valuable tool for transport researchers aiming to understand spatial accessibility and service distribution in urban environments.

2.3. Equity

Equity and equality are related concepts often discussed in the context of fairness and justice, but they have distinct meanings. While equality is distributing resources equally, equity involves tailoring the amount and type of resources to ensure solutions meet the diverse needs and preferences of different groups. Equity emphasizes a “people-first” approach focusing on access to opportunities and dismantling systemic inequalities through transportation (Stacy et al., 2020).

Equity refers to the aim of reducing inequalities and is closely linked to principles of justice, fairness, and social balance (Bruzzone et al., 2023). Equity in the transportation sector has been extensively explored and is frequently associated with concepts like accessibility and social cohesion. However, these notions are not entirely synonymous, and their definitions often vary and overlap, leading to conceptual ambiguity. This lack of clarity poses challenges for effectively integrating equity objectives into transport planning and decision-making processes.

2.3.1. Transportation equity

Research on equity in the transport sector is extensive and is frequently understood in terms of accessibility and social cohesion (Bruzzone et al., 2023). As cited in their study, Foth et al. (2013) referred to a definition of equity as: equity planning focuses on expanding options for individuals with limited choices, this concept is highly relevant as policy makers must balance between delivering the most efficient service for the majority of users and extending coverage to less-populated areas to ensure broader accessibility.

Similarly, Stacy et al., (2020) defined transportation equity as the practice of making mobility-related decisions through inclusive and thoughtful engagement with communities. This approach ensures that transport systems and land use planning promote public health, environmental sustainability, and fair access to essential services and opportunities for all individuals (Stacy et al., 2020).

Examining equity

Equity is commonly examined through two primary lenses: horizontal equity often associated with fairness and egalitarianism and vertical equity which related to social justice, environmental justice, and social inclusion (Litman, 2024). Horizontal equity is concerned with providing equal resources to individual or groups considered equal in ability and need, which means the public policies avoid favoring one individual or group over another. Horizontal equity ensures equal distribution of resources among groups with similar needs, while vertical equity focuses on addressing disparities by allocating additional support to disadvantaged populations. Vertical equity can be assessed through ‘equity of opportunity,’ measured by access to services, or ‘equity of outcome,’ evaluated by actual usage across groups.

Litman (2024) states the best way to include equity in to planning requires clear, measurable objectives. Horizontal equity emphasizes fair distribution of resources and minimizing external costs, while vertical equity focuses on inclusivity, affordability, and social justice. Together, these principles ensure that public policies both distribute resources fairly and prioritize disadvantaged groups.

2.3.2. Transportation equity measures

Transportation equity measures are policies, strategies, or tools designed to ensure fair and just access to transportation resources and services for all individuals, particularly those in underserved or marginalized communities. These measures aim to address disparities in transportation access, affordability, safety, and environmental impact ensuring that everyone can benefit from transportation systems regardless of income, race, age, disability, or geographic location.

Implementing an equity measure requires careful consideration of three key elements: first, clearly specifying the benefit or burden under evaluation, to ensure the selected metric accurately represents what is being measured; second, establishing precise criteria, to differentiate between population groups or spatial zones; and third, determining the appropriate equity standard, (whether horizontal or vertical) that best aligns with the objectives of the study (Martens et al., 2019).

Choosing what to measure is a crucial step in evaluating transport equity, as different conceptual approaches can reveal varying patterns of inequality within society. As noted by Martens et al. (2019), four key dimensions can guide this assessment: available resources, access to opportunities or exposure to risks, achieved outcomes, and overall wellbeing. Each offers a distinct lens through which equity can be understood and addressed.

Table 2: Examples of equity indicators for measuring mobility/ accessibility (Martens et. al., 2019)

Possible equity measure	Possible operationalization	Possible disaggregation
Ownership of transport means	Average number of cars in household	by income group
	Average number of bicycles in household	by ethnic group
Public transport availability	Number of buses stops within 400 m walking distance	by neighborhood
		by ethnic group
Walkability	Area that can be reached within a ten minutes' walk	by age
Access to local parks	Number of parks that can be reached safely on foot within a ten minutes' walk	by age
		by gender
Access to jobs	Number of jobs that can be reached within 30 minutes travel time	by mode availability
		by neighborhood
Access to health care	Number of health clinic that can be reached within 15 minutes travel time	by age
		by neighborhood
Trip frequency	Average number of trips per day per person	by gender
Trip distance	Total trip distance per week per household	by income

		by gender
Transport costs	Percentage of income spend on travel per year	by income
Number of activities	Average number of out-of-home activities per week per household	by income
		by ethnicity
Satisfaction with vehicle ownership	Self-reported satisfaction with ownership of a motor vehicle	by income
Enjoyment of travel	Self-reported satisfaction with travel	by primary mode of transport
Enjoyment of activities	Self-reported satisfaction with participation in (out-of-home) activities	by gender

- **Methods of evaluating transportation equity**

The way equity is conceptualized and measured significantly influences evaluation outcomes. Since transportation equity cannot be assessed through a single method, it is most effective to examine it from multiple perspectives and dimensions. A practical strategy is to establish a set of clearly defined, measurable equity objectives (Litman, 2024). A wide range of research methodologies has been applied in the study of transportation equity. As Yan and Howe (2020) describes, transportation equity methods differ in purpose, strengths, and limitations so the choice depends on research goals, and combining approaches often yields more comprehensive results.

As Litman (2024) describes equity strategies are generally divided into two types: programmatic approaches, which provide targeted benefits to specific groups, and structural approaches, which reform planning practices to create more inclusive, affordable, and efficient transportation systems.

Transportation equity centers on two key issues: accessibility inequality, where certain groups consistently face reduced access to opportunities, and accessibility poverty, where individuals lack sufficient access to essential services needed for a dignified life (Alex et al., 2024).

The way opportunities and social groups are distributed across space plays a key role in explaining why disparities persist among users of the same transport mode in different areas. This influence is evident not only in the impedance functions used to estimate accessibility across income levels, but also in expenditure-related variables. These variables highlight how certain motorized transport options, such as public transit and private vehicles can enhance accessibility, especially for individuals with lower incomes.

2.3.3. Transportation equity analysis

The way equity is conceptualized and assessed can greatly influence the outcomes of an analysis (Litman, 2002). In transportation studies, evaluating outcomes at the individual level is often impractical due to population size, complex travel behavior, and privacy constraints. Equity is therefore commonly assessed by comparing outcomes among groups defined by spatial factors such as residence, work, school, or other activities.

Transportation planning is experiencing a paradigm shift that redefines how problems are framed and solutions are assessed (Litman, 2024). This shift moves from a mobility-focused approach, which measures system performance primarily through vehicle travel speeds and indicators such as roadway level of service (LOS) and congestion delays, to an accessibility-oriented perspective. The new framework emphasizes that the ultimate purpose of travel is to reach services and activities, with accessibility shaped not only by vehicle travel but also by the quality of non-automobile modes, network connectivity, urban density, and affordability.

Guo et al., (2020) apply a clearly defined spatial unit as the basis of analysis, using aggregated population counts to evaluate both horizontal and vertical equity. They generalized existing methods of transportation equity in to three-step frame work consisting of population measurement, cost-benefit assessment and inequality evaluation.

Accessibility's equity analysis frequently emphasizes ensuring fundamental access for individuals who are physically, economically, or socially disadvantaged (Raza & Zhong, 2018). In many communities, individuals who own and can afford to operate a vehicle generally face few difficulties in reaching essential services such as healthcare, shopping, education, employment, and social or recreational activities

Greater mobility tends to enhance accessibility, while limitations like traffic congestion and transportation costs can hinder it. However, accessibility is also shaped by other elements, such as how close essential services and destinations are (for example, the distance between residential areas, public facilities, and workplaces) (Raza & Zhong, 2018).

Ensuring equitable distribution of transportation resources is essential for improving access to key activity locations such as employment, healthcare, and shopping centers. Low-income and socially disadvantaged groups, who primarily rely on public transport, are most affected. Therefore, analyzing the availability of opportunities within a region requires careful evaluation of how public transport services are distributed.

Luis et al., (2017), assessed vertical equity by comparing accessibility to work and study opportunities across the population. They illustrated this by plotting accessibility levels against population percentiles to reveal disparities among income groups.

2.3.4. Visualizing and quantifying equity in spatial context

Spatial equity is an essential concern in urban planning and infrastructure development emphasizing the fair distribution of resources and opportunities across different populations, hence it is grounded in principles of distributive justice, focusing on accessibility to opportunities and services. Spatial equity assessment requires integrating spatial syntax with socio-economic indicators to capture both physical and social dimensions of accessibility (Garau et al., 2025).

In order to quantify spatial equity several quantitative measures can be used. For example, accessibility metrics like cumulative and gravity-based measures can be used to evaluate service accessibility (Geurs & Wee, 2013), statistical equity measures like Gini coefficient and Lorenz curves can be used to quantify the in equality in service distribution (Karner et al., 2024), other composite indices can also enable multi-dimensional assessment other than single variable.

The Lorenz curve and Gini coefficient tools have been increasingly applied to spatial equity studies beyond income analysis. For example, they were used to examine population distribution across regions, revealing significant disparities between urban and rural areas (Siddiq et al., 2023). Their work demonstrates the adaptability of these measures to geographic contexts, where they can be used to assess access to infrastructure, public services, and transport networks.

The Gini coefficient was also applied to evaluate the fairness of accessibility to facilities across different income groups (Tahmasbi et al., 2019). Other studies have also applied it to assess the equity of service distribution and user accessibility. More broadly, it is recognized as a standard statistical measure of inequality, most commonly used to examine how income or resources are distributed across a nation's population. The Lorenz curve illustrates the cumulative distribution of income or resource across the cumulative population arranged by ascending income share (Lucas et al., 2016).

In transport equity research, the Gini coefficient is often used to quantify disparities in accessibility. For example, Zhu and Rui (2025) applied a multi-scale spatiotemporal framework to evaluate urban rail accessibility by calculating Gini values across different zones and time periods, they identified persistent inequalities in access to metro services, particularly in peripheral districts.

Similarly, Luis et al., (2017) applied the Lorenz curves and Gini are employed to analyze accessibility disparities, helping to reveal how variations in service coverage, as well as social, economic, and geographic factors influencing travel choices, shape the distribution of accessibility across urban and metropolitan areas.

In transport equity, Karner et al., (2024) emphasized the utility of Gini and Lorenz-based methods in identifying accessibility inequality and accessibility poverty. They argued that these measures can reveal systemic disadvantages faced by low-income and marginalized groups, especially when access to essential services is unevenly distributed. However, they also cautioned that these tools may oversimplify complex social dynamics unless paired with context-sensitive indicators.

Although the results of Gini coefficient are influenced by the specific indicator selected for analysis, its scale independent behavior is its key strength as its results is not affected when the unit measurement is changed (Lucas et al., 2016).

2.3.5. Accessibility per capita as a lens for measuring transport equity

As cities grow and diversify, the need for equitable access to opportunities becomes increasingly urgent. One metric gaining importance in transport equity research is accessibility per capita, which evaluates how many opportunities, such as jobs, schools, or health services, are reachable by each individual within a given area. This population-normalized measure offers a nuanced lens for assessing spatial justice, especially in urban environments marked by socioeconomic disparities.

Accessibility per capita builds on foundational accessibility theory, which considers the interaction between land use, transport systems, and individual characteristics. Unlike raw accessibility counts, per capita measures normalize access by population, allowing for more meaningful comparisons across zones with varying densities. Van Wee (2022) emphasizes that equity in accessibility should be evaluated not only by absolute levels but also by how access is distributed among individuals, aligning with ethical principles such as sufficientarianism and egalitarianism.

Similarly, Luis et al. (2017) applied accessibility per capita in to assess disparities in access to employment and education. Their findings revealed that low-income populations had significantly lower accessibility per capita, especially when dependent on traditional public transport. This approach highlighted how transport infrastructure and land-use decisions can reinforce social inequalities.

Correspondingly, Mazzulla and Pirrone (2024) classify accessibility metrics into passive and active categories, placing per capita measures within the passive group. These metrics do not account for individual preferences but are valuable for large-scale equity assessments, particularly in transport planning and policy analysis. Similarly, Ghosh and Shivani (2025) extended this analysis by evaluating accessibility across urban zones by using accessibility per capita alongside the Accessibility Gini coefficient to reveal steep gradients in opportunity access.

Moreover, accessibility per capita has been integrated into GIS-based equity evaluations, allowing planners to visualize disparities through spatial mapping. When combined with Gini and Lorenz analyses, it provides a strong framework for both quantifying and visualizing equity in urban environments.

2.3.6. Composite equity metrics

In order to account for both straightforward opportunity counts and realistic distance-decay effects, a composite index can be developed by integrating cumulative and gravity-based accessibility measures with per-capita normalization (Palacios & El-geneidy, 2022).

Aggregate measures of accessibility often conceal inequities by focusing only on total opportunity counts. Evaluating accessibility on a per capita basis is therefore crucial to highlight distributional fairness, ensuring that rankings capture residents' actual experiences rather than just area-wide totals (Geurs & Wee, 2013).

Integrating cumulative thresholds, gravity-based metrics, and per capita normalization into composite accessibility indices helps minimize the impact of parameter selection and aggregation bias, thereby improving both fairness and the policy relevance of spatial equity assessments (El-Geneidy & Levinson, 2006).

Generally, Combining and normalizing diverse accessibility measures into a composite index reflects best practice in transport equity research, as it addresses the shortcomings of individual metrics and offers a more comprehensive view of how opportunities are distributed (Geurs & Wee, 2013; El-Geneidy & Levinson, 2006).

3. Materials and Methods

3.1. Data sources and preprocessing

This thesis utilized a combination of spatial and tabular datasets to model transportation accessibility, from residential areas to public health care and school, and assess spatial equity of taxi transportation system to reach the opportunities across Mekelle's sub-cities. It uses both primary and secondary data. The secondary spatial data included road networks from OpenStreetMap (OSM), population data from the Mekelle city planning and finance office, and administrative boundaries for sub-cities from Mekelle land mines bureau. Crucially, primary data like the locations of public educational facilities (primary and secondary schools) and health care centers were collected through field surveys using SW Maps, a mobile GIS application that enabled accurate geotagging and attribute recording of service points. These field-collected datasets were validated for completeness and spatial accuracy before integration into the analysis.

All spatial layers were reprojected to a common coordinate system, UTM Zone 37N, to ensure consistency in distance-based calculations. Residential origin points were generated by extracting centroids from populated polygons. The road network was cleaned to remove disconnected segments and ensure topological integrity, which was essential for accurate impedance modeling. Facility layers were enriched with categorical attributes such as school level and health center type to support sector-specific accessibility analysis.

Preprocessing was conducted in QGIS 3.42.0, where all spatial data were harmonized and prepared for cumulative and gravity-based accessibility modeling. The integration of field-collected facility data with validated population and network layers ensured that the analysis was grounded in accurate, context-specific spatial information. This robust data foundation enabled the generation of reliable accessibility surfaces and equity metrics that informed the subsequent analysis and policy recommendations.

3.2. Tools used

The analysis employed a blend of mobile-based field mapping and desktop geospatial tools to evaluate accessibility of taxi transport mode to public schools and healthcare centers across Mekelle. SW Maps, a GPS-enabled data collection application, was used to capture real-world taxi routes and geolocate healthcare and school facilities, enabling a grounded representation of both origin mobility and destination points. These field-tracked paths were instrumental in building a hybrid road network that reflects actual movement dynamics, rather than relying solely on theoretical routing assumptions.

OpenStreetMap provided foundational base map layers and was used to supplement road network geometry and context. Its open, editable format allowed integration with field-collected data to validate and refine urban mobility routes, especially in underrepresented zones.

For the core spatial analysis, QGIS version 3.42.0 served as the main platform, supporting workflows such as the creation of 500m × 500m grid cells to represent residential blocks, generation of origin-destination matrices for travel time estimation, computation of cumulative and gravity-based accessibility measures, and calculation of opportunity-based metrics using the Field Calculator. Advanced symbology tools facilitated the visualization of accessibility ranks and spatial disparities, while the Layout Designer was used to visualize choropleth maps and equity dashboards.

Microsoft Excel was employed as a complementary analytical tool to support the interpretation and visualization of accessibility metrics derived from QGIS. After computing cumulative and gravity-based accessibility scores in QGIS, the results were exported to Excel for further statistical processing. Sub-city level averages were calculated using built-in functions to summarize accessibility performance across sub-cities. These averages formed the basis for ranking sub-cities, enabling comparative equity assessments across sectors.

Additionally, Microsoft Excel was also used to compute the percentage share of cumulative accessibility, by dividing each sub-city’s accessibility score by the total accessibility across all sub-cities. These percentages were essential for constructing Lorenz curves. The curves were generated using scatter plots with cumulative values sorted in ascending order, allowing visual interpretation of equity patterns.

Microsoft Excel’s formula capabilities and cell referencing were used to automate these Gini coefficient calculations across sectors. Additionally, bar charts were created to visualize sub-city rankings. These visualizations improved the clarity of equity findings and supported narrative synthesis in the Results and Policy Recommendations sections.

3.3. Data preparation

This thesis utilized a combination of spatial and tabular datasets to model accessibility and assess spatial equity across Mekelle’s sub-cities. It incorporates both primary and secondary data to ensure a comprehensive and contextually grounded analysis.

3.3.1. Secondary data

This thesis adopts a quantitative research approach, relying on secondary data to evaluate spatial equity in taxi transport accessibility to essential opportunities. The analysis integrates geospatial techniques and equity metrics including the Gini coefficient, Lorenz curve, and accessibility per capita to assess disparities in access to opportunity points such as public schools, and health centers. Secondary data were sourced from a range of reputable platforms.

To establish a reliable basis for taxi route tracking, first key destinations served by minibus taxis along with associated fares and distances obtained from the Mekelle transport bureau was compiled as shown in annex I. These records provided origin and destinations of taxi routes, and length in kilometers of the taxi route which helped later in geolocating the taxi routes using SW Maps. This foundational dataset offered structured insight into the spatial dimensions of taxi mobility. By anchoring taxi route tracking in real-world fare zones and trip lengths, SW Maps was leveraged to log GPS coordinates of actual taxi movements, enabling validation and refinement of taxi routes.

The base map and sub-city boundaries used in this thesis were obtained from the Mekelle land and mines bureau as shown in annex II and III. These official datasets provided accurate administrative divisions and spatial context essential for mapping and analysis. Incorporating data directly from the Mekelle land and mines bureau ensures reliability and aligns the study with current urban planning frameworks. This foundational layer supported the integration of accessibility measures, equity metrics, and opportunity distribution within clearly defined spatial units.

To ensure up-to-date spatial coverage, Google Satellite imagery was also utilized in this thesis. While the base map acquired from the Mekelle land and mines bureau provided essential administrative boundaries, it lacked several newly developed residential areas and recently constructed roads. By integrating high-resolution satellite imagery from Google, the analysis was able to capture these additions accurately, enhancing the reliability of accessibility mapping and opportunity assessment. This approach allowed for more precise delineation of built-up areas and supported the creation of a comprehensive hybrid road network.

OpenStreetMap (OSM) served as the foundational source for road network geometry, offering detailed vector data on primary, secondary, and tertiary roads, as well as footpaths and intersections. The OSM data was downloaded and topologically cleaned to support network-based routing and multimodal travel time estimation as shown in annex IV.

Public healthcare facility numbers and locations were taken from Mekelle zonal health office. These records provided names and their sub-cities which helped later in geolocating the healthcare centers as shown in annex V.

Schools that are found in Mekelle city were taken from Tigray Education Bureau. These records provided the names of the governmental schools that are found in Mekelle city as shown in the annex VI, which helped later in geolocating the schools using SW Maps.

Population data was obtained from Mekelle city planning and finance office. These records provided population size for each of the sub-cities as shown in the annex VII which later used to derive per capita accessibility metrics. Together, these secondary data sources ensured consistency, enhanced spatial coverage, and allowed for normalization of access metrics by population, strengthening the study's equity assessment.

All datasets were processed and analyzed using QGIS. Non-spatial datasets were georeferenced using coordinate matching and administrative boundaries, while data cleaning procedures were applied to address duplicates, missing values, and inconsistencies. Multiple layers including population, transport routes, and opportunity points were integrated to build a comprehensive spatial accessibility model.

The use of secondary data was justified by its cost-effectiveness, broad temporal coverage, and scalability across multiple urban zones. While secondary data offer extensive coverage, limitations such as outdated records and spatial resolution inconsistencies were mitigated through triangulation with field-verified data from SW Maps and google satellite imagery. This methodological framework ensures a strong and replicable analysis of transport equity in the Ethiopian urban context.

3.3.2. Primary data

To complement the secondary data analysis, this study incorporates primary data collection to capture real-time, location-specific insights into urban transport accessibility and equity. Primary data were essential for validating spatial models, identifying informal mobility patterns, and enriching the analysis of opportunity points and transport routes in the study area.

Primary data for this thesis were collected through SW Maps, field-based GPS taxi route tracking and geolocate schools and healthcare facility locations. Using SW Maps, a mobile GPS application, taxi routes were recorded by tracing actual taxi travel paths across Mekelle's urban road network using taxi. This data provided fine-grained spatial traces of commonly used transport corridors and allowed the construction of a road network that reflects taxi routes. Additionally, public healthcare centers, like hospitals, clinics, and health centers, and public schools like primary and secondary schools were geolocated directly using SW Maps in the field. This ensured the precise spatial placement of opportunity points, especially for facilities not well-documented in secondary datasets. The real-world tracking and direct mapping of destinations helped anchor the analysis in observed transport dynamics and avoid reliance on assumptions or incomplete institutional data. This high-resolution primary dataset enabled a more accurate calculation of travel times and accessibility metrics, particularly in zones where conventional transport data is sparse or outdated. In general, all datasets underwent careful preprocessing to ensure analytical accuracy and spatial integrity.

3.3.3. GIS-Based data preparation workflow

The GIS-based data preparation process was essential for ensuring the accuracy and analytical integrity of the accessibility modeling. Public school and health care facility locations that were collected through field surveys using SW Maps were exported in shapefile format and imported into QGIS 3.42.0 as shown in appendix A and B for further processing. Road network data were sourced from OpenStreetMap (OSM) and filtered to retain walkable segments relevant to and from taxi stations. The network layer was cleaned to remove disconnected paths and ensure topological consistency, which was critical for distance-based analysis. The base-map and sub-city boundaries that were taken from the Land Mines Bureau was also imported in shape file and raster format in to QGIS 3.42.0.

All spatial layers were reprojected to a common coordinate system, UTM Zone 37N, to maintain consistency in spatial calculations. Administrative boundary shapefiles for Mekelle's sub-cities were used to aggregate accessibility scores and visualize equity metrics.

The prepared datasets were then used to compute both cumulative and gravity-based accessibility measures. This workflow ensured that all spatial inputs were clean, harmonized, and analytically strong, forming a reliable foundation for the subsequent equity analysis and policy interpretation.

- **Residential origin layer preparation**

In this thesis, hexagonal grid cells with sides of 500 meters were selected to represent residential areas due to their geometric advantages and analytical consistency in spatial modeling using QGIS as shown in appendix C. Hexagon grids offer uniform distance between cell centroids and neighbors, minimizing directional bias and improving the accuracy of spatial connectivity analysis. Each hexagon has six equidistant neighbors, which enhances the representation of movement patterns and accessibility, especially in urban contexts where travel occurs in multiple directions. Additionally, hexagonal grids are more compact and closer to circular shapes, resulting in a lower perimeter-to-area ratio. This reduces edge effects and sampling distortion, making them ideal for visualizing continuous spatial phenomena such as population density or accessibility scores. These properties make hexagonal gid particularly suitable for equity analysis, where subtle spatial variations in access to services must be captured with precision and clarity. To implement a hexagonal grid system in QGIS for spatial analysis, the horizontal and vertical spacing was defined between the centers of adjacent hexagons. These values depend on the side length (s) of each hexagon.

As Patel (2025) tries to illustrate, as shown in the Figure 1 below in a regular hexagonal grid, each hexagon is offset horizontally by equation 3.1:

$$h = \frac{3}{2} * s - Eq. 3.1$$

This accounts for the fact that each hexagon shares sides with two neighbors horizontally, and the centers are spaced 1.5 times the side length apart.

Similarly, the vertical spacing depends on the height of the hexagon, which is illustrated by equation 3.2:

$$v = \sqrt{3} * s - Eq. 3.2$$

This is derived from the geometry of equilateral triangles forming the hexagon. It ensures that the rows of hexagons are staggered properly to maintain uniform coverage (Patel, 2025).

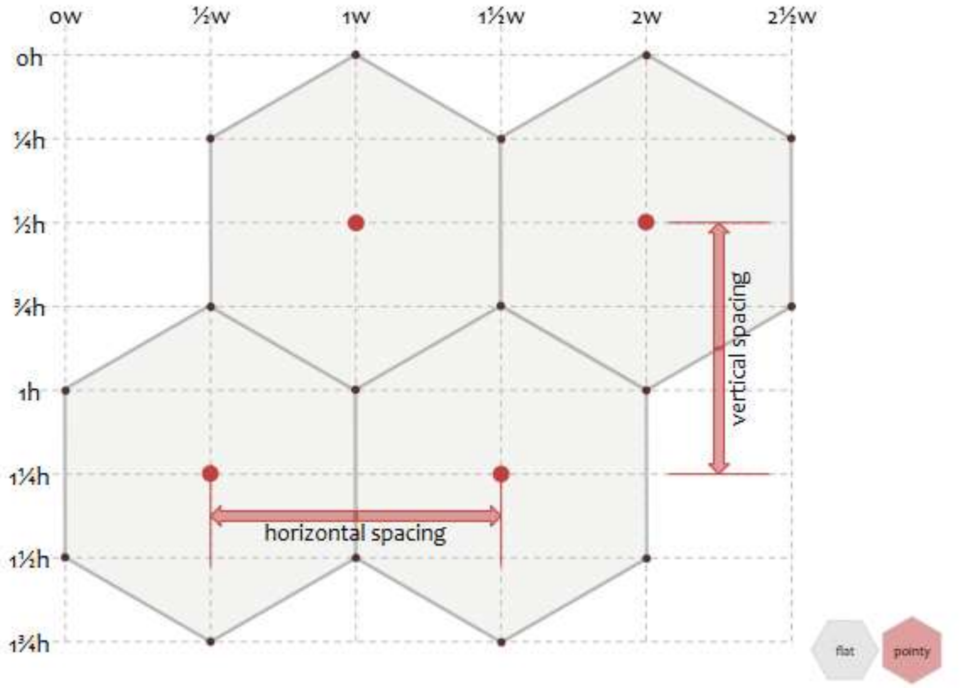

Figure 1: Horizontal and vertical spacing of hexagonal grid cells (Patel, 2025)

This approach ensures spatial consistency and fine-grained coverage across Mekelle city. The grid was generated using QGIS and overlaid onto Google Satellite imagery to visually confirm alignment with built-up residential areas, especially in locations where the Mekelle land and mines bureau base-map lacked recent development updates. After validation, each grid cell acted as a proxy for a residential block, providing evenly distributed origin points across the study area. The centroids of these cells were extracted and used as origin locations for calculating travel times to opportunity centers (school and health care centers).

- **Opportunity destination layer preparation**

To prepare the opportunity destination layer, GPS-based field data collection was conducted using SW Maps for both public schools and healthcare facilities. This ensured high spatial accuracy and inclusion of newly established or previously unmapped facilities. For each opportunity point, whether a school or healthcare center, geotags were verified against satellite imagery and OpenStreetMap entries to check for alignment and remove duplicates. The dataset included various facility types, such as primary schools, secondary schools, hospitals, clinics, and health centers. Each point underwent topological validation using QGIS tools ('Check Validity', 'Fix Geometries') to ensure integrity and compatibility with routing networks.

To support routing analysis, facilities located off-network or in disconnected areas were snapped to the nearest traversable road segment using the ‘Snap Points to Lines’ tool. Attribute tables were enriched with relevant details of facility name and ID to enable disaggregated equity assessments. These finalized layers served as destination inputs in OD Matrix calculations and as anchors for accessibility and opportunity-per-capita visualizations in the equity analyses. The prepared layers formed the core of opportunity-per-capita metrics used for equity visualization in subsequent mapping and statistical analyses.

- **Road network data preparation**

To construct an accurate and navigable road network for taxi transport accessibility analysis, multiple data sources and processing steps were integrated. The base road geometry was initially extracted from OpenStreetMap, offering a comprehensive spatial layout of major and minor roads across the study area. However, to reflect real-world travel dynamics, the GPS-tracked taxi routes collected via SW Maps were incorporated as dedicated taxi-only paths as shown in Appendix D.

Taxi station points were created using QGIS for each of 500 meters. Using QGIS’s OD Matrix plugin, travel times were calculated from each origin centroid to all taxi station points, and from destinations (schools and health care facilities) to all taxi station points to simulate walking only paths. From the OD Matrix results only the fastest paths were taken. And these fastest path results were taken as the walking only paths.

Fragmented paths and overlaps were corrected using Snap Geometries to Layer, Intersection, and Delete Duplicate Geometries tools in QGIS. Field-collected taxi tracks from SW Maps were merged with this network using the Merge Vector Layers function, producing a hybrid routing system that reflects both pedestrian paths and actual taxi route paths.

The walking-only paths and GPS-tracked taxi routes were combined into a unified transport road network using the “Merge Vector Layers” tool in QGIS as shown in Appendix E and F. This step facilitated the integration of multimodal mobility options by consolidating separate layers into a single dataset, enabling seamless routing analysis through the OD Matrix plugin.

- **Road network cleaning**

Before routing analysis, the network was subjected to topological validation to eliminate disconnections and ensure seamless connectivity. Tools such as Snap Geometries to Layer were used to align road endpoints and eliminate minor gaps, while Intersection, Difference, and Delete Duplicate Geometries functions resolved overlapping features and redundant segments. Loops, dangles, and misaligned intersections were corrected manually and through topology checker to prevent broken routes during OD matrix calculations.

Prior to multimodal routing and opportunity calculations, the raw road network required extensive cleaning to ensure spatial and topological integrity. The walking path and taxi paths were first evaluated using QGIS's 'Check Validity' and 'Topology Checker' tools to identify errors such as overlapping segments, gaps, and self-intersections. Disconnected road sections were resolved by applying the 'Snap Geometries' and ‘Fix Geometries’ tool with a calibrated tolerance value, ensuring endpoints and junctions aligned across adjacent features.

The refined network was then validated by overlaying on satellite imagery and base maps that was taken from Mekelle land and mines bureau, confirming both spatial coverage and modal realism. This cleaning process was essential for generating accurate OD matrices and opportunity accessibility surfaces across Mekelle city.

- **OD Matrix setup**

To evaluate accessibility across residential origins and opportunity destinations, the OD Matrix plugin in QGIS was configured to simulate multimodal travel scenarios. Prior to setup, a cleaned and connected road network was prepared by merging GPS-tracked taxi routes and walking paths into a unified layer. Separate speed profiles were defined for each mode: pedestrian segments were assigned a speed of 4 km/h, while taxi-only paths used a speed of 30 km/h, reflecting real-world travel behavior. The residential origin layer, served as the input origin points. Schools and healthcare facilities were designated as opportunity destinations. Fastest path was used as optimization criterion and Matrix geometry follows the routes was used as the generated matrix geometry style. The OD Matrix plugin calculated direct travel times and reachable destinations for each origin under both walking and taxi scenarios. Outputs included travel time surfaces and count-based accessibility metrics, which were later used to generate equity maps and rank sub-cities by opportunity access. This setup ensured a realistic and spatially inclusive assessment of accessibility across the study area.

- **Fastest path extraction**

To identify the most time-efficient travel routes in a multimodal urban transport setting, fastest paths were extracted directly from the OD matrix results generated via QGIS's Network Analysis tools. The hybrid road network layer, comprising both pedestrian and taxi-accessible routes, was first assigned mode-specific travel speeds (4 km/h for walking, 30 km/h for taxi) to support realistic routing. OD matrix results included travel durations between origin grid centroids and selected destinations. The travel durations were converted into minute by dividing it by 60. Then using the 'Select Features by Expression' functionality in QGIS, the fastest path for each origin-destination pair was isolated by identifying records with least travel time values. These selected records which represented optimal routes based on mode-specific speed assumptions and network topology were saved as fastest path to health care centers, fastest path to primary schools, and fastest path to secondary schools from the OD matrix from origin to healthcare centers, OD Matrix from origins to primary schools, and OD Matrix from origin to secondary schools respectively. The extracted paths were then visualized and validated against observed travel patterns and taxi GPS traces to ensure routing fidelity. This approach enabled granular analysis of accessibility, highlighting route disparities across neighborhoods and transport modes.

This setup enabled the identification of optimal routes for each origin-destination pair, facilitating the calculation of minimum travel times across the network. As shown in appendix G, H, and I only paths with a least duration were retained for further analysis, forming the basis of accessibility, and per capita metrics. By grounding routing logic in actual speed profiles and street-level geometry, the fastest path extraction ensured that accessibility measurements were both context-sensitive and reflective of real-world travel behavior.

3.4. Accessibility modeling

To deliver a comprehensive assessment of spatial equity in accessibility of public school and health infrastructure, this thesis employed both cumulative and gravity-based measures of accessibility. Each method offers distinct analytical strengths. The cumulative measure evaluates access based on the number of facilities reachable within a defined threshold (e.g., distance or travel time), making it particularly effective for identifying service deserts and quantifying minimum access levels. In contrast, the gravity-based measure incorporates both proximity and facility attractiveness (e.g., capacity or service quality), weighted by distance decay, thereby capturing the nuanced influence of spatial interaction and competition among origins and destinations.

Using both methods allow for a more strong and multidimensional understanding of accessibility. While cumulative metrics highlight binary access gaps (served vs. underserved), gravity-based metrics reveal gradations of accessibility intensity and spatial advantage. This dual approach ensures that both threshold-based equity and continuous spatial influence are accounted for, enabling more precise identification of priority zones and informing targeted policy interventions. The integration of these measures enhances the validity of the equity analysis and supports more inclusive infrastructure planning.

3.4.1. Cumulative accessibility calculation

Cumulative accessibility was measured by counting the total number of primary and secondary schools, and healthcare facilities reachable from each residential origin within a thirty-minute travel time threshold. Using statistics by category plugin, opportunity count thirty minutes were computed from the fastest path from origins to healthcare facilities, fastest path from origin to primary schools, and fastest path from origin to secondary schools. Next, by using Join attributes by field value tool was applied linking aggregated destination statistics back to the origin grid based on unique cell IDs. This enriched origin layer captured the quantity of accessible services, supporting detailed choropleth mapping and comparative equity assessments of origins across sub-cities. By quantifying categorical accessibility and joining results spatially, the approach offered a fine-grained and equitable lens for evaluating transport-based opportunity reach.

To assess equity across sub-cities, cumulative accessibility scores were normalized by population for each origin to obtain per capita accessibility aggregated at sub-city level, to plot Lorenz curve, to calculate Gini coefficient and visualized using choropleth maps and grouped bar charts.

3.4.2. Gravity-based accessibility calculation

To assess spatial accessibility for both healthcare and school services, gravity-based models were applied independently, with equal weights assigned to all destination facilities due to the lack of detailed capacity data (such as bed counts for health care centers or enrollment numbers for schools). Therefore, raw scores were used for ranking and equity analysis without additional weighting, as all opportunity points were assumed to be equally attractive.

$$A_i = \sum_{j=1}^{n} \frac{1}{c_{ij}^{\beta}} ----------------------------- Eq. 3.3$$

Where: C_{ij} is the travel cost (travel time) from origin i to destination j, and β is the distance decay parameter, set to 1.5 in this study to moderately penalize distant facilities.

For public healthcare centers, the gravity accessibility score for each origin was calculated by summing the inverse of the travel cost raised to a decay parameter (β = 1.5) between residential grid centroids and mapped healthcare facilities. These travel costs were derived from an origin-destination (OD) matrix constructed using a hybrid multimodal network that integrated walking paths with real-world taxi routes collected via SW Maps.

In parallel, public-school accessibility was assessed using a similar formulation, with destinations representing geolocated public educational institutions such as primary schools, and secondary schools. Separate OD matrices were built to avoid mixing healthcare and education networks, ensuring specificity in routing patterns and travel cost surfaces. The resulting gravity scores were normalized by population at each origin point to generate per capita accessibility values. These values were then aggregated at the sub-city level to reveal spatial disparities and were visualized through choropleth maps, and bar charts to facilitate comparative interpretation between sub-cities and across service types.

Similar to cumulative accessibility scores gravity accessibility scores were also normalized by population for each origin to obtain per capita accessibility aggregated at sub-city level, to plot Lorenz curve, to calculate Gini coefficient and visualized using choropleth maps and grouped bar charts to assess equity across sub-cities.

3.5. Spatial units and aggregation procedure

The accessibility analysis that was initially conducted using $500\,\mathrm{m} \times 500\,\mathrm{m}$ grid cells representing residential blocks had 558 total grid cells. From these blocks only 257 grid cells were identified as predominantly residentials only. These residentials grid cells served as origin points from which opportunities such as primary schools, secondary schools, and healthcare facilities calculated using a hybrid transport network. This approach allowed for high-resolution measurement of accessible opportunities at a micro-spatial level.

Once accessibility from each origin cell was determined, spatial aggregation was performed by assigning each residential grid cell to its respective sub-city boundary. This enabled the computation of sub-city-level metrics, including opportunity accessibility, and opportunity per capita. The aggregation process preserved the granularity of origin-level access patterns while aligning results with administrative units, facilitating equity assessments and targeted planning interventions.

3.6. Equity metrics: Opportunity per capita, Lorenz curve, and Gini coefficient

To evaluate spatial equity in Mekelle city taxi transport systems, this thesis employs a set of quantitative equity metrics that capture both the distribution and intensity of access to urban opportunities. The selected indicators, Opportunity Per Capita, Lorenz Curve, and Gini Coefficient, offer complementary perspectives on how transport infrastructure and land-use patterns affect different population groups or zones.

To normalize accessibility across varying population densities, this thesis applied the Opportunity Per Capita metric. Accessibility scores were normalized by population to produce per capita values, allowing for equity-sensitive comparisons across sub-cities. This was computed by dividing the total number of reachable opportunities within each sub cities by the population residing in each sub-cities and multiplying by one thousand for cumulative-based measure of accessibility in order to show how many opportunities are reachable per one-thousand people within a thirty-minute time threshold. Cumulative-based opportunity per capita helps to highlight raw service gaps.

In the same way, the gravity-based opportunity per capita is computed by dividing the sum of gravity-based accessibility by the population residing in each sub-cities and multiplying by one thousand in order to reflect weighted access (based on time decay) per one-thousand people. Gravity-based opportunity per capita captures behavioral realism and equity together. The resulting values provide a per one-thousand-person measure of access, enabling fair comparisons between densely populated urban cores and sparsely populated peripheral zones. Sub-cities with high opportunity accessibility but large populations may score poorly on per capita metrics, exposing potential service strain. This metric is particularly useful for identifying underserved areas where transport infrastructure may be insufficient relative to population needs.

To assess the equity of accessibility distribution across sub-cities, Lorenz curves and Gini coefficients were also computed for public primary schools, secondary schools, and health care centers independently. The Lorenz curve was constructed by first sorting sub-city-level accessibility data in ascending order of accessibility scores. For each sub-city, cumulative population shares and cumulative accessibility shares were calculated by dividing the running totals by the overall population and total accessibility, respectively. These normalized values were plotted with cumulative population share on the x-axis and cumulative accessibility share on the y-axis. The equity line, representing perfect equality, was included as a reference diagonal from (0,0) to (1,1).

The Gini coefficient was derived from the Lorenz curve using the trapezoidal rule for numerical integration. Specifically, the coefficient was calculated by equation 3.4:

$$G = 1 - \sum_{i=1}^{n} (X_i - X_{i-1})(Y_i + Y_{i-1}) ----------------- Eq. 3.4$$

where X_i and Y_i represent the cumulative population and accessibility shares respectively at each interval. This method ensures accurate estimation of the area under the Lorenz curve. All calculations of the equity metrics were performed using Microsoft Excel and validated through manual cross-checking to ensure consistency and accuracy.

Together, these metrics form a strong framework for evaluating spatial equity in urban mobility. By combining normalized indicators (Opportunity Per Capita), and distributional tools (Lorenz Curve and Gini Coefficient), the methodology ensures a comprehensive assessment of how transport systems serve different population groups.

3.7. Equity visualization

To effectively communicate spatial disparities in transport accessibility, this thesis employs a series of equity visualizations that translate quantitative metrics into spontaneous, map-based representations. These visualizations serve as critical tools for identifying underserved areas, comparing accessibility across population groups, and supporting evidence-based planning decisions.

The visualizations were developed using QGIS which enabled the integration of multiple spatial layers including population density, transport routes, and opportunity points. The core equity metrics, Opportunity Accessibility, Opportunity Per Capita, Lorenz Curve, and Gini Coefficient, were spatially linked to residential areas at sub-city level, allowing for detailed geographic analysis.

Choropleth maps were generated to display opportunity access levels across sub-cities, using classification modes quantile to highlight disparities. Additionally, bar charts were produced to rank sub-cities by opportunity access, enabling direct comparison of equity gaps. Bar chart visualizations were employed to compare opportunity per capita against sub cities identifying sub-cities with high facility counts but large populations may score poorly exposing potential service strain. These visualization outputs helped uncover spatial inequalities and guided interpretation of multimodal transport performance in relation to urban equity objectives.

4. Results and Discussions

4.1. Accessibility analysis

This section presents the analytical framework used to evaluate spatial accessibility to public school and healthcare opportunities across Mekelle city. To capture the full range of spatial accessibility across Mekelle's sub-cities, both cumulative and gravity-based measures were analyzed and visualized.

By visualizing both measures side by side, this thesis provided a multidimensional understanding of spatial equity. The cumulative maps offered clarity on threshold-based access, while gravity-based maps revealed continuous spatial influence. This dual approach strengthened the interpretation of Lorenz curves and Gini coefficients, ensuring that both absolute service gaps and relative accessibility advantages were accounted for in the equity assessment.

4.1.1. Cumulative accessibility

This section presents the results of the cumulative accessibility analysis, which evaluates the number of public schools and healthcare opportunities reachable within a defined travel threshold, thirty-minutes, from all origin points across Mekelle city. By treating each opportunity within the thirty-minute threshold equally this measure highlights zones of absolute access and identifies areas with limited-service coverage.

4.1.1.1. Accessibility to public primary and secondary schools

The spatial accessibility to primary and secondary schools via multimodal transport, walking to and from taxi stations and taxi mode of transport, revealed notable variations in service reach across sub-cities. Cumulative-based measures highlighted the absolute number of reachable opportunities, effectively identifying underserved zones based on service count. From 257 residential blocks only 105 residential bocks are served, access primary schools within thirty-minute travel time, and only 56 residential blocks are served, access secondary schools within thirty-minute travel time.

The opportunity counts of each sub-cities and the number of origins within each sub-cities were used to calculate the percentage of accessibility from residential areas to the primary and secondary schools as shown in the Table 3 below.

Table 3: Percentage of accessibility of primary and secondary schools

Sub city	Total number of Origins	Number of Accessible primary Schools	Percentage of accessible primary Schools	Number of Accessible Secondary Schools	Percentage of Accessible Secondary Schools
Hadnet	62	29	46.8	11	17.7
K/Weyane	9	9	100.0	4	44.4
Adihaki	6	4	66.7	4	66.7
Hawelti	26	24	92.3	10	38.5
Ayder	54	28	51.9	19	35.2
Quiha	72	2	2.8	4	5.6
Semien	37	9	24.3	4	10.8

The percentage of cumulative accessibility highlights spatial equity of taxi route transportation accessibility to primary and secondary schools as shown in Table 3 above, and it is further visualized by using the bar chart in Figure 2 below.

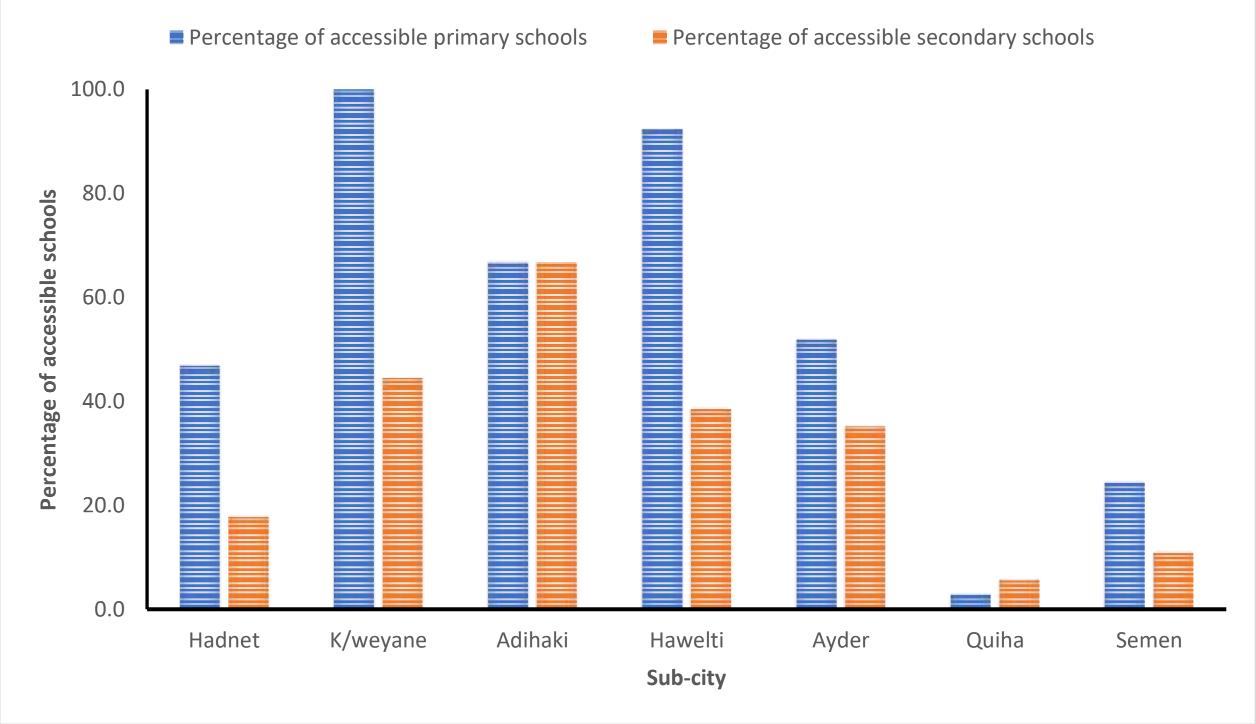

Figure 2: Percentage of accessibility of primary and secondary schools

The analysis revealed large contrasts in primary and secondary schools accessibility across the seven sub-cities of Adihaki, Ayder, Hawelti, Kedamay Weyane, Quiha, Semien, and Hadnet. Accessibility was assessed using cumulative measure of accessibility.

The cumulative accessibility analysis reveals substantial variation in the percentage of accessible schools across Mekelle sub-cities. For primary schools, Kedamay Weyane leads with 100% accessibility, followed by Hawelti (92.3%) and Adihaki (66.7%). Hadnet and Ayder show moderate access levels at 46.8% and 51.9%, respectively, while Semien (24.3%) and Quiha (2.8%) rank lowest, indicating significant spatial gaps. In contrast, secondary school accessibility is markedly lower than primary schools across all sub-cities except for Adihaki that ranks highest with 66.7%, followed by Kedamay Weyane (44.4%) and Hawelti (38.5%). Ayder (35.2%), Hadnet (17.7%), Semien (10.8%), and Quiha (5.6 %) show limited access, underscoring a pronounced accessibility gap in secondary school. These results highlight the need for targeted taxi route planning, particularly in sub-cities like Semien and Quiha, where both primary and secondary school access remains critically low.

Overall, the computation of accessible public primary and secondary schools independently helps to understand the spatial taxi transport accessibility disparities across the sub-cities clearly. These findings underscore the need for targeted infrastructure expansion, improved transport connectivity, and equitable facility distribution to bridge gaps in access to public primary and secondary schools using multi modal transportation system.

4.1.1.2. Accessibility to public healthcare centers

The spatial accessibility to public healthcare centers using multi modal transport system, taxi and walking to and from taxi stations, displays pronounced unevenness across sub-cities, shaped by facility distribution, transport network integrity, and residential density. Using multimodal transport modeling, combining walking from and to taxi stations and taxi-route paths, accessibility scores were calculated for each origin, reflecting both travel time and reachability. Cumulative-based measures highlighted the absolute number of reachable opportunities, effectively identifying underserved zones based on service count. From 257 residential blocks only 56 residential blocks are served, access health care centers within thirty-minute travel time.

The opportunity counts of each sub-cities and the number of origins within each sub-cities were used to calculate the percentage of accessibility from residential areas to health care centers as shown in Table 4.

Table 4: Percentage of accessibility of health care centers

Sub city	Total number of origins	Number of Accessible health care centers	Percentage of accessible health care centers
Hadnet	62	11	17.7
K/weyane	9	4	44.4
Adihaki	6	2	33.3
Hawelti	26	5	19.2
Ayder	54	16	29.6
Quiha	72	9	12.5
Semien	37	9	24.3

Generally, the percentage of accessible health care centers for all sub-cities is less than 45%. But compared to the other sub-cities Kedamay-Weyane sub-city emerged as highly accessible, with 44.4% of its origins reachable within 30-minute travel time to the nearest healthcare facility. This was largely due to its central location, and hybrid road connectivity. In contrast, peripheral zones like Quiha sub-city experienced accessibility deficits: only 12.5% of cells exceeded the 30-minute threshold, exposing critical gaps in taxi route proximity and transport connectivity. Sub-cities like Adihaki with 33.3%, Ayder with 29.6%, Hawelti with 19.2%, Semien with 24.3%, and Hadnet with 17.7% of their origins are accessible to their nearest healthcare centers within the 30-minute threshold.

4.1.2. Gravitational accessibility

Gravitational accessibility incorporates both the quantity of opportunities and their spatial proximity, using a decay function to weight closer opportunities more heavily. This approach reflects the intuitive notion that nearer facilities are more likely to be utilized. By applying this measure to all residential origin points, the analysis captured the overall spatial pull of public school and healthcare services across Mekelle city, highlighting zones of high opportunity per capita and efficient spatial distribution.

To assess equity more precisely, gravitational accessibility was calculated using only residential origin points. This ensures that the analysis reflects the lived experience of residents rather than including non-residential zones. By comparing this measure with the cumulative accessibility measure at sub-city level, disparities in access between sub-cities can be identified, offering critical insights into spatial justice and the targeting of underserved communities.

These findings emphasize that equitable public school and healthcare accessibility planning demands a multi-dimensional strategy; balancing facility count, location efficiency, and transport reach. Priority sub-cities identified here would guide future investments, ensuring resource allocation aligns with population density, access gaps, and transport feasibility.

Together, these measures provide a multi-dimensional view of public school and healthcare facility accessibility, balancing simplicity, spatial realism, and equity sensitivity. The following sections detail the results of each measure and explore their implications for equitable urban planning.

4.1.2.1. Accessibility of residential origins to public primary schools

The gravity-based accessibility analysis reveals significant disparities in how origins across Mekelle's sub-cities access public primary schools using taxi transport system as shown in the Figure 3 below and the results of gravitational accessibility are present in appendix G for each of the origins.

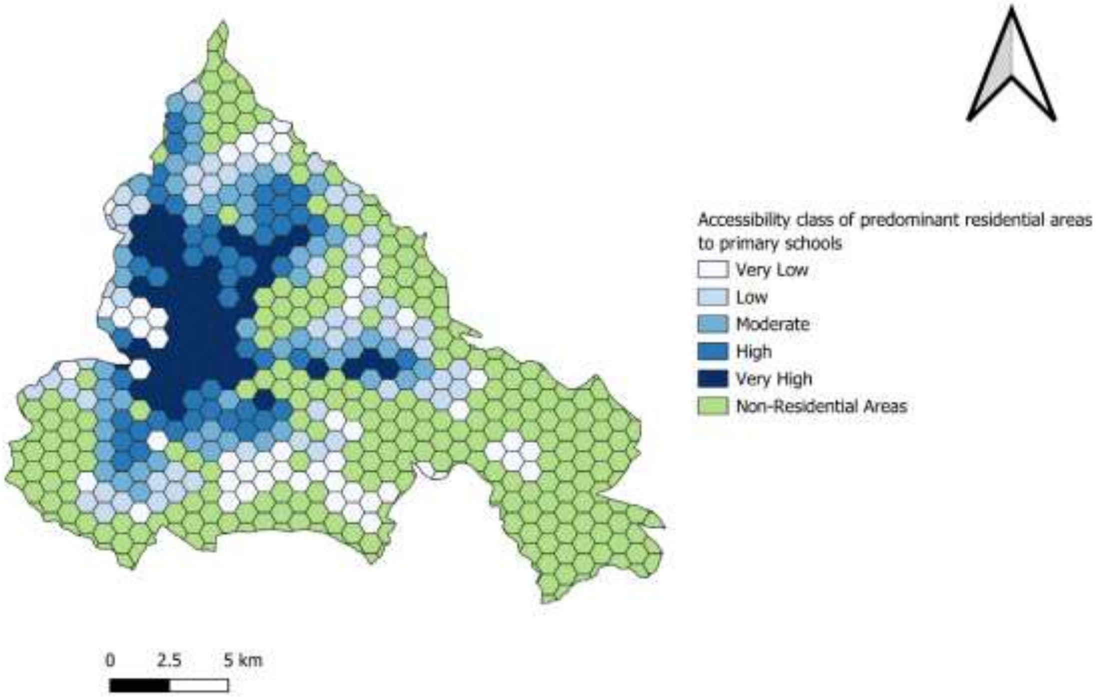

Figure 3: Accessibility of residential areas to public primary schools

The above figure illustrates the spatial distribution of public primary school accessibility across Mekelle using a gravity-based measure. Each hexagon represents a spatial unit of analysis, with darker blue shades indicating higher accessibility scores, lighter blue shades representing lower accessibility and green shaded hexagon represents non-residential areas. The gravity model accounts for both the proximity of schools and their density relative to residential origins, offering an important view of functional access.

The map reveals clear spatial clustering of high accessibility zones in western part of the sub-cities. These areas are characterized by dense public-school networks that are located near taxi routes, resulting in strong gravitational pull and high accessibility scores. High-accessibility clusters in central part of the sub-cities reflect planning decisions that have historically favored densely populated urban cores. These areas benefit from both infrastructural concentration near the taxi routes and transport connectivity, enabling efficient access to primary school.

In contrast, peripheral areas of the sub-cities exhibit widespread areas of low accessibility, with lighter blue hexagons dominating the spatial landscape. These zones are marked by greater distance between origins and taxi routes and schools that are located far from taxi routes, leading to diminished access. The spatial dispersion of schools, combined with limited proximity to transport routes and walkable paths, reduces the gravitational influence of existing facilities. This pattern reinforces the findings from tabular analyses and equity metrics, confirming that physical presence alone does not guarantee functional access.

From a policy perspective, the above map serves as a powerful diagnostic tool for identifying underserved areas and guiding targeted interventions. It supports the case for redistributive infrastructure planning, emphasizing the need to expand taxi transport networks to public-school in low-access areas and improve last-mile connectivity. By visualizing accessibility as a spatial gradient rather than a binary condition, the gravity-based map helps translate technical findings into actionable insights for equitable urban development.

Generally, the above figure is summarized in the Table 5 by calculating the percentage of origins in each sub-cities that are found within each accessibility class category.

Table 5: Percentage of accessibility class of sub-cities to primary schools using gravity-based accessibility measure

Gravity index	Accessibility class	Percentage of accessibility of residential origins to primary school in each sub-city						
		Hadnet	K/Weyane	Adihaki	Hawelti	Ayder	Quiha	Semien
0 - 0.007	Very low	1.6	0.0	16.7	23.1	0.0	9.7	0.0
0.007- 0.012	Low	0.0	0.0	0.0	0.0	0.0	16.7	0.0
0.012- 0.021	Moderate	16.1	0.0	0.0	3.9	29.6	29.2	18.9
0.021-0 .0382	High	32.3	12.5	0.0	15.4	29.6	33.3	24.3
0.0382 - 0.189	Very high	50.0	87.5	83.3	57.7	40.7	11.1	56.8

Sum		100	100	100	100	100	100	100

By categorizing gravity index values into five accessibility classes as Very High, High, Moderate, Low, and Very Low the percentage distribution of origins within each sub-city was examined. The results show that Adihaki, and Kedamay-Weyane stand out with the highest shares of origins in the Very High accessibility class. Specifically, Adihaki has 83.33% and Kedamay-Weyane has 87.5% of origins in the Very High accessibility class category. These sub-cities benefit from dense school networks and favorable proximity and taxi transportation accessibility, resulting in strong gravitational pull.

In contrast, Quiha demonstrate considerable accessibility deficits. It has 26.39% of origins in the Very Low and Low accessibility class and 44.44% in the High, and Very High category, while Adihaki shows a similar pattern with 83.33% of origins in the Very high class and 16.67 % of origins in the very low accessibility class. Similarly, Hawelti sub-city also has 57.69% of origins that fall under very high accessibility class and 23.1 % of origins that fall in to very low accessibility class. These figures suggest that some of residents in these areas face substantial barriers to accessing primary schools, either due to long travel distances or location of primary schools far from taxi routes. On the other hand, Hadnet and Semien present more balanced distributions moderate shares across all classes, with Hadnet showing more than 82.26% of origins in the High and Very high accessibility class category.

The gravity-based results underscore the spatial inequities embedded in Mekelle's educational infrastructure. Kedamay-Weyane sub-city benefit as the primary schools are located near the taxi routes. The high percentage of origins in the Very High and High accessibility classes in this sub-city suggests that residents enjoy relatively easy access to primary education.

Conversely, the predominance of Low and Very Low accessibility scores in Quiha, Hawelti, Adihaki, and Hadnet highlights the challenges faced by peripheral parts of the sub-cities. Despite the presence of schools, their spatial inefficiency, due to their spatial detachment from taxi transport networks. In these areas, the majority of origin points are located far from established taxi routes and disconnected walkable paths, which significantly increases travel impedance and reduces the effective reach of nearby facilities. The gravity-based model penalizes such distance, resulting in low accessibility scores even when schools are technically present within the broader sub-city boundary. This disconnect between infrastructure and mobility networks means, and pedestrian paths and taxi routes that residents face compounded barriers: not only are schools distant, but the lack of proximate transport options and pedestrian connectivity further diminishes their functional accessibility. Addressing these gaps requires not only facility placement but also strategic improvements in last-mile connectivity and pedestrian infrastructure being located far from residential clusters, that diminishes their functional accessibility. The gravity model's sensitivity to distance and reveals these shortcomings more sharply, offering a deep understanding of how accessibility is experienced across the urban landscape.

From a policy perspective, these findings point to the need for targeted interventions in underserved sub-cities. Accessibility-sensitive planning approaches; such as gravity-weighted demand mapping can guide future taxi route defining to ensure equitable access. Establishing minimum accessibility thresholds may also help prevent any sub-city from having a majority of origins in the Very Low class. Ultimately, the gravity-based accessibility measure serves not only as a diagnostic tool but also as a strategic guide for equity-sensitive educational planning in Mekelle.

4.1.2.2. Accessibility of residential origins to secondary schools

The following map illustrating gravity-based accessibility to secondary schools reveals a distinct spatial pattern across Mekelle city. Each hexagon represents a spatial unit, with darker blue shades indicating higher accessibility scores, lighter blue shades representing lower values, and green shades representing non-residential areas. The gravity model integrates both the proximity of secondary schools to taxi routes and their density relative to residential origins, offering a refined measure of functional access.

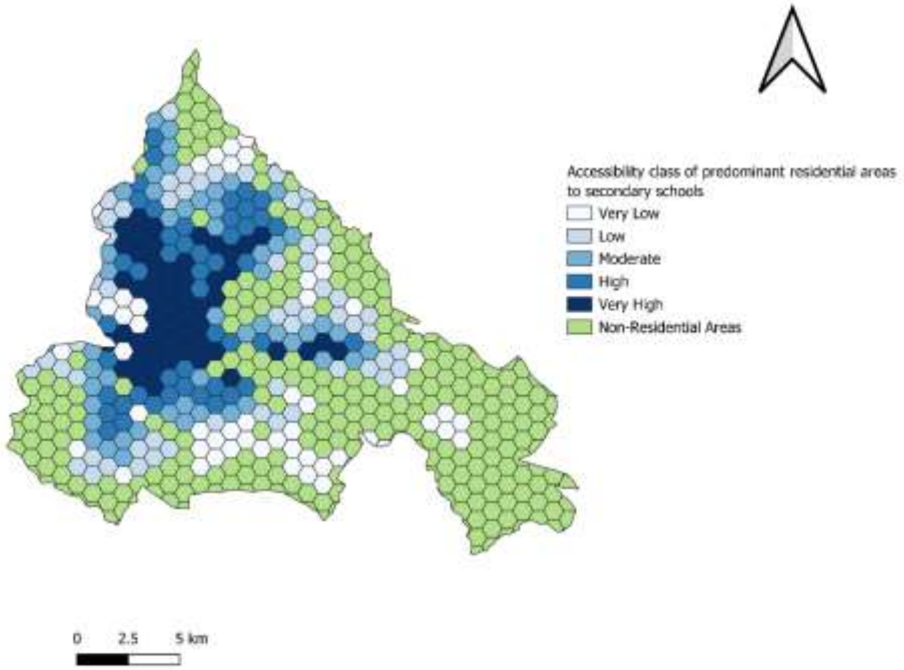

Figure 4: Accessibility of residential areas to secondary schools

High-accessibility zones are concentrated in sub-cities such as Adihaki, Kedamay-Weyane, Hawelti, Ayder and Hadnet, where a significant proportion of origins fall into the dark blue hexagons. These areas benefit from compact urban form and strategic placement of secondary schools near taxi routes. These areas are well-served not only by the presence of schools but also by their integration into the surrounding transport and pedestrian networks.

In contrast, peripheral areas of sub-cities exhibit widespread areas of lighter blue hexagons dominating the map. These regions are characterized by sparse facility distribution and greater distances between taxi routes and origins or schools, resulting in diminished gravitational influence. Despite the presence of secondary schools in some cases, their spatial inefficiency being located far from residential origins and disconnected from major taxi routes limits their functional accessibility. The gravity model's sensitivity to both distance and facility clustering reveals these shortcomings more sharply reinforcing the need for equity-sensitive planning.

Generally, Figure 4 is summarized with Table 6 below by calculating the percentage of origins that are found within each accessibility class category. The gravity-based accessibility analysis for secondary schools reveals a similarly uneven distribution of access across Mekelle's sub-cities, though with distinct patterns compared to primary schools. Using the same gravity index classification; Very High, High, Moderate, Low, and Very Low the percentage of origins falling into each category was calculated for every sub-city as shown in the Table 6 below.

Table 6: Percentage of accessibility of origins to secondary schools using gravity-based accessibility measure

Gravity index	Accessibility class	Percentage of accessibility of residential origins to secondary schools in each sub-city						
		Hadnet	K/Weyane	Adihaki	Hawelti	Ayder	Quiha	Semien
0 - 0.002	Very low	1.6	0.0	16.7	23.1	0.0	9.7	0.0
0.002 - 0.004	Low	0.0	0.0	0.0	0.0	0.0	16.7	0.0
0.004 - 0.008	Moderate	4.8	0.0	0.0	0.0	13.0	20.8	5.4
0.008 - 0.0172	High	50.0	25.0	0.0	19.2	46.3	44.4	40.5
0.0172 - 0.164	Very high	43.6	75	83.33	57.7	40.7	8.3	54.1

From the Table 6 above although Adihaki sub-city has favorable results of very low accessibility class, it has a substantial share of origins in the very high accessibility class categories; Adihaki, and Kedamay-Weyane sub-cities, emerge as the most accessible sub-cities, with 83.3%, and 75%, of origins respectively falling into the Very High accessibility class. Similarly, Hawelti sub-city also perform well with 76.9% of the residential origins falling under the High and very high accessibility class categories. Semen and Hadnet sub-cities also perform well, with more than 93% of origins in the Very High, and High category of accessibility class, indicating broad coverage and proximity-weighted access. Semien, and Ayder show moderate accessibility, with 54.1% and 40.74% of the origins in the very high category and 40.5% and 46.3% of the origins categorized in the high category of accessibility with 0% accessibility share in the low and very low category, suggesting partial infrastructural gaps.

In contrast, Quiha shows significant accessibility challenges, with only 8.3% of origins in the Very High class and 44.4% in high, with notable shares in the moderate, low and very low accessibility class reflecting spatial isolation and poor gravitational pull from existing facilities. Quiha and Hadnet sub-cities present more mixed profiles, with moderate shares of origins in both high and low accessibility classes, reflecting partial infrastructural coverage.

The gravity index's sensitivity to both distance and facility clustering provides a more refined lens, revealing how spatial configuration directly impacts functional access. These findings call for targeted interventions: expanding transportation accessibility to secondary school infrastructure in underserved sub-cities by improving pedestrian and taxi transport connectivity, and prioritizing equitable facility placement in future planning.

From a policy standpoint, the map visualization serves as a diagnostic tool for identifying underserved zones and guiding targeted interventions. Expanding secondary school infrastructure in low-access areas, improving last-mile connectivity, and aligning facility placement with residential demand are critical steps toward achieving spatial equity. By visualizing accessibility as a continuous spatial gradient, the gravity-based map translates technical findings into actionable insights for inclusive educational planning.

4.1.2.3. Accessibility of residential areas to health care centers

The following map visualizing gravity-based accessibility to health care centers reveals distinct spatial patterns across Mekelle's sub-cities. Each hexagon represents a spatial unit, with darker blue shades indicating higher accessibility scores, lighter blue shades reflecting lower values and green shades reflecting the non-residential areas. The gravity model accounts for both the proximity of health care centers and their density relative to residential origins, offering a detailed measure of functional access.

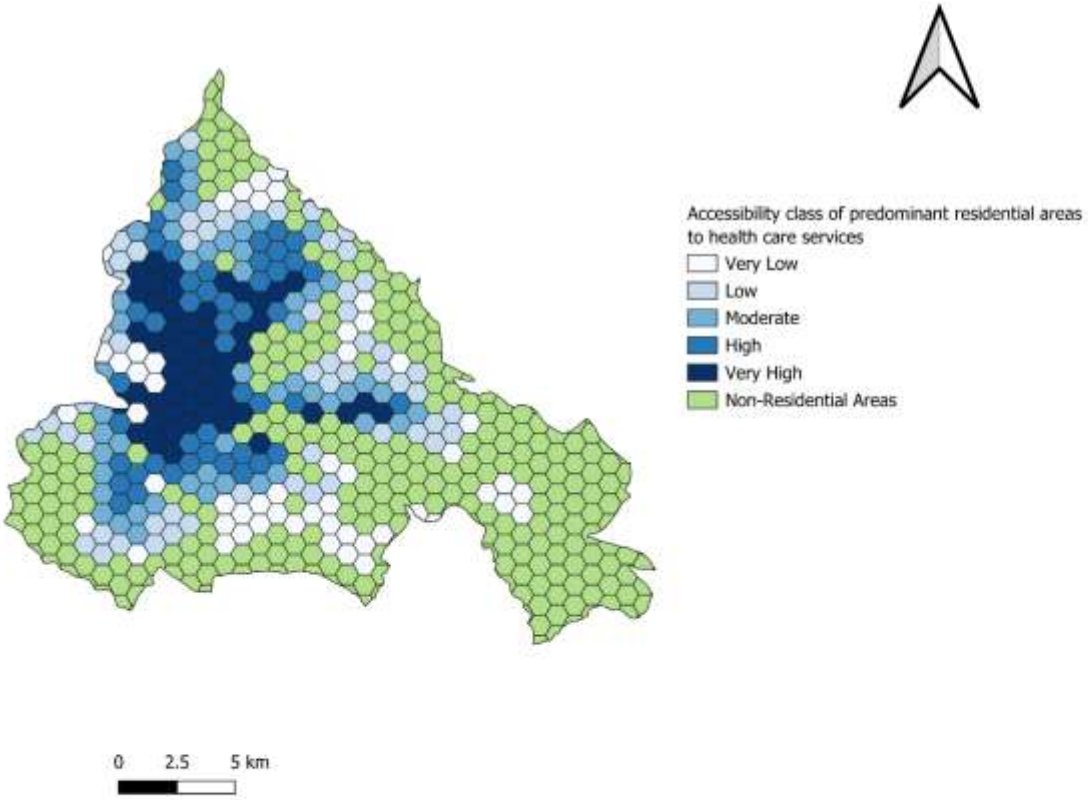

Figure 5: Accessibility of residential areas to health care centers

High-accessibility zones are concentrated in western part of the city, where health care centers are densely located near residential clusters near taxi routes. These areas exhibit strong gravitational pull, resulting in large shares of origins falling into the Very High and High accessibility classes. Sub-cities with high accessibility scores reflect planning decisions that have accessible and concentrated health infrastructure in central part of the sub-cities, densely populated areas. These zones benefit not only from facility proximity but also from integration with taxi transport routes, enabling efficient access to essential services.

In contrast, the peripheral areas of the sub-cities show widespread areas of low accessibility, with lighter hexagons dominating the spatial landscape. These zones are characterized by long distance between taxi routes from residential areas and health care centers, leading to diminished access. The prevalence of low-accessibility zones in the peripheral areas of the sub-cities underscores the compounded disadvantages faced by peripheral and underserved communities. Despite the presence of health care centers in some cases, their spatial inefficiency, being located far from residential origins and disconnected from major mobility corridors, limits their functional accessibility. The gravity model's sensitivity to both distance and facility clustering reveals these disparities more sharply than traditional metrics, reinforcing the need for equity-sensitive planning.

Generally, Figure 5 is further summarized in with Table 7 by calculating the percentage of origins that are found within each accessibility class category.

Table 7: Percentage of accessibility of origins to health care facilities using gravity-based accessibility measure

Gravity index	Accessibility class	Percentage of health care centers accessibility of origins in each sub-city						
		Hadnet	K/Weyane	Adihaki	Hawelti	Ayder	Quiha	Semien
0 - 0.024	Very low	1.6	0.0	16.7	23.1	0.0	9.7	0.0
0.024 - 0.048	Low	0.0	0.0	0.0	0.0	0.0	16.7	0.0
0.048 - 0.096	Moderate	4.8	0.0	0.0	0.0	13.0	20.8	5.4
0.096 - 0.206	High	50.0	25.0	0.0	19.2	46.3	44.4	40.5
0.206 - 1.968	Very high	43.6	75.0	83.3	57.7	40.7	8.3	54.1

The gravity-based analysis of health care center accessibility reveals substantial spatial disparities across Mekelle’s sub-cities. Origins were classified into five accessibility classes Very Low, Low, Moderate, High, and Very High based on gravity index thresholds as shown in the Table 7 above. The percentage distribution of origins within each sub-city across these classes provides a nuanced understanding of service coverage and infrastructural equity.

From the Table 7 above Adihaki sub-city demonstrate strong performance, with 83.33% of its origins falling into the Very High accessibility class. This figure suggests that these area benefit from a dense concentration of health facilities and favorable proximity to taxi routes, resulting in efficient transport service coverage. Semien and Ayder sub-cities also perform relatively well, with more than 94% of origins in the Very High class, and high class of accessibility and 0% in the low and very low accessibility class.

Similarly, Hadnet presents a more balanced profile. While 50% of its origins fall into the High accessibility class and 43.6% into the Very High class, it also retains 1.6% of origins in the Very Low categories. This mixed distribution suggests that while Hadnet is generally well-served, certain zones within the sub-city still face accessibility challenges.

On the other hand, Hawelti has 76.9% of origins in the Very high and High classes, and 23.1% of origins fall into the Very low class with no representation in the Moderate or Low categories; Similarly, Adihaki with 83.3% of origins in the very high accessibility class, and 16.7% in the very low with no representations in the middle accessibility classes. The absence of middle-tier accessibility suggests a polarized distribution and potential service fragmentation.

In contrast, Quiha exhibit pronounced accessibility deficits. It has 26.4% of origins in the Very Low and Low classes; while 8.3%of the origins are categorized in the very high accessibility class. These findings highlight the need for targeted taxi route planning and improved connectivity in these sub-cities.

Overall, the gravity-based classification reveals that relying solely on facility counts confuses critical gradations in service accessibility. Sub-cities with high shares of origins in the Very Low and Low classes, particularly, Quiha sub-city, should be prioritized for taxi route improvement, last-mile transport improvements, and equity-sensitive planning. These interventions are essential to ensure that health care services are not only available but equitably distributed across the urban landscape.

4.2. Equity analysis

4.2.1. Equity analysis using cumulative-based measure of accessibility

This section presents the findings of the equity analysis conducted using the cumulative-based measure of accessibility. The cumulative approach evaluates the number of opportunity points; primary schools, secondary schools, and health care centers, reachable within a predefined, thirty-minute, travel time threshold.

4.2.1.1. Equity Analysis of schools using cumulative-based accessibility measure

This section presents the findings of the equity analysis of primary and secondary school accessibility using a cumulative-based measure. The cumulative approach evaluates the number of primary and secondary schools reachable within thirty-minute travel time threshold, offering a straightforward and policy-relevant indicator of spatial equity. By assessing how many public-school opportunities are accessible to residents across different urban zones, this method reveals disparities in service provision and transport connectivity.

- **Demographic accessibility of sub cities to schools**

To evaluate the spatial and demographic accessibility of primary and secondary school distribution, using cumulative accessibility measure, across Mekelle sub-cities, a complementary metric opportunity per capita (schools per 1,000 residents) was employed. This indicator reveals not only where opportunities are concentrated but also how accessible, opportunity per capita reveals the demographic adequacy of these services relative to population distribution., it is using multi modal transportation system, using taxi and walking to and from the taxi station mode of transportation.

Analyzing per capita access to primary and secondary schools, measured as the number of accessible schools per 1,000 residents, reveals substantial equity gaps across sub-cities as shown in the Table 8 below.

Table 8: Accessibility per capita of primary and secondary schools and equity status of sub cities

Sub city	Population	Accessible primary school	Accessible primary school per capita	Sub-cities Primary school Equity status	Accessible secondary school	Accessible secondary school per capita	Sub-cities Secondary school Equity rank
Adihaki	143764	4	0.028	Very low	4	0.028	Very low
Ayder	148657	28	0.188	Very high	19	0.128	Very high
Hawelti	212263	24	0.113	High	10	0.047	High
K/Weyane	95818	9	0.094	Moderate	4	0.042	Moderate
Quiha	133000	2	0.015	Very low	4	0.03	Low
Semien	173119	9	0.052	Low	4	0.023	Very low
Hadnet	222048	29	0.131	Very high	11	0.05	Very high

These results shows that Ayder and Hadnet sub cities ranks very high in opportunity per capita metric, indicating that its primary school and secondary school accessibility using taxi transportation system is well-aligned with population size, offering relatively balanced transportation access to school. Correspondingly, Kedamay-Weyane sub-city also have moderate opportunity per capita of both primary and secondary schools. In contrast, Adihaki sub city report the lowest primary and secondary school per capita values, suggesting that despite their land area or possible urban development, they fall short in population-proportional access to primary education. Similarly, Quiha sub-city has very low and low opportunity per capita of primary and secondary schools respectively; and Semien sub-city has also low and very low opportunity per capita for primary and secondary schools respectively. This disparity could point to longer commute times for primary and secondary school students. Generally, these results can be visualized and summarized by the following choropleth maps.

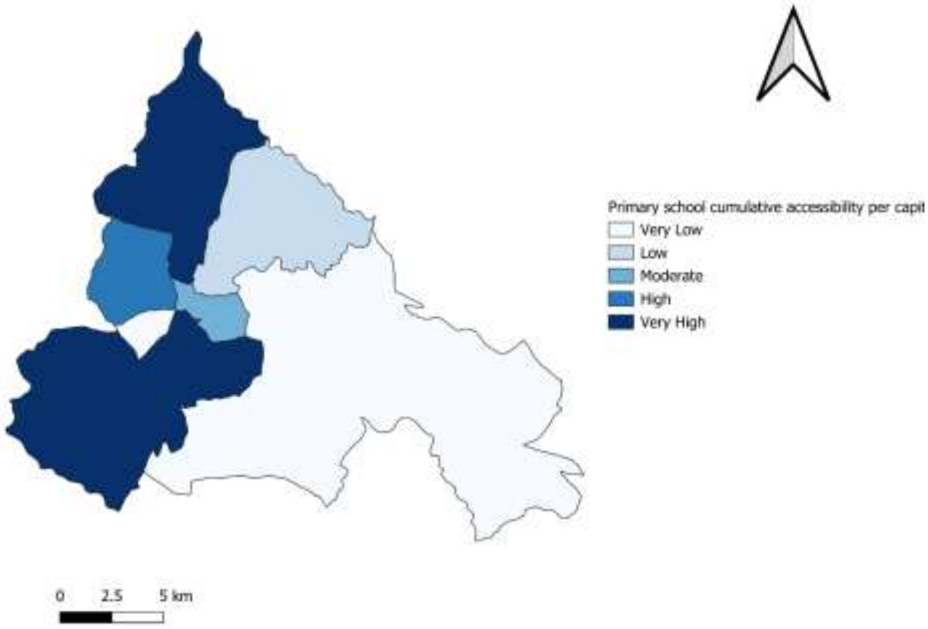

Figure 6: Accessibility per capita of sub-cities to primary schools

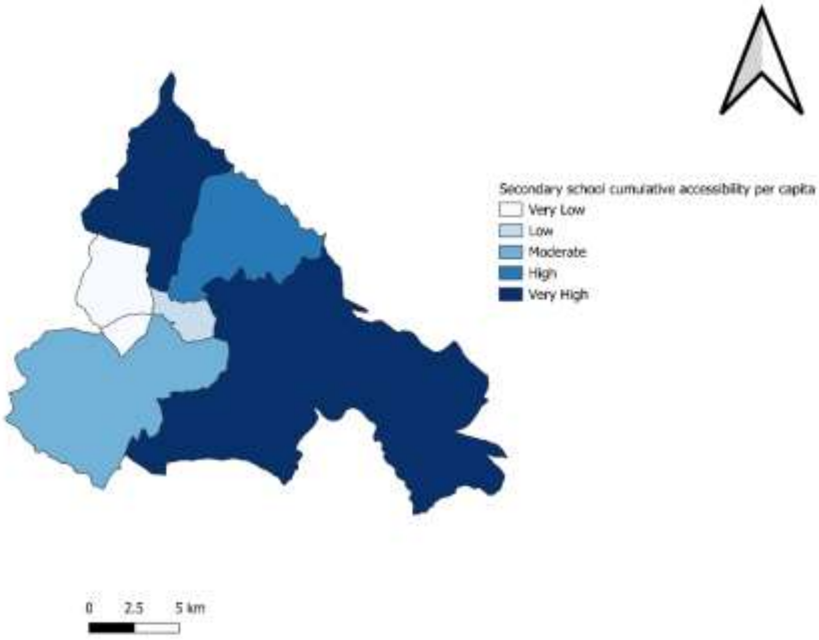

Figure 7: Accessibility per capita of sub-cities to secondary schools

These patterns emphasize the need for nuanced taxi route planning approaches that consider population demands. Prioritizing per capita access ensures that investments in taxi route accessibility directly benefit residents and not just contribute to spatial concentration.

- **Lorenz curve and Gini coefficient of primary and secondary schools**

The Lorenz curve constructed from cumulative accessibility scores illustrates the degree of inequality in service distribution across sub-cities. The calculation that had been done to plot the Lorenz curve and Gini coefficient is summarized in the Table 9.

Table 9: Cumulative-based Lorenz curve and Gini coefficient calculation steps of primary schools

Sub city	Population	%Accessibility (Primary school)	cumulative _accessibility	Cumulative accessibility share (Y)	Cumulative Population	Cumulative Population share (X)	Yi + Yi-1	Xi - Xi-1	(Yi + Yi-1)*(Xi - Xi-1)
Quiha	133000	0.028	0.028	0.01	133000	0.12	0.0073	0.1178	0.000857
Semien	173119	0.243	0.271	0.07	306119	0.27	0.0777	0.1534	0.011918
Hadnet	222048	0.468	0.739	0.19	528167	0.47	0.2625	0.1967	0.051638
Ayder	148657	0.519	1.258	0.33	676824	0.60	0.519	0.1317	0.068354
Adihaki	143764	0.667	1.925	0.50	820588	0.73	0.8272	0.1274	0.105362
Hawelti	212263	0.923	2.848	0.74	1032851	0.92	1.2404	0.1881	0.233273
K/Weyane	95818	1	3.848	1.00	1128669	1.00	1.7401	0.0849	0.147727
								Sum	**0.61913**
								Gini	**0.38087**

The Lorenz curve of primary schools deviates markedly from the line of equality as shown in the Figure 8 below, indicating that accessibility is not evenly shared.

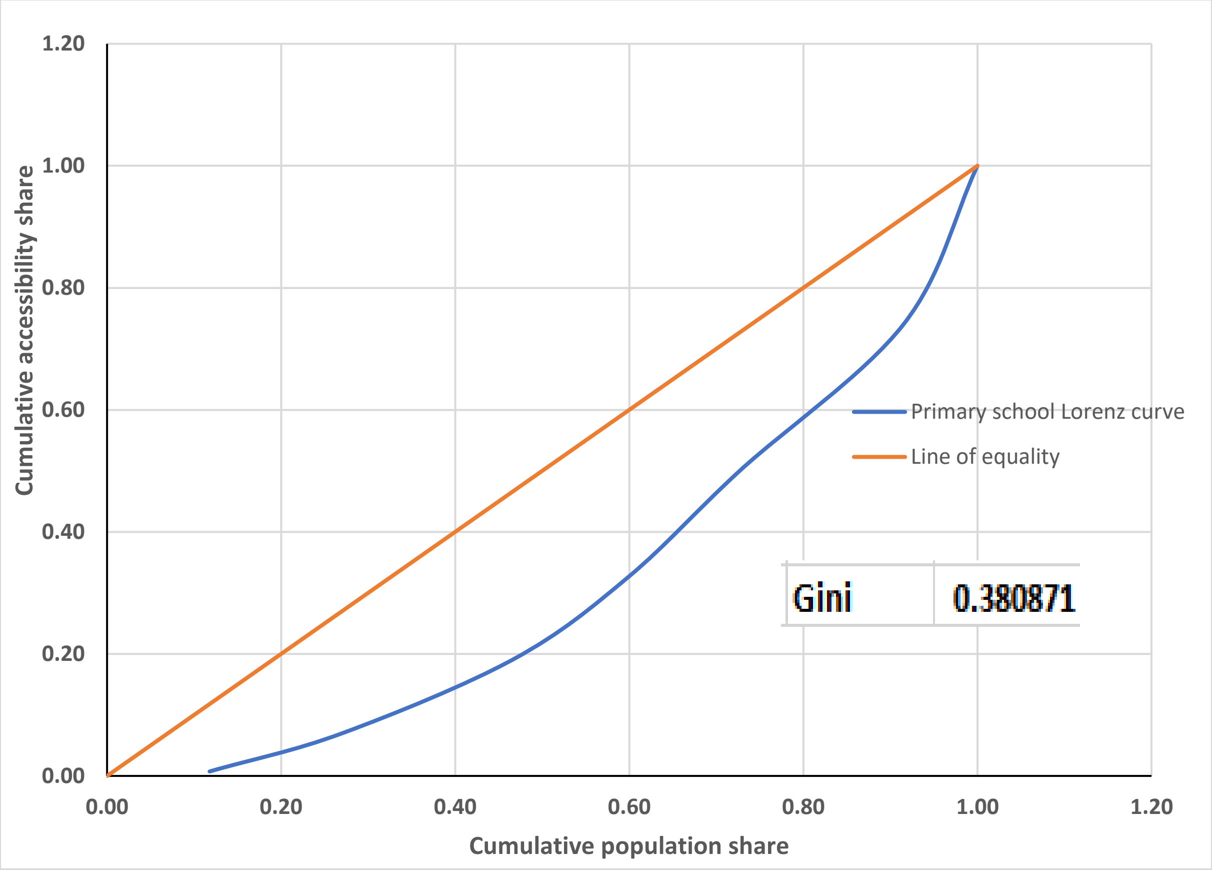

Figure 8: Cumulative-based Lorenz curve and Gini coefficient of primary schools

The Lorenz curve for cumulative accessibility to primary schools as shown in figure 8 reveals a notable degree of spatial inequality. The curve deviates significantly from the line of equality, indicating that taxi transport access to primary education is unevenly distributed across sub-cities. It reveals a pronounced level of inequality in the distribution being analyzed. For instance, the bottom 12% of the population controls only 1% of accessible primary schools, while the top 8% (from 92% to 100%) holds a striking 26% of accessible primary schools. This steep gradient near the end of the curve suggests a concentration of access among the top percentile. The overall shape of the curve implies that the majority of the population has limited taxi transport access to primary schools, and the distribution is far from equitable.

The calculated Gini coefficient of 0.38 suggests inequity, with a concentration of accessibility in a few well-served zones. Sub-cities in the lower deciles show limited reachability to nearby primary schools, often due to poor taxi transport connectivity. These findings highlight the need for targeted expansion of taxi transportation accessibility to primary school in underserved areas to ensure that foundational education is accessible to all children, regardless of geographic location.

Similarly, the calculation that had been done to plot the Lorenz curve and Gini coefficient of secondary schools is summarized in the Table 10 below.

Table 10: Cumulative-based Lorenz curve and Gini coefficient calculation steps of secondary schools

Sub city	Population	%Accessibility (Secondary school)	cumulative _accessibility	Cumulative accessibility share (Y)	Cumulative Population	Cumulative Population share (X)	Yi + Yi-1	Xi - Xi-1	(Yi + Yi-1)*(Xi - Xi-1)
Quiha	133000	0.06	0.06	0.03	133000	0.12	0.03	0.12	0.0030
Semien	173119	0.11	0.16	0.07	306119	0.27	0.10	0.15	0.0154
Hadnet	222048	0.18	0.34	0.16	528167	0.47	0.23	0.20	0.0454
Ayder	148657	0.35	0.69	0.32	676824	0.60	0.47	0.13	0.0622
Hawelti	212263	0.39	1.08	0.49	889087	0.79	0.81	0.19	0.1522
K/Weyane	95818	0.44	1.52	0.70	984905	0.87	1.19	0.08	0.1008
Adihaki	143764	0.67	2.19	1.00	1128669	1.00	1.70	0.13	0.2159
								sum	**0.5950**
								Gini	**0.4050**

The Lorenz curve of secondary schools deviates markedly from the line of equality as shown in the Figure 9 below, indicating that accessibility is not evenly shared. The Lorenz curve for secondary school taxi transport accessibility shows an even steeper deviation from the line of equality compared to primary schools. Quantitatively, the curve reveals a pronounced level of inequality in the distribution being analyzed. The curve bows significantly below the line of equality, indicating that a small portion of the population holds a disproportionately large share of the total accessibility. For instance, the bottom 12% of the population controls only 3% of the accessible secondary schools, while the top 13% (from 87% to 100%) holds a striking 30% of accessible secondary schools. This steep gradient near the end of the curve suggests a concentration of access among the top percentile. The overall shape of the curve implies that the majority of the population has limited taxi transport access, and the distribution is far from equitable.

This skewed distribution is further confirmed by the Gini coefficient of 0.405, reflecting higher levels of spatial inequity. These findings suggest that transportation accessibility is not spatially balanced, and that accessibility is concentrated in a few well-served zones.

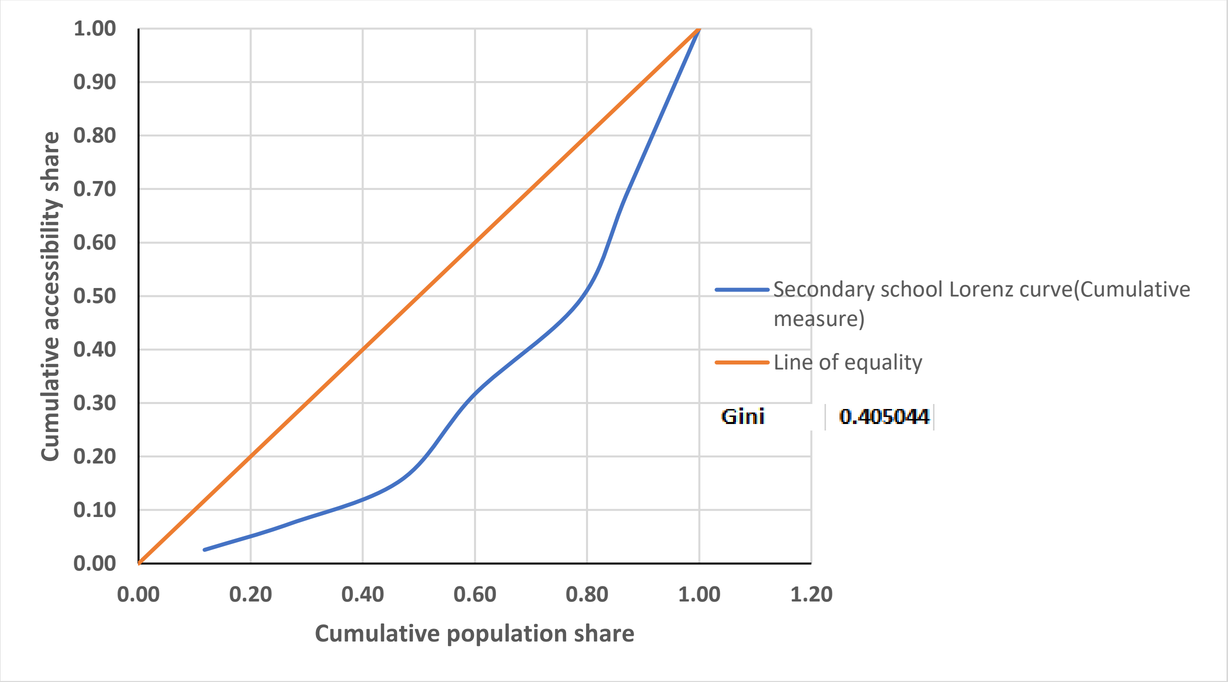

Figure 9: Cumulative- based Lorenz curve and Gini coefficient of secondary schools

This disparity may reflect taxi routes are not passing through or near secondary schools, limiting opportunities for students in outlying areas. The results underscore the importance of consideration of taxi route planning to ensure that routes pass through or near schools to make secondary schools more easily accessible to students living far from the current taxi routes and promote equitable access.

4.2.1.2. Equity analysis of health care centers using cumulative-based accessibility measure

This section presents the findings of the equity analysis of health care centers using a cumulative-based accessibility measure. By examining how access to health centers varies across sub-cities, this analysis reveals critical disparities in urban health infrastructure.

- **Demographic accessibility of sub-cities to health care facilities**

To evaluate the demographic accessibility of health care facility distribution, using cumulative accessibility measure, across Mekelle sub-cities, opportunity per capita (health care facilities per 1,000 residents) metric was used. This approach allowed for identification of systemic disparities, beyond mere facility count, by capturing how effectively healthcare centers serve populations within realistic transport boundaries. This indicator reveals not only where health care infrastructure is concentrated but also how accessible it is using multi modal transportation system.

The analysis of per capita access to healthcare centers uncovered notable disparities in equity of transport accessibility across sub-cities. By normalizing facility availability using population estimates within sub-cities, the opportunity per capita metric offered a more nuanced view of healthcare reach than absolute counts alone.

Analyzing per capita access to health care centers, measured as the number of schools per 1,000 residents, reveals substantial equity gaps across sub-cities as shown in the Table 11 below.

Table 11: Accessible health care centers per capita

Sub city	Accessible Health care	Population	Accessible health care per capita	Equity rank
Adihaki	2	143764	0.014	Very low
Ayder	16	148657	0.108	Very high
Hawelti	5	212263	0.024	Moderate
K/Weyane	4	95818	0.042	Moderate
Quiha	9	133000	0.068	High
Semien	9	173119	0.052	High
Hadnet	11	222048	0.05	High

Relatively, Ayder sub-city demonstrated the most equitable distribution, an outcome driven by compact urban form, strategically placed facilities, and strong transport connectivity with taxi routes. In contrast, Adihaki sub-city, though hosting several facilities, recorded only 0.014 centers per 1000 residents due to its dispersed residential patterns and gaps in road network geometry. The findings are further visualized and summarized in figure 10 by using choropleth map.

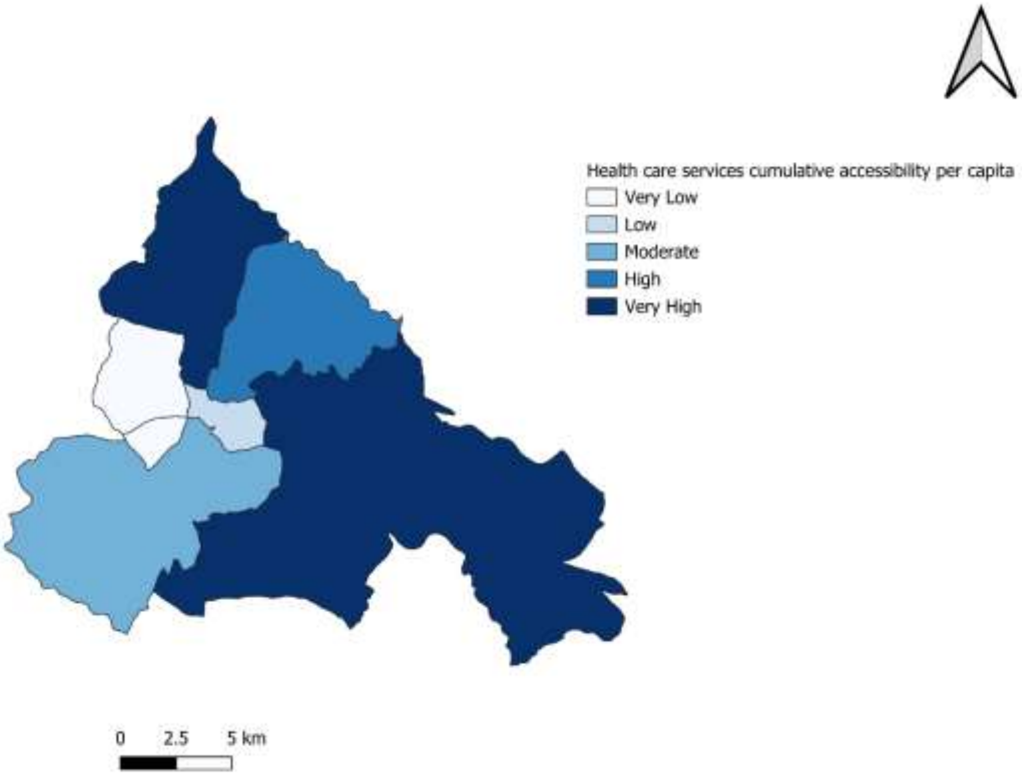

Figure 10: Health care centers per capita for each sub cities

Unlike to the sub-city cumulative accessibility of healthcare centers, Quiha, and Ayder sub-cities score high health care per capita access followed by Semien sub-city. Incontrast, Hawelti, and Adihaki followed by Kedamay-Weyane scores lower health care accessibility per capita. These patterns emphasize the need for nuanced taxi route planning approaches that consider population demands. Prioritizing per capita access ensures that investments in health care accessibility using taxi mode of transportation directly benefit residents and not just contribute to spatial concentration.

- **Lorenz curve and Gini coefficient of health care centers**

The Lorenz curve constructed from cumulative accessibility scores illustrates the degree of inequality in service distribution across sub-cities. The calculation that had been done to plot the Lorenz curve and Gini coefficient is summarized in the Table 12 below.

Table 12: Cumulative-based Lorenz curve and Gini coefficient calculation steps of health care centers

Sub-city	Population	%Accessibility (Health care centers)	cumulative _accessibility	Cumulative accessibility share (Y)	Cumulative Population	Cumulative Population share (X)	Yi + Yi-1	Xi - Xi-1	(Yi + Yi-1)*(Xi - Xi-1)
Quiha	133000	0.125	0.125	0.07	133000	0.12	0.0691	0.1178	0.008138
Hadnet	222048	0.177	0.302	0.17	355048	0.31	0.2359	0.1967	0.046412
Semien	173119	0.243	0.545	0.30	528167	0.47	0.468	0.1534	0.071777
Hawelti	212263	0.192	0.737	0.41	740430	0.66	0.7083	0.1881	0.133204
Ayder	148657	0.296	1.033	0.57	889087	0.79	0.9779	0.1317	0.128799
Adihaki	143764	0.333	1.366	0.75	1032851	0.92	1.3254	0.1274	0.168824
K/Weyane	95818	0.444	1.81	1.00	1128669	1.00	1.7547	0.0849	0.148964
								sum	**0.70612**
								Gini	**0.29388**

The Lorenz curve of health care centers deviates markedly from the line of equality as shown in the Figure 11 below, indicating that accessibility is not evenly shared.

Figure 11: Cumulative-based Lorenz curve and Gini coefficient of health care centers

The Lorenz curve for healthcare center accessibility presents the lowest level of inequality among the three service types, with a Gini coefficient of 0.29 as shown in figure 11. The Lorenz Curve reveals a moderate unequal distribution taxi transport access. The bottom 12% of the population, accumulated 7% of the total health care, indicating that a small population share controls the small accessibility share. Meanwhile, the top 8% of the population holds only 25%, and even halfway through the population (47%), the cumulative share reaches just 30%. Generally, the curve highlights a small imbalance in accessibility to health care centers distribution that would reflect less inequality.

This disparity may reflect taxi routes are not passing through or near health care facilities, limiting opportunities for residents in outlying areas. The results underscore the importance of consideration of taxi route planning to ensure that routes pass through or near health care services to make services more easily accessible to residents living far from the current taxi routes and promote equitable access.

4.2.2. Equity analysis using gravity-based measure of accessibility

This section presents the results of the equity analysis conducted using the gravity-based measure of accessibility. This approach reflects the intuitive notion that closer opportunities are more accessible than distant ones, even if both are technically reachable.

4.2.2.1. Equity analysis of schools using gravity-based accessibility measure

This section presents the results of the equity analysis of school accessibility using a gravity-based measure. Gravity-based models incorporate both the number of public-schools and the impedance of travel typically expressed as time through a decay function. This allows for a deeper understanding of how proximity and travel effort shape access to public school opportunities.

- **Demographic accessibility of sub-cities to schools**

The gravity index was measured followed by opportunity per capita to assess the transportation accessibility disparities to schools across different sub-cities of Mekelle.

The gravity-based accessibility scores, when normalized by sub-city population, reveal disparities in public-school opportunity per capita across Mekelle’s sub-cities. Table 13 below shows the results of the gravity-based per capita accessibility metric values of primary and secondary schools across the sub-cities.

Table 13: Primary school and secondary school accessibility per capita equity status

Sub-city	Primary school		Secondary school	
	Per capita	Equity status	Per capita	Equity status
Hadnet	0.008	Very high	0.003	Moderate
K/Weyane	0.004	Very low	0.003	Moderate
Adihaki	0.002	Very low	0.001	Very low
Hawelti	0.005	Low	0.003	Moderate
Ayder	0.011	Very high	0.006	Very high
Quiha	0.006	High	0.002	Very low
Semien	0.005	Low	0.002	Very low

The comparative analysis of sub-cities reveals outstanding disparities in per capita access to primary, and secondary schools. Ayder sub-city stand out with very high ranking in both primary schools, and secondary schools suggesting strong taxi route planning to primary and secondary schools. In contrast, Adihaki sub-city rank very low in both primary schools and secondary schools per capita rank, indicating potential gaps in taxi transport accessibility. Similarly, Semien sub-city also present low and very low equity status in primary and secondary schools respectively suggesting at low development taxi route planning. Meanwhile, Kedamay-Weyane sub-city show very low and moderate performance in primary and secondary schools per capita respectively. Similarly, Hawelti sub-city show low and moderate performance in primary and secondary schools per capita respectively. Quiha sub-city scores very low in secondary school accessibility per capita, unlike to its high performance of primary schools per capita. These variations underscore the need for targeted policy interventions to balance service delivery and ensure equitable access across all sub-cities.

Generally, the findings are further visualized and summarized in figure 12 and figure 13 by using choropleth map.

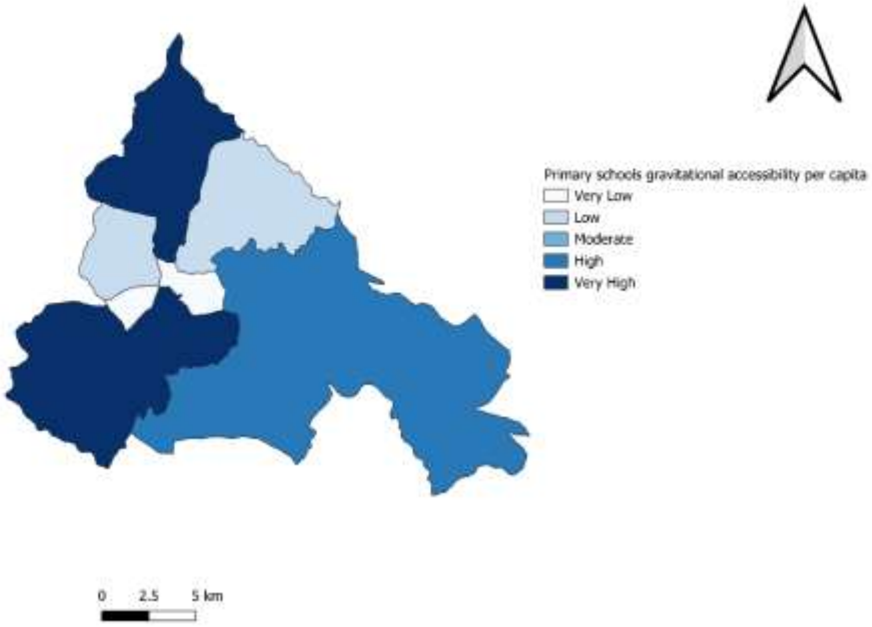

Figure 12: Sub-cities accessibility per capita to primary schools

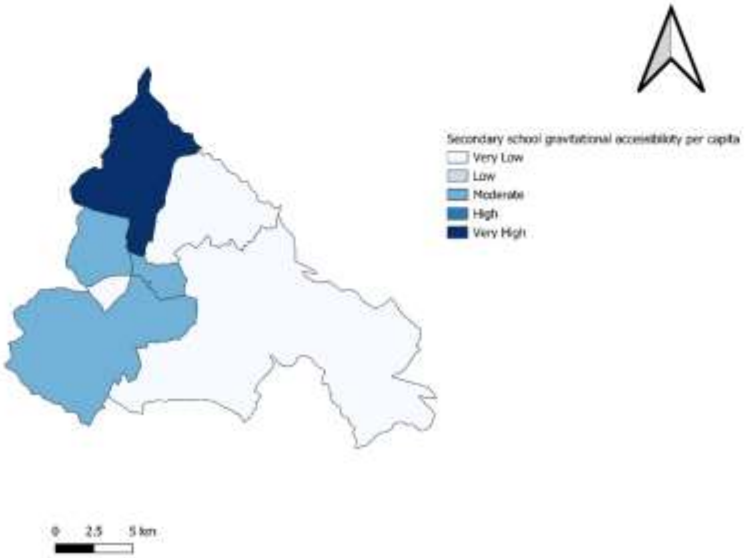

Figure 13: Sub-cities accessibility per capita to secondary schools

These results highlight the importance of evaluating accessibility not only in spatial terms but also in relation to demographic demand. Sub-cities with high opportunity per capita are better positioned to meet equity of taxi transportation accessibility to primary and secondary schools, while those with low values may require targeted taxi route planning and improved last-mile connectivity to ensure inclusive access.

- **Lorenz curve and Gini coefficient of schools**

The Lorenz curve for primary and secondary school accessibility presents a visual representation of how taxi transport access to educational infrastructure is distributed across Mekelle's population. The curve plots cumulative population share against cumulative accessibility share, with the equity line representing perfect equality. In this case, the Lorenz curve bows noticeably below the equity line, indicating a substantial degree of inequality in the distribution of taxi transport access to primary and secondary schools. The sub-city-level population and accessibility data used to construct the Lorenz curve and calculate the Gini coefficient is provided in Table 14 below. These datasets served as the basis for computing Gini coefficients and plot Lorenz curves in primary and secondary school accessibility.

Table 14: Gravity-based Lorenz curve and Gini coefficient calculation steps of primary schools

Sub-city	Population	Accessibility	Cumulative _accessibility	Cumulative accessibility share (Y)	Cumulative Population	Cumulative Population share (X)	$Y_i + Y_i-1$	$X_i - X_i-1$	$(Y_i + Y_i-1)*(X_i - X_i-1)$
Adihaki	143764	0.335	0.335	0.05	143764	0.13	0.05	0.13	0.01
K/Weyane	95818	0.393	0.728	0.10	239582	0.21	0.15	0.08	0.01
Semien	173119	0.943	1.671	0.24	412701	0.37	0.35	0.15	0.05
Hawelti	212263	1.121	2.792	0.40	624964	0.55	0.64	0.19	0.12
Quiha	133000	0.759	3.551	0.51	757964	0.67	0.91	0.12	0.11
Ayder	148657	1.569	5.12	0.74	906621	0.80	1.25	0.13	0.16
Hadnet	222048	1.825	6.945	1.00	1128669	1.00	1.74	0.20	0.34
								Sum	**0.81**
								Gini	**0.193**

The Lorenz curve of primary schools deviates slightly from the line of equality as shown in the Figure 14 below, indicating that accessibility is not evenly shared.

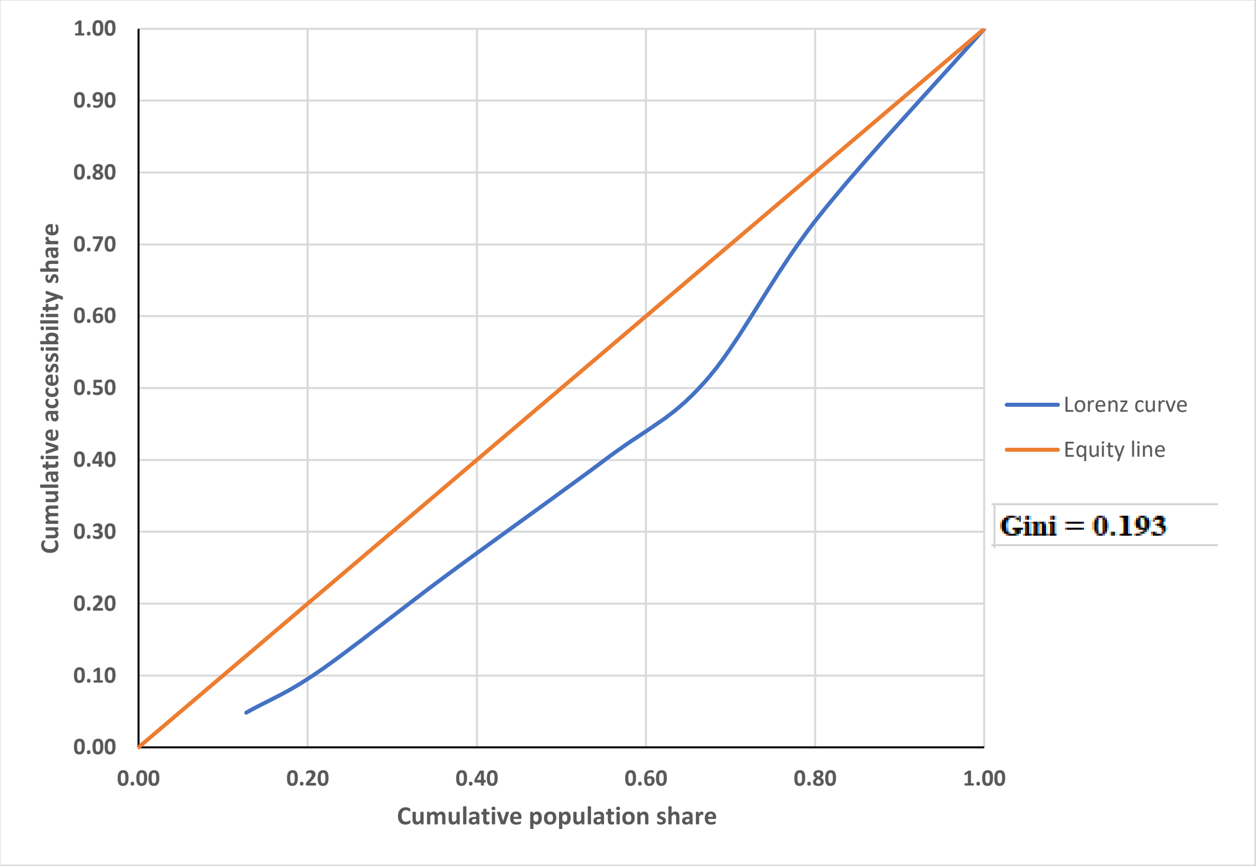

Figure 14: Gravity-based Lorenz curve and Gini coefficient of primary schools

The Lorenz curve for taxi transport accessibility to primary schools reveals a relatively slight level of inequality in the distribution of taxi transport accessibility to primary schools. The curve consistently lies below the line of perfect equality, indicating that the cumulative share of accessibility disproportionately concentrated among the upper segments of the population. For instance, the bottom 13% of the population controls only 5% of accessible primary schools, while the top 20% (from 80% to 100%) holds a 26%.

The calculated Gini coefficient of 0.193 supports this interpretation, suggesting a relatively equitable distribution with some degree of disparity. This value falls within the lower range of inequality implying that while the distribution is not perfectly equal, it is far from severely skewed. Such a profile reflect a society where redistributive mechanisms or inclusive policies are partially effective though further improvements could still be made to enhance equity.

Similarly, the calculation that had been done to plot the Lorenz curve and Gini coefficient of secondary schools is summarized in the Table 15.

Further, the Lorenz curve of secondary schools deviates markedly from the line of equality as shown in Figure 15, indicating that accessibility is not evenly shared.

Table 15: Gravity-based Lorenz curve and Gini coefficient calculation steps of secondary schools

Sub-city	Population	Accessibility	Cumulative accessibility	Cumulative accessibility share (Y)	Cumulative Population	Cumulative Population share (X)	Yi + Yi-1	Xi - Xi-1	(Yi + Yi-1)*(Xi - Xi-1)
Adihaki	143764	0.125	0.125	0.04	143764	0.13	0.04	0.1274	0.0051
K/Weyane	95818	0.273	0.398	0.13	239582	0.21	0.167	0.0849	0.0142
Quiha	133000	0.296	0.694	0.22	372582	0.33	0.349	0.1178	0.0411
Semien	173119	0.387	1.081	0.35	545701	0.48	0.567	0.1534	0.0870
Hawelti	212263	0.538	1.619	0.52	757964	0.67	0.862	0.1881	0.1622
Hadnet	222048	0.636	2.255	0.72	980012	0.87	1.237	0.1967	0.2434
Ayder	148657	0.876	3.131	1.00	1128669	1.00	1.72	0.1317	0.2266
								Sum	0.7795
								Gini	**0.2205**

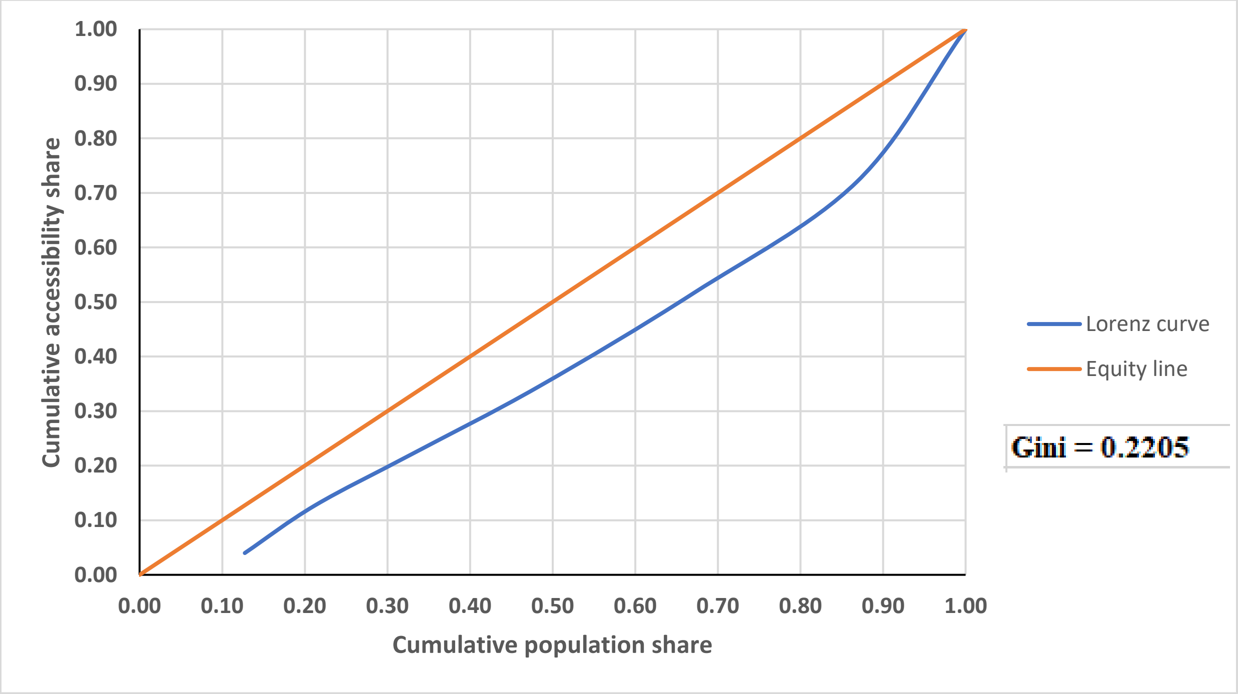

Figure 15: Gravity-based Lorenz curve and Gini coefficient of secondary schools

The Lorenz curve for accessibility of taxi transport to secondary schools illustrates a moderate level of inequality in the distribution of transportation accessibility across a population. The curve lies below the line of perfect equality, indicating that the cumulative share of the resource is not evenly distributed. For example, the bottom 13% of the population holds only 4% of the accessible secondary schools, while the top 13% (from 87% to 100%) controls 28%. This gradual upward slope suggests that although inequality exists, it is not extreme. The Gini coefficient of 0.2205 reinforces this interpretation, placing the distribution in a relatively equitable range. Such a profile reflects a system where redistributive policies or inclusive planning have had a positive impact, though there remains room for improvement to achieve greater equality

By visualizing accessibility as an equity metric, the Lorenz curve complements offering a powerful diagnostic tool for policy intervention. It underscores the importance of integrating equity-sensitive metrics into taxi route planning to ensure that primary and secondary schools are not only available but fairly distributed across all segments of the population.

4.2.2.2. Equity Analysis of health care centers using gravity-based accessibility measure

This section presents the findings of the equity analysis of health care centers using a gravity-based accessibility measure. Gravity-based models incorporate both the quantity of health care centers and the impedance of travel typically expressed as time through a decay function. This approach provides a more nuanced understanding of how proximity and travel effort shape access to essential health services.

- **Demographic accessibility of sub-cities to health care centers**

Analyzing per capita access to health care centers, measured as the accessibility of schools per 1,000 residents, reveals substantial equity gaps across sub-cities. The results of the gravity-based per capita accessibility metric values of health care centers across the sub-cities are shown in table 16 below.

Table 16: Equity status accessibility per capita of health care centers

Sub-city	Health care centers	
	Per capita	Equity status
Hadnet	0.034	High
K/Weyane	0.034	High
Adihaki	0.01	Very low
Hawelti	0.03	Moderate
Ayder	0.071	Very high
Quiha	0.027	Very low
Semien	0.027	Very low

The comparative analysis of sub-cities reveals outstanding disparities in per capita access to health care centers. Ayder sub-city stand out with very high rankings in equity status of health care centers per capita, suggesting strong taxi route planning to reach healthcare centers. In contrast, sub-cities like Adihaki, Quiha, and Semien rank very low in equity status of health care centers per capita rank, indicating potential gaps in last mile connectivity and taxi transport accessibility. Kedamay-Weyane, and Hadnet sub-cities presents an interesting case with a high equity status in health care centers per capita. Meanwhile, Hawelti sub-city show moderate performance in equity status of health care centers per capita. These variations underscore the need for targeted policy interventions to balance service delivery and ensure equitable access across all sub-cities.

Generally, the above result is visualized in figure 16 using choropleth maps.

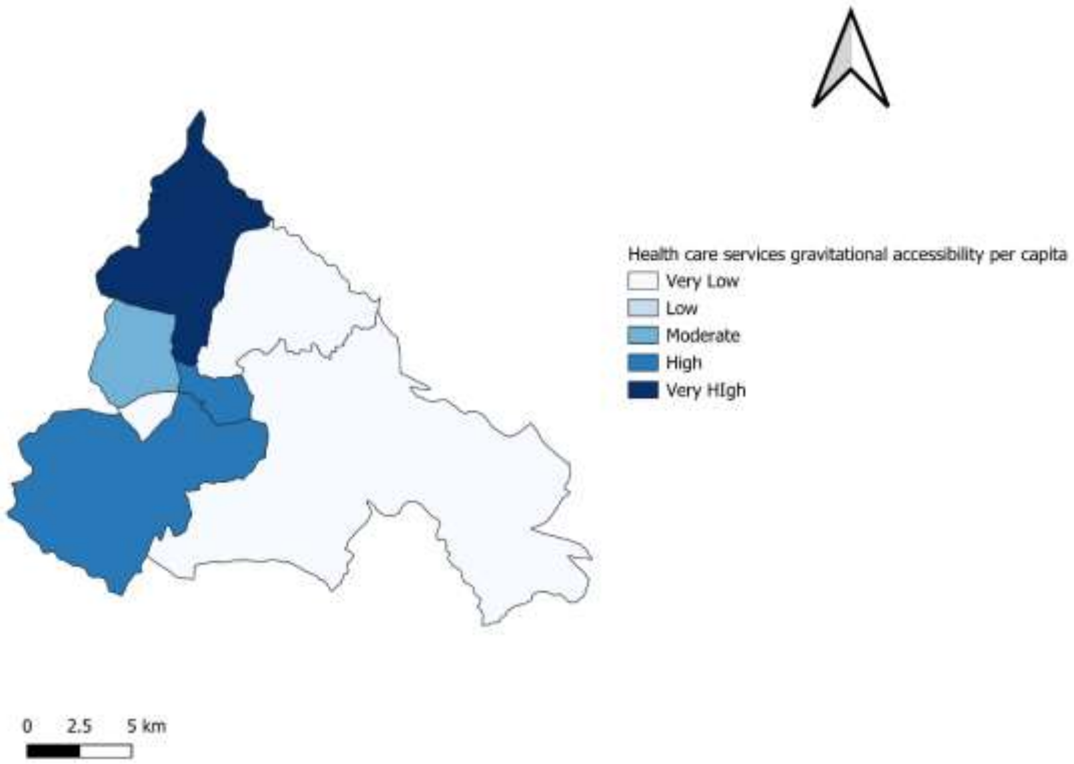

Figure 16: Health care centers accessibility per capita

The per capita lens complements gravity-based accessibility analysis by highlighting demand-side pressures often masked by spatial metrics alone. These findings advocate for population-sensitive planning, where future taxi route planning improvements prioritize underserved zones not only by spatial coverage but also by demographic need.

- **Lorenz curve and Gini coefficient of health care centers**

To assess the fairness of taxi transport to health care centers, accessibility distribution Lorenz curve and Gini coefficient was employed. The sub-city-level population and accessibility data used to construct the Lorenz curve and calculate the Gini coefficient is provided in the Table 17 below. These datasets served as the basis for computing Gini coefficients and plot Lorenz curves in primary and secondary school accessibility.

Table 17: Gravity-based Lorenz curve and Gini coefficient calculation steps of health care centers

Sub-city	Population	Accessibility	Cumulative accessibility	Cumulative accessibility share (Y)	Cumulative Population	Cumulative Population share (X)	Yi + Yi-1	Xi - Xi-1	(Yi + Yi-1)*(Xi - Xi-1)
Adihaki	143764	1.5	1.5	0.04	143764	0.13	0.04	0.127	0.0051
K/weyane	95818	3.276	4.776	0.13	239582	0.21	0.17	0.085	0.0142
Semien	173119	4.644	9.42	0.25	412701	0.37	0.38	0.153	0.058
Quiha	133000	3.552	12.972	0.35	545701	0.48	0.6	0.118	0.0702
Hawelti	212263	6.456	19.428	0.52	757964	0.67	0.86	0.188	0.1622
Hadnet	222048	7.632	27.06	0.72	980012	0.87	1.24	0.197	0.2434
Ayder	148657	10.512	37.572	1.00	1128669	1.00	1.72	0.132	0.2266
								Sum	0.7796
								Gini	**0.2204**

To evaluate the equity of access to health care infrastructure across Mekelle's sub-cities, a Lorenz curve was constructed using sub-city level population and gravity-based accessibility scores as shown in the Figure 17 below. The curve plots cumulative population share against cumulative accessibility share, with the equity line representing perfect equality.

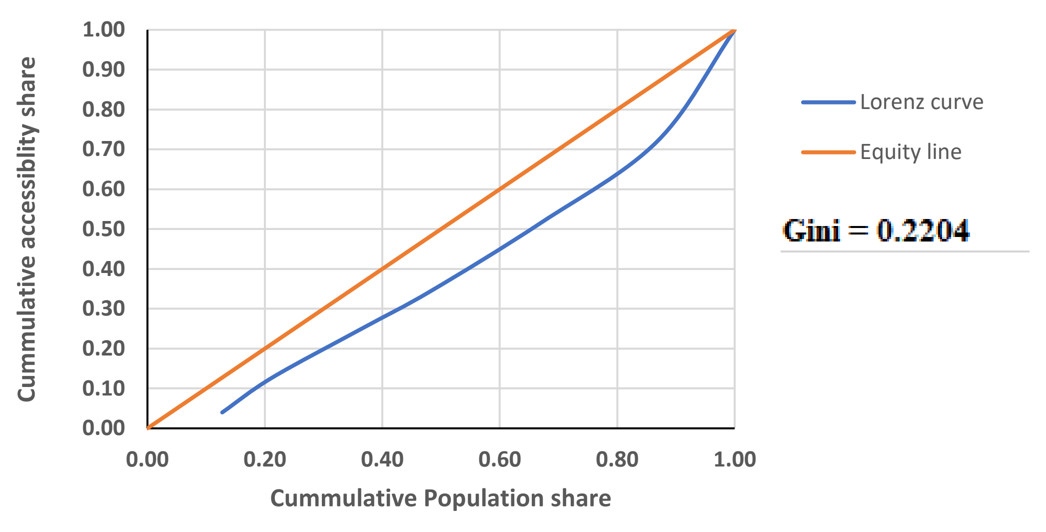

Figure 17: Gravity -based Lorenz curve and Gini coefficient of health care centers

As with educational services, the Lorenz curve for health care illustrates a moderately unequal distribution of taxi transport access across the population. The curve consistently lies below the line of perfect equality, indicating that the cumulative share of the accessibility is disproportionately concentrated among the upper segments of the population. For instance, the bottom 13% of the population holds only 4% of the resource, while the top 13% (from 87% to 100%) controls 28%. This gradual upward slope suggests that while inequality exists, it is not extreme. The Gini coefficient of 0.2204 reinforces this interpretation, placing the distribution in a relatively equitable range. This value suggests that although the system is not perfectly equal, it reflects a level of fairness that result from redistributive policies or inclusive planning efforts. Nonetheless, there remains room for improvement to further reduce disparities and promote more balanced equity of taxi transport access.

4.3. Composite equity ranking

A composite equity ranking was developed to evaluate the relative equity of accessibility of public schools and healthcare opportunities across sub-cities in Mekelle, as assessing spatial equity in urban accessibility requires a multidimensional approach that captures not only the presence of infrastructure but also its proximity, efficiency, and demographic alignment. This framework integrates four key metrics like cumulative access, accessibility per capita via cumulative accessibility, gravity-based access, and accessibility per capita via gravity-based accessibility, each offering a distinct lens on how services are distributed and experienced. By ranking sub-cities across these indicators and calculating an average rank, the composite method synthesizes complex spatial and demographic data into a clear, interpretable equity scorecard.

In the composite ranking, per capita access highlights demographic disparities in opportunity provision, ensuring that spatial equity assessments are sensitive to both infrastructure and population scale. It complements gravity-based and cumulative metrics by introducing a fairness lens, helping identify sub-cities where accessibility gaps are driven by population pressure rather than spatial isolation.

4.3.1. Cumulative-based equity ranking

This section presents the results of the equity ranking derived from cumulative-based accessibility measures. The cumulative approach evaluates the number of opportunity points, primary schools, secondary schools, and health centers, reachable within thirty-minute travel time threshold. By ranking residential zones based on their cumulative accessibility scores, and cumulative accessibility per capita scores this method offers a clear and interpretable framework for identifying spatial disparities and prioritizing areas for intervention.

4.3.1.1. Cumulative-based accessibility measure rank

The cumulative accessibility metric reflects the percentage of educational facilities, both primary and secondary schools, and health care facilities that are reachable within thirty-minutes using multi modal, taxi and walking to and from taxi stations, transportation systems from each origin and then aggregated in to sub-cities as shown in the Table 18.

Table 18: Cumulative-based accessibility measure rank

Sub-city	Cumulative accessibility (%)					
	Primary schools		Secondary schools		Health care centers	
	Cumulative accessibility (%)	Rank	Cumulative accessibility (%)	Rank	Cumulative accessibility (%)	Rank
Hadnet	46.8	5	17.7	5	17.7	6
K/Weyane	100	1	44.4	2	44.4	1
Adihaki	66.7	3	66.7	1	33.3	2
Hawelti	92.3	2	38.5	3	19.2	5
Ayder	51.9	4	35.2	4	29.6	3
Quiha	2.8	7	5.6	7	12.5	7
Semien	24.3	6	10.8	6	24.3	4

Within the composite equity ranking, this percentage serves as a critical indicator of spatial opportunity, capturing how well each sub-city is served by the existing multi modal transportation network.

4.3.1.2. Cumulative- based accessibility per capita rank

Per capita accessibility was calculated by dividing the total accessibility score, cumulative-based, by the population of each sub-city that ensures that comparisons reflect not just infrastructure presence, but its proportional availability to residents to compare the cumulative-based accessibility per capita of the sub-cities the following ranking is done as shown in the Table 19 below.

Table 19: Cumulative- based accessibility per capita rank

Sub-city	Per capita access (Cumulative based)					
	Primary schools		Secondary schools		Health care centers	
	Per capita	Rank	Per capita	Rank	Per capita	Rank
Hadnet	0.008	2	0.003	2	0.034	2
Kedamay-Weyane	0.004	6	0.003	2	0.034	2
Adihaki	0.002	7	0.001	7	0.01	7
Hawelti	0.005	4	0.003	2	0.03	4
Ayder	0.011	1	0.006	1	0.071	1
Quiha	0.006	3	0.002	5	0.027	5
Semien	0.005	4	0.002	5	0.027	5

From Table 19, sub-cities like Kedamay-Weyane with high percentage of cumulative accessibility to primary schools, have large population rank lower in per capita terms; Similarly, Adihaki with high percentage of cumulative accessibility to secondary school facilities but large populations rank lower in per capita terms, revealing potential taxi transport equity deficits. Conversely, smaller sub-cities with modest infrastructure like Ayder scored higher as their population demands are relatively well met.

4.3.2. Gravity-based equity ranking

This section presents the results of the equity ranking derived from gravity-based accessibility measures. Gravity-based models incorporate both the quantity of opportunities and the impedance of travel typically expressed as time through a decay function. This approach provides a more nuanced and behaviorally sensitive understanding of accessibility, reflecting the diminishing likelihood of accessing distant services.

4.3.2.1. Gravity-based accessibility measure rank

In the composite ranking, gravity-based opportunity scores help identify sub-cities where infrastructure is not only present but spatially efficient, ensuring that equity assessments reflect both reach and realism in access.

Table 20 showed that the gravity-based accessibility measure rank across all sub-cities for the three opportunities, primary schools, secondary schools, and health care centers.

Table 20: Gravity-based accessibility measure rank

Sub-city	Gravity-based scores					
	Primary schools		Secondary schools		Health care centers	
	Gravity based score	Rank	Gravity based score	Rank	Gravity based score	Rank
Hadnet	1.825	1	0.636	2	7.632	2
K/Weyane	0.393	6	0.273	6	3.276	6
Adihaki	0.335	7	0.125	7	1.5	7
Hawelti	1.121	3	0.538	3	6.456	3
Ayder	1.569	2	0.876	1	10.512	1
Quiha	0.759	5	0.296	5	3.552	5
Semien	0.943	4	0.387	4	4.644	4

As shown in the Table 20 above, Hadnet sub-city demonstrate highest values of gravity score for accessible primary schools, similarly Ayder sub-city demonstrate high values of gravity score for accessible secondary schools and health care centers. This indicates not only presence but spatially efficiency, ensuring that equity assessments reflect both reach and realism in access. compared to the other sub-cities. In contrast, sub-cities like Kedamay-Weyane and Adihaki score lowest gravity-based accessibility for all the three opportunities, primary school, secondary school, and health care centers, revealing significant gaps in facility reach.

4.3.2.2. Gravity-based accessibility per capita rank

The per capita gravity-based accessibility metric captures the average ease with which residents in each sub-city can reach educational and healthcare facilities, factoring both proximity and impedance (travel time). The normalized per capita scores reveal how effectively the taxi transport system and spatial distribution of services serve the population, independent of facility count as shown in the Table 21 below.

Table 21: Gravity-based accessibility per capita rank

Sub-city	Per capita access (Gravity based)					
	Primary school		Secondary school		Health care centers	
	Access per capita	Rank	Access per capita	Rank	Access per capita	Rank
Hadnet	0.008	2	0.003	2	0.034	2
K/Weyane	0.004	6	0.003	2	0.034	2
Adihaki	0.002	7	0.001	7	0.01	7
Hawelti	0.005	4	0.003	2	0.03	4
Ayder	0.011	1	0.006	1	0.071	1
Quiha	0.006	3	0.002	5	0.027	5
Semien	0.005	4	0.002	5	0.027	5

Sub-cities such as Ayder, and Hadnet rank high in gravity-based per capita access, indicating not only spatial proximity to primary schools, secondary schools, and health care facilities but also efficient transport connectivity. Conversely, Adihaki sub-city show low scores, suggesting that even when facilities exist, they are less accessible due to travel barriers. Within the composite equity ranking, this metric functions as a population-sensitive indicator of functional accessibility, highlighting disparities in actual reachability rather than mere facility presence. Its inclusion ensures that equity assessments reflect both spatial and social dimensions of access, especially for underserved populations.

4.3.3. Summary of composite equity ranking

The composite equity ranking integrates the above four distinct but complementary accessibility metrics, cumulative access, per capita via cumulative accessibility, gravity-based access, and per capita opportunity via gravity-based accessibility, to provide a holistic assessment of spatial equity across sub-cities. Cumulative accessibility captures the sheer number of facilities reachable within a defined travel threshold, thirty-minutes, offering a straightforward measure of service coverage. Also, Gravity-based accessibility refines this by weighting opportunities according to distance decay, emphasizing proximity and travel efficiency. Likewise, per capita opportunity adjusts for population size, revealing whether access is proportionate to demand and highlighting underserved areas with high population-to-facility ratios. Together, these metrics reveal nuanced disparities: for instance, a sub-city that score high in cumulative access but low in per capita equity, signaling infrastructural imbalance. Table 22, 23, 24 and 25 help to synthesize and summarize these dimensions. By synthesizing these dimensions, the composite ranking enables targeted policy interventions that address both quantity and quality of access, ensuring that spatial equity is not only measured but meaningfully pursued.

The following accessibility ranking tables present a comparative evaluation of sub-cities based on their ability to reach key urban opportunities, public primary schools, secondary schools and healthcare facilities, using multiple accessibility metrics. Each sub-city is assigned a rank for cumulative accessibility, per capita access via cumulative accessibility, gravity-based scores, and gravity-based per capita access, allowing for a multidimensional assessment of spatial equity. These ranks reflect relative performance, with lower values indicating stronger access and higher values signaling infrastructural or demographic disadvantage.

Table 22: Summary of primary school composite equity ranking

Sub-city	Primary schools rank					
	Cumulative-based accessibility		Gravity-based accessibility		Average rank	Equity status
	Cumulative accessibility	Per capita access	Gravity based scores	Per capita access		
Hadnet	5	2	1	2	2.5	Very high
Kedamay-Weyane	1	6	6	6	4.75	Moderate
Adihaki	3	7	7	7	6	Very Low
Hawelti	2	4	3	4	3.25	Very high
Ayder	4	1	2	1	2	Very high
Quiha	7	3	5	3	4.5	Moderate
Semien	6	4	4	4	4.5	Moderate

Table 23: Summary of secondary school's composite equity ranking

Sub-city	Secondary schools rank					
	Cumulative-based accessibility		Gravity-based accessibility		Average rank	Equity status
	Cumulative accessibility	Per capita access	Gravity based scores	Per capita access		
Hadnet	5	2	2	2	2.75	Very high

K/Weyane	2	2	6	2	3	Very high
Adihaki	1	7	7	7	5.5	Very low
Hawelti	3	2	3	2	2.5	Very high
Ayder	4	1	1	1	1.75	Very high
Quiha	7	5	5	5	5.5	Very low
Semien	6	5	4	5	5	Low

Table 24: Summary of health care centers composite equity ranking

Sub-city	Health care centers rank					
	Cumulative-based accessibility		Gravity-based accessibility		Average rank	Equity status
	Cumulative accessibility	Per capita access	Gravity based scores	Per capita access		
Hadnet	6	2	2	2	3	Very high
K/Weyane	1	2	6	2	2.75	Very high
Adihaki	2	7	7	7	5.75	Very low
Hawelti	5	4	3	4	4	Moderate
Ayder	3	1	1	1	1.5	Very high
Quiha	7	5	5	5	5.5	Very low
Semien	4	5	4	5	4.5	Low

Table 25: Summary of primary schools, secondary schools and health care centers composite equity ranking

Sub-city	Primary school average rank	Secondary school average rank	Health care center average rank
Hadnet	2.5	2.75	3
K/Weyane	4.75	3	2.75
Adihaki	6	5.5	5.75
Hawelti	3.25	2.5	4
Ayder	2	1.75	1.5
Quiha	4.5	5.5	5.5
Semien	4.5	5	4.5

The average accessibility ranking table consolidates multiple metrics; cumulative-based accessibility, gravity-based accessibility and per capita facility reach via cumulative based and gravity-based accessibility measure, into a single composite score for each sub city. This synthesis enables a holistic comparison of spatial equity across urban zones, smoothing out metric-specific biases and highlighting consistent patterns of advantage or disadvantage. Sub-cities with lower average ranks, such as Ayder, and Hadnet for primary schools, Ayder, and Hawelti for secondary schools, and Ayder, and Kedamay-Weyane, for health care facilities, demonstrate strong and equitable taxi transportation access to opportunities, reflecting well-distributed infrastructure and favorable population-service ratios. Conversely, sub-cities like Adihaki, Semien and Quiha exhibit highest average ranks, indicating persistent spatial and demographic barriers to taxi transportation access.

Generally, by integrating the above composite accessibility measures into a unified ranking with five equity status by using quantile mode of classification, table 26 serves as a diagnostic tool for identifying priority areas for intervention, guiding planners toward targeted investments that promote inclusive urban development.

Table 26: Equity status of sub cities

Sub-city	Primary school equity status	Secondary school equity status	Health care center equity status
Hadnet	Very high	Very high	Very high
K/Weyane	Moderate	Very high	Very High
Adihaki	Very low	Very low	Very Low
Hawelti	Very high	Very high	Moderate
Ayder	Very high	Very high	Very high
Quiha	Moderate	Very low	Very Low
Semien	Moderate	Low	Low

5. Conclusion

This thesis examined spatial equity in the accessibility of multi-modal transportation systems, specifically taxis and walking from and to taxi stations, to public schools and healthcare infrastructure in Mekelle city. Using cumulative and gravity-based accessibility models, the thesis evaluated how these opportunity points are distributed and accessed across various residential blocks using taxi and walking mode of transportation. The primary aim was to determine whether existing taxi transport routes provide equitable access to essential services, particularly public schools and healthcare centers. By integrating geospatial analysis, equity metrics, and population-normalized indicators, this thesis aimed to identify disparities in equity of taxi transport accessibility and inform evidence-based planning strategies for promoting inclusive urban mobility.

The methodological approach combined manual data cleaning, spatial modeling, and visualization through QGIS plugins and SQL expressions, ensuring both analytical precision and clarity. The composite equity rankings and priority sub-city identification provide a strong framework for targeting infrastructure investments and policy interventions. By integrating Lorenz curves, Gini coefficients, and composite rankings, the analysis revealed persistent disparities in service distribution, highlighting areas of both privilege and neglect.

The thesis employed a holistic approach to assess transportation accessibility across sub-cities, using both cumulative-based and gravity-based metrics. Key indicators calculated for each sub-city included cumulative accessibility counts, accessibility per capita (cumulative-based), gravitational accessibility sums, and gravity-based accessibility per capita. These indicators were synthesized to create a composite equity ranking table, offering a comprehensive view of how opportunities and services are distributed relative to population size and spatial proximity. Cumulative-based measures highlighted significant disparities, revealing that only 105 out of 257 residential blocks accessed primary schools within a thirty-minute travel time, with even fewer, 56 residential blocks accessed secondary schools and health care centers within thirty-minute travel time.

While cumulative measures exposed raw disparities, gravity-based models offered a more nuanced understanding of accessibility. Gravity-based measures provided deeper insights by incorporating travel impedance, illustrating that effective accessibility diminishes with distance and inadequate mobility options. The gravity-based accessibility analysis indicated that sub-cities like Hadnet and Ayder consistently ranked highest due to their good transport connectivity and shorter travel times, while Kedamay-Weyane and Adihaki ranked lowest. However, adjusting for population size exposed equity gaps, revealing that sparsely populated peripheral sub-cities like Kedamay-Weyane ranked higher due to a few accessible services serving large populations. This divergence underscores the importance of normalizing accessibility metrics to reveal hidden inequities, emphasizing the compounded disadvantages faced by underserved communities.

On the other hand, the independently calculated Lorenz curves and Gini coefficients for both cumulative-based and gravity-based measures further reinforced these disparities. Cumulative Gini values for primary schools, secondary schools, and healthcare centers were 0.381, 0.405, and 0.294 respectively, while gravity-based Gini values were 0.193, 0.205, and 0.204. These results suggest moderate inequality in accessibility distribution for the cumulative based and slightly lower inequality in accessibility for the gravity based, underscoring the importance of equity-driven policy design where planning decisions account for both service quantity and fairness in distribution. Additionally, the Lorenz curve and Gini coefficient analysis provided quantitative evidence of spatial inequality in access to public primary schools, secondary schools, and healthcare centers.

The composite equity ranking, derived from multiple accessibility indicators, provided a holistic view of spatial equity across sub-cities. Ayder, and Hadnet sub-cities ranked highest in equity of accessibility of the public primary schools, secondary schools and health care centers, similarly Kedamay-Weyane also ranks highest equity of taxi transport accessibility to reach secondary schools and healthcare centers, Hawelti sub-city also ranked highest equity of taxi transport accessibility to reach secondary schools. In contrast Adihaki followed by Quiha and Semien Sub-cities fell into the lowest equity tiers for secondary schools and health care centers using taxi transport system. Similarly, Adihaki sub-city fell in to the lowest tiers of equity of taxi transport accessibility for primary schools. The use of choropleth maps further illustrated these disparities, reinforcing the need for coordinated planning that addresses both service accessibility and population demand. Overall, the findings emphasize the urgent need for equity-centered urban strategies of taxi route planning and highlight the importance of using complementary metrics to inform inclusive urban development.

This thesis contributes to the discourse on spatial justice by translating complex geospatial analysis into actionable insights. It affirms that equity is a measurable and achievable goal if planning is guided by data and a commitment to inclusivity. Although constrained by static temporal data and limited-service categories, the research lays the groundwork for future studies that incorporate dynamic accessibility, demographic shifts, and participatory planning inputs.

6. Recommendation

Based on the findings of this thesis, several key recommendations emerge to guide future urban planning and policy development. The holistic framework used to evaluate accessibility including cumulative accessibility counts, cumulative-based accessibility per capita, gravitational accessibility sums, and gravity-based accessibility per capita provided a comprehensive lens for assessing the equity status of each sub-city. This approach highlighted notable inequity in service reach using taxi mode of transportation, emphasizing the need for targeted interventions.

Sub-cities such as Adihaki, Quiha, and Semien, which exhibited large composite accessibility scores and higher inequality indicators, should be prioritized for taxi route transportation accessibility improvement and expansion. Improving transport connectivity in these areas can help bridge existing gaps and promote more balanced development. Urban planners are encouraged to adopt this integrated methodology, as it captures both proximity-based and population-weighted dimensions of access, offering a nuanced understanding of spatial equity.

To ensure sustained progress, accessibility and equity should be monitored regularly using updated data and refined indicators. Incorporating these measures into routine urban assessments will help track improvements and identify emerging challenges. Additionally, engaging local communities in participatory planning processes can foster responsive and inclusive solutions, ensuring that interventions align with residents' lived experiences and needs.

Finally, future research should explore temporal changes in accessibility, integrate multimodal transport networks such as bajaj and bus routes, and assess qualitative aspects like service quality and user satisfaction. Expanding the analytical scope will enrich the understanding of urban equity and support the development of more resilient and inclusive cities.

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8. Annex

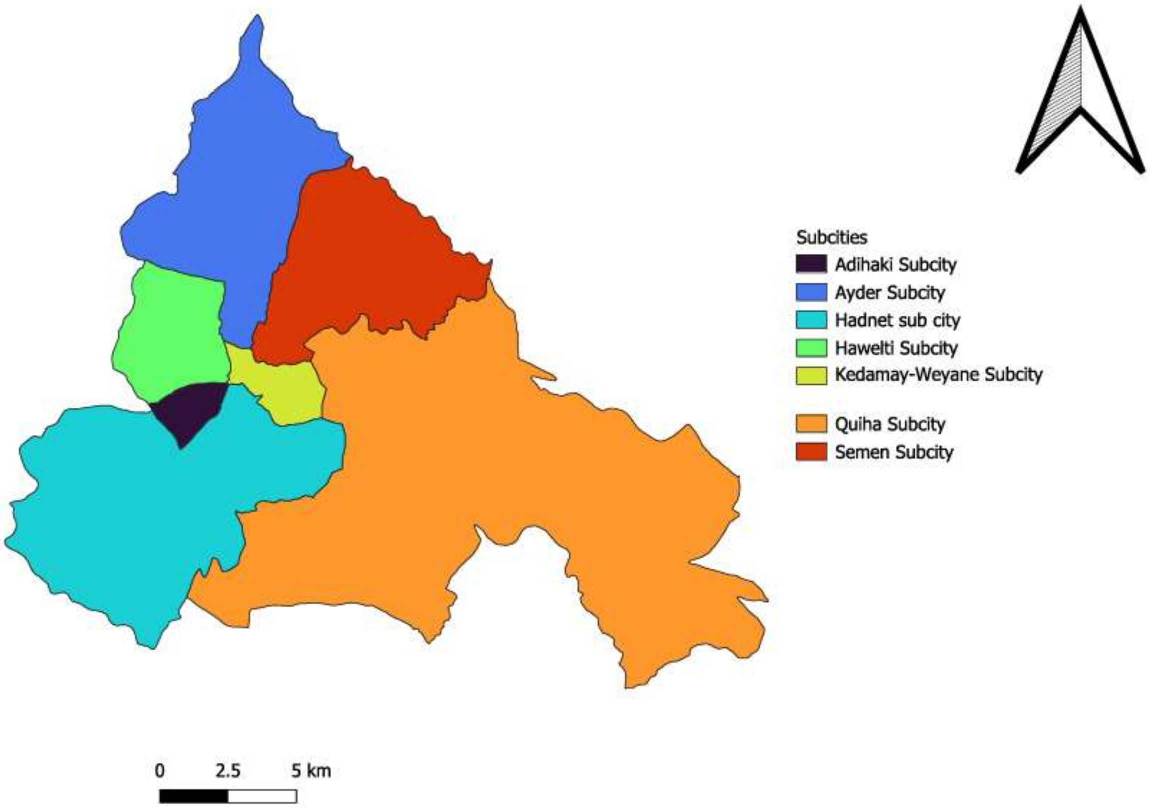
Annex I: Taxi origin and destination data

Origin	Destination	Distance(km)
Ketema	Dagimamsal	4.2
Ketema	Dagimamsal condominium	5
Jibruk	Adihawsi market	2.9
Jibruk	Kelkeldebri	3.5
Ketema	Kebele 05	3.2
Ketema	Kebele 03	2.5
Ketema	Ayder	3.2
Ketema	Adishumdihun	3.5
Ketema	Kebele 18	2.5
Kebele 16	Diaspora	5
Begoadragot	Debri	6.5
Bitsuan café	Lachi menehareya	5
Nebar mennehareya	Lachi menehareya	4.7
Bego adragot	Serawat	5
11 kebele	Adiha ketena 28	6.5
11 kebele	Daero	5.7
11 kebele	Medhanialem church	6.3
11 kebele	Adiha hadush mender	5
Ketema	Laelay Lachi	6.3
Ketema wewekma	Adicheindog	6.8
16 kebele	Arid	3.5
16 kebele	Aynalem	6
Quiha terminal	Quiha Genet hotel	10
Begoadragot	Romanat	15.5
Jibruk	Adihaki secondary school	3.5
Begoadragot	Mayweyni school	9
Adihaki Market	Medhanialem church	5.3
Adihaki Market	Daero	4.6
Ketema	Midregenet madeya	4

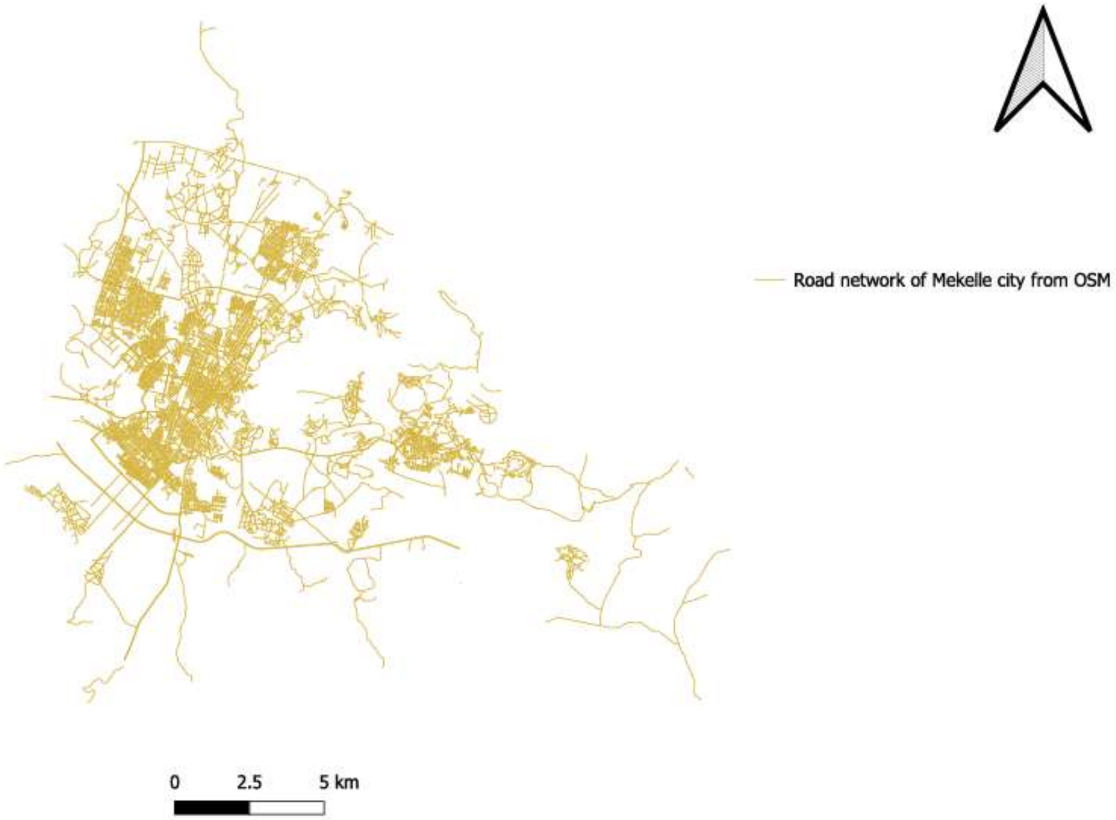
Midregenet	Dingur	4.1
Adiha	Lachi menehareya	7.4
Begoadragot	Mizer 70 care	6
Ketema	Midregenet 70 care	4.7
Jibruk	22 70 care	5
Adiha	Romanat	10.5
Adiha	Lachi hadushmender	7.1
Jibruk	70 care mizer Riwyet hospital	4.8
Begoadragot	Welela	6.3
Adihawsi market	Debri	3.6
11 kebele	Medhanialem church	5.5
Adihaki Market	Adiha hadush mender	6.4
Ketema wewekma	Lachi hadushmender	7.5
Ketema	Dingur	7.5
Jibruk	24 70 care	5.8

Annex II: Base-map

Annex III: Sub-city boundaries



Annex IV: Road network from OpenStreetMap



Annex V: Health care facilities

Healthcare facilities	**Sub city**
Mekelle General Hospital	Semen
Lachi Health Center	Semen
Ayder Referal Hospital	Ayder
Semien Health Center	Ayder
Adiha Health Center	Ayder
Adi-shumdihun Health Center	Hawelti
Momona Health center	Hawelti
Yekatit 11 Primary Hospital	Adihaki
Industrial Park Health center	Adihaki
Mekelle Health Center	Kedamay Weyane
Kasetch Health center	Hadnet
Debri Health Center	Hadnet
Aynalem Health Center	Hadnet
Quiha General Hospital	Quiha
Quiha Health center	Quiha
Hewo Primary Hospital	Quiha

Annex VI: Public schools found within Mekelle city

Region	Zone	Woreda	Ownership	Sector	Location	School
Tigray	Mekelle	Adihaki	Government	Secondary	Urban	Adi Haqi
Tigray	Mekelle	Adihaki	Government	Primary	Urban	Adi Haqi
Tigray	Mekelle	Adihaki	Government	Primary	Urban	Adi Hawsi
Tigray	Mekelle	Adihaki	Government	Primary	Urban	Debregenet
Tigray	Mekelle	Adihaki	Government	Primary	Urban	Mai Weyni No.2
Tigray	Mekelle	Adihaki	Government	Primary	Urban	Zkre Semaetat
Tigray	Mekelle	Ayder	Government	Secondary	Urban	Adiha
Tigray	Mekelle	Ayder	Government	Primary	Urban	Ayder
Tigray	Mekelle	Ayder	Government	Secondary	Urban	Ayder
Tigray	Mekelle	Ayder	Government	Secondary	Urban	Bet Hintset
Tigray	Mekelle	Ayder	Government	Primary	Urban	Bet Hintset
Tigray	Mekelle	Ayder	Government	Primary	Urban	Felege Hiwot
Tigray	Mekelle	Ayder	Government	Primary	Urban	Fresweat
Tigray	Mekelle	Ayder	Government	Primary	Urban	Gembela
Tigray	Mekelle	Ayder	Government	Secondary	Urban	Lekatit 23
Tigray	Mekelle	Ayder	Government	Primary	Urban	Mariam Dehan
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Adi Amique
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Aynalem
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Dagya
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Debri
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Fereselam
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Hadnet
Tigray	Mekelle	Hadnet	Government	Secondary	Urban	Hadnet
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Kisanet
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Mai Weyni
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Mekelle University Community School
Tigray	Mekelle	Hadnet	Government	Secondary	Urban	Mekelle University Community School
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Metkel
Tigray	Mekelle	Hadnet	Government	Primary	Urban	Shafat
Tigray	Mekelle	Hawelti	Government	Primary	Urban	Adshumduhen
Tigray	Mekelle	Hawelti	Government	Primary	Urban	Ethio China

Tigray	Mekelle	Hawelti	Government	Primary	Urban	Hawelti
Tigray	Mekelle	Hawelti	Government	Secondary	Urban	Hawelti
Tigray	Mekelle	Hawelti	Government	Primary	Urban	Hayelom
Tigray	Mekelle	Hawelti	Government	Primary	Urban	Momona
Tigray	Mekelle	Hawelti	Government	Secondary	Urban	Momona
Tigray	Mekelle	K/Weyane	Government	Primary	Urban	Atseyohannse
Tigray	Mekelle	K/Weyane	Government	Secondary	Urban	Atseyohannse
Tigray	Mekelle	K/Weyane	Government	Primary	Urban	Gerebtsedo
Tigray	Mekelle	K/Weyane	Government	Secondary	Urban	Kedamay Weyane
Tigray	Mekelle	K/ Weyane	Government	Primary	Urban	Lemlem Daero
Tigray	Mekelle	Quiha	Government	Primary	Urban	Kiros Gesese
Tigray	Mekelle	Quiha	Government	Primary	Urban	Mai Shibti
Tigray	Mekelle	Quiha	Government	Primary	Urban	Quiha
Tigray	Mekelle	Quiha	Government	Primary	Urban	Shibta
Tigray	Mekelle	Quiha	Government	Primary	Urban	Tahtay Egrihariba
Tigray	Mekelle	Quiha	Government	Primary	Urban	Tekeste Hailkiros
Tigray	Mekelle	Quiha	Government	Secondary	Urban	Weldengus
Tigray	Mekelle	Quiha	Government	Primary	Urban	Weldetatios
Tigray	Mekelle	Semen	Government	Primary	Urban	Adisalem
Tigray	Mekelle	Semen	Government	Secondary	Urban	Alene
Tigray	Mekelle	Semen	Government	Primary	Urban	Elala
Tigray	Mekelle	Semen	Government	Primary	Urban	Lachi
Tigray	Mekelle	Semen	Government	Primary	Urban	Lekatit 11
Tigray	Mekelle	Semen	Government	Primary	Urban	Mai Leham
Tigray	Mekelle	Semen	Government	Primary	Urban	Mekelle Primary School
Tigray	Mekelle	Semen	Government	Primary	Urban	Merah Eweran
Tigray	Mekelle	Semen	Government	Secondary	Urban	Mesebo
Tigray	Mekelle	Semen	Government	Primary	Urban	Msmae Ztesanom

Annex VII: Population data

Subcity	**Population size**
Adihaki	143764
Ayder	148657
Hadnet	222048
Hawelti	212263
Kedamay weyane	95818
Quiha	133000
Semen	173119
Total	1128669

9. Appendix

Appendix A: Public schools shape file

ID	Name	Latitude	Longitude	Elevation	_H_ACC	_V_ACC	_SPEED	_BEARING
1	weldu niguse highschool	13.47411	39.540433	2260.3	2	2	0	210.974
2	Weldetatyos Yiheyish primary school	13.47083	39.544267	2255.6	2.5	3	0	225.668
3	Tahtay egrihariba primary school	13.4727	39.555038	2275	2	2	0	232.225
4	Quiha primary school	13.47982	39.546592	2225.9	4.5	11	0	240.063
5	Kiros Gesese Primary school	13.47674	39.536377	2253	4	5	0	237.466
7	Mayshibti primary school	13.48756	39.522882	2228.5	6	9	0	230.909
8	Mekelle university community primary and secondary school school	13.46218	39.490847	2195.5	2.5	3	0	166.741
9	Aynalem primary school	13.45954	39.490955	2194.9	4	5	0	66.646
10	Shibta primary school	13.45683	39.522913	2223.3	3.5	6	0	62.123
15	Dagiya primary school	13.43613	39.4799	2188	3	5	0	325.66
16	Shafat primary school	13.44635	39.493945	2188.7	4	6	0	110.893
17	Mayweyni primary school	13.47301	39.463295	2133.3	5.5	9	0	142.969
23	Debri primary school	13.45517	39.436152	2102.6	5	8	0	1.077
24	Adiamuk Primary school	13.47321	39.412478	2143.2	2.5	3	0	228.585
28	Adihaki secondary school	13.47499	39.448613	2156.9	6.5	10	0	225.8
36	Adihawsi Elementary School	13.47295	39.453638	2159.3	4.5	7	0	193.784
37	Kisanet Primary School	13.47286	39.459668	2148.7	6	11	0	282.824
39	Hadinet primary school	13.47862	39.464113	2100.9	5	7	0	32.946
42	Adihaki primary school	13.48456	39.459242	2116.4	6	9	0	139.876
43	Hawelti secondary school	13.49181	39.462672	2072.6	3.5	5	0.051	87.793
44	Lemlem Daero primary school	13.49108	39.478788	2083.9	7.5	10	0	140.061

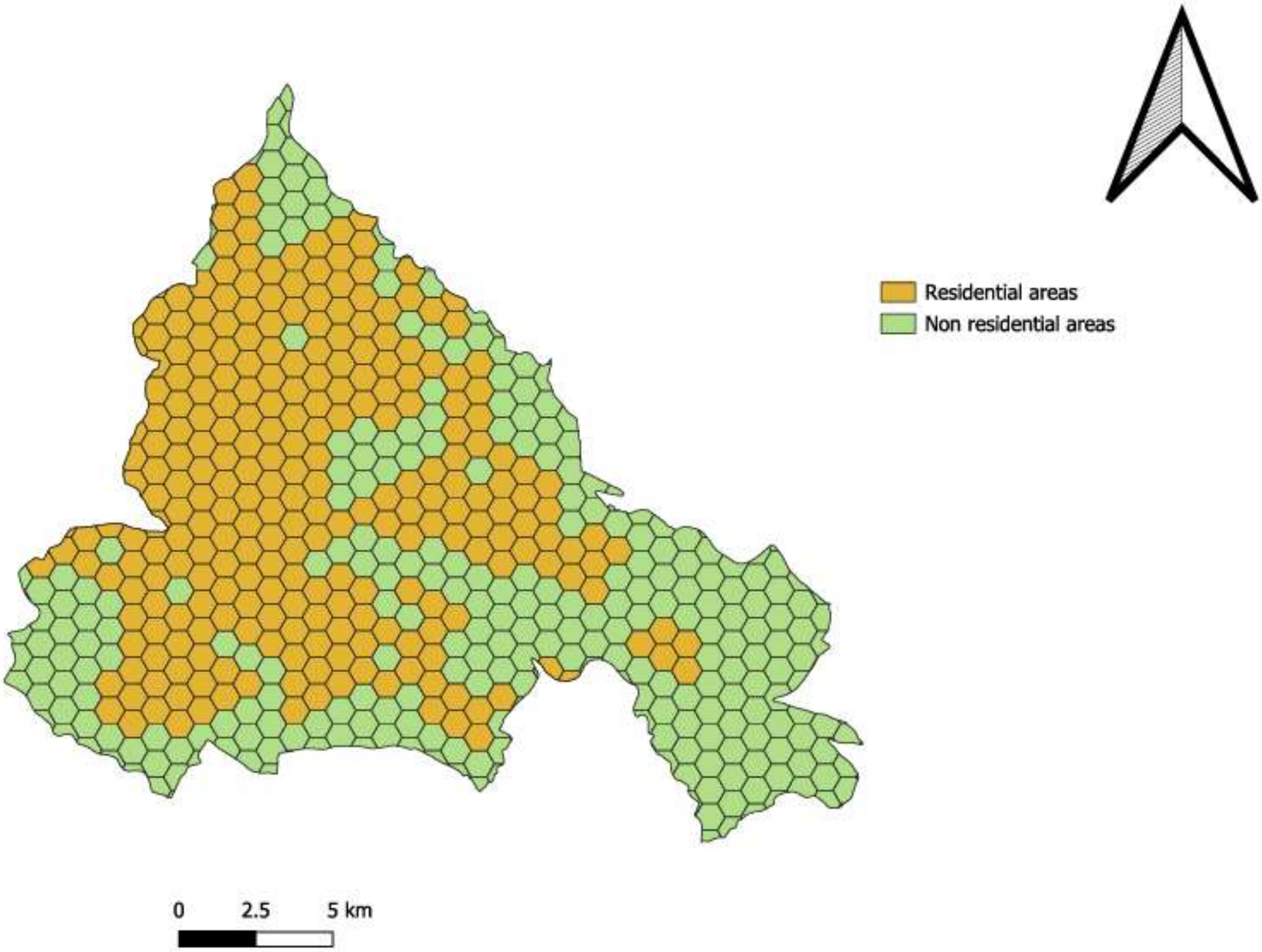
45	Atse Yohanns secondary school	13.48929	39.475967	2090.8	3.5	5	0	235.103
46	Metkel primary school	13.48282	39.47082	2092.4	8	15	0	86.372
47	Atse Yohanns Primary School	13.4897	39.474193	2078.4	2	2	0	104.003
49	Mekelle primary school	13.50336	39.473987	2056.5	3.5	6	0	83.645
50	Ayder primary school	13.51173	39.469255	2048.9	5	9	0	97.444
51	Ayder secondary school	13.51429	39.47013	2009.1	4	8	0	146.86
52	Lekatit 23 Secondary school	13.51107	39.463208	2022.9	3	5	0	338.97
53	Adishmdihun Primary School	13.51195	39.456793	2028.9	7	10	0	132.467
63	Zikresemaetat Primary School	13.48333	39.441648	2131	2.5	3	0	263.714
64	Mayweyni(@ Mayemori) Primary school	13.48916	39.400572	2165.4	2	2	0	242.646
65	Debregenet primary school	13.50286	39.413547	2135.1	3.5	4	0	7.317
66	Momoa Secondary school	13.51017	39.445002	2054.2	2.5	3	0.669	210.433
71	Adiha secondary school	13.52441	39.456927	2004.1	6.5	8	0	335.465
73	Ethio-China Primary School	13.52066	39.447928	2030.3	4	5	0	233.761
79	Momona primary school	13.504	39.449558	2070.6	6	9	0	317.673
81	Hawelti primary school	13.4995	39.458783	2057.1	3.5	5	0	124.443
83	Hayelom primary school	13.5006	39.453805	2064.3	6	8	0	192.028
86	Gerebtsedo primary school	13.50102	39.46714	2047.2	2.5	4	0.103	300.872
87	Gerebtsedo secondary school	13.50215	39.465778	2047.6	4	5	0	114.477
88	Eilala primary school	13.51001	39.482295	2034.4	3	5	0	297.344
89	Lekatit 11 primary school	13.5169	39.482435	2015.3	9	14	0.051	309.004
92	Alene secondary school	13.50107	39.480373	2054.3	4.5	6	0	105.909
93	Mayliham primary school	13.49946	39.48228	2069.4	3	4	0	307.099
97	Messebo secondary school	13.53445	39.500187	2026.3	9.5	12	0	5.085
99	Lachi primary school	13.53607	39.488655	2022.3	7	10	0	238.337

100	Mariamdehan primary school	13.55865	39.468625	1962.9	2.5	3	0	244.31
101	Bethintset primary and secondary school	13.55128	39.451437	1941.1	6.5	7	0	203.262
103	Adisalem primary school	13.52379	39.521943	2034.4	6	8	0.154	129.498
104	Freswuat primary school	13.52073	39.47557	2005.5	7	12	0	85.09

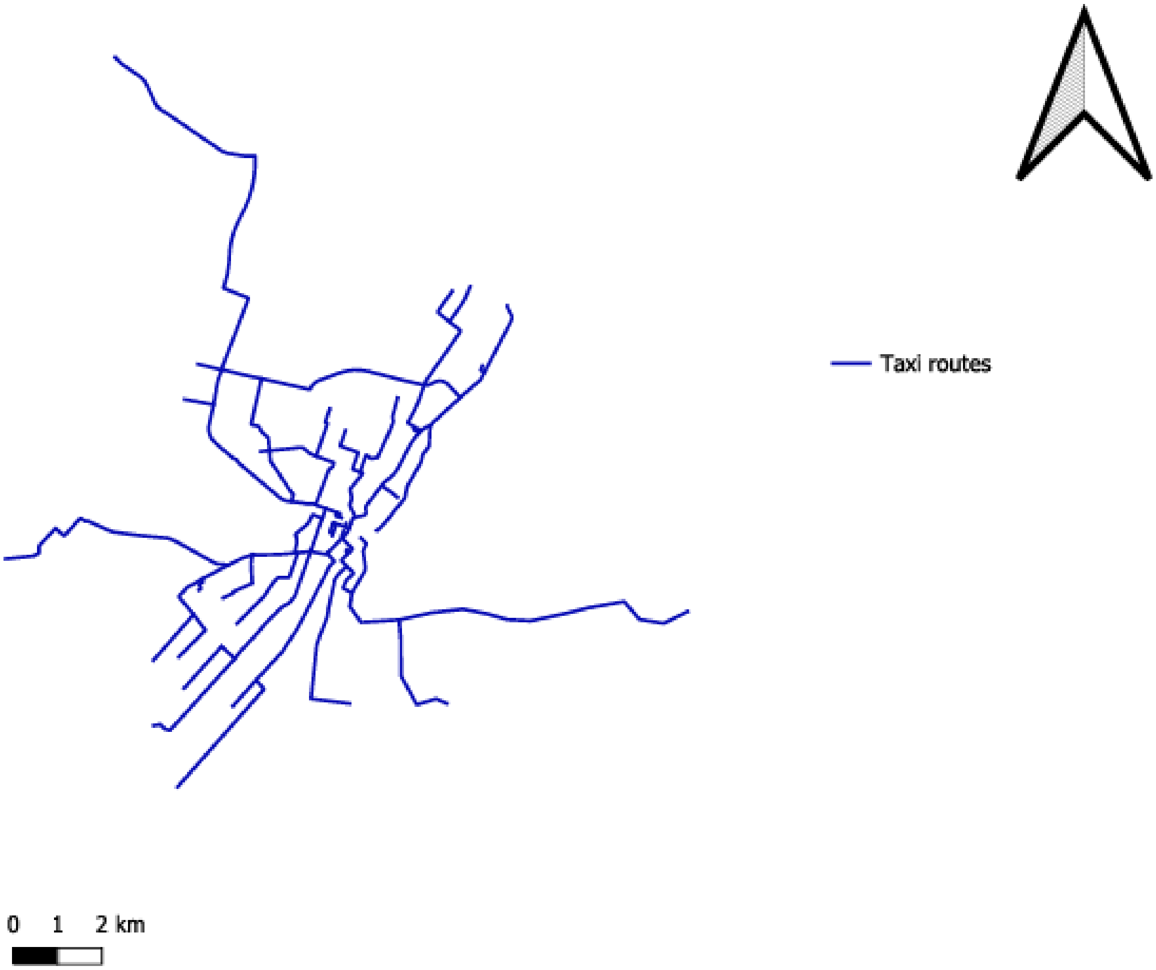
Appendix B: Health care centers shape file

ID	Name	Latitude	Longitude	Elevation	Ortho_ht	H_accuracy	V_accuracy	Speed	Bearing
1	quiha general hospital	13.47399	39.53713	2270.3	0	2	2	0	231.731
2	Quiha health care	13.46906	39.54586	2253.6	0	2	2	0	261.884
3	Hewo primary hospital	13.48407	39.53636	2239.8	0	3	4	0	244.717
4	Aynalem healthcare	13.4586	39.49453	2198.7	0	4	7	0	139.728
5	Debri Health care	13.44332	39.43729	2108.9	0	2.5	4	0	36.341
6	Kassech Asfaw healthcare	13.47705	39.46059	2109	0	3.5	5	0	67.017
7	Mekelle health care	13.48614	39.47303	2088.8	0	3	3	0	11.985
8	Semien health center	13.51071	39.475	2027.5	0	2	3	0	248.799
9	Ayder referral hospital	13.51155	39.46916	2026.9	0	2.5	2	0	181.485
10	Lekatit 11 primary hospital	13.48284	39.44663	2127.4	0	2.5	4	0	234.887
12	Adishimdhun health care	13.51673	39.45334	2028.6	0	4.5	6	0	135.122
13	Adiha health care	13.5261	39.4524	2015.8	0	4.5	5	0	109.069
14	Momona health centre	13.50127	39.44791	2071.9	0	2.5	4	0	202.308
15	Mekelle General Hospital	13.50025	39.4835	2073.4	0	4	5	0	359.383
16	Lachi health centre	13.53916	39.49717	2024.4	0	3	6	0	36.272

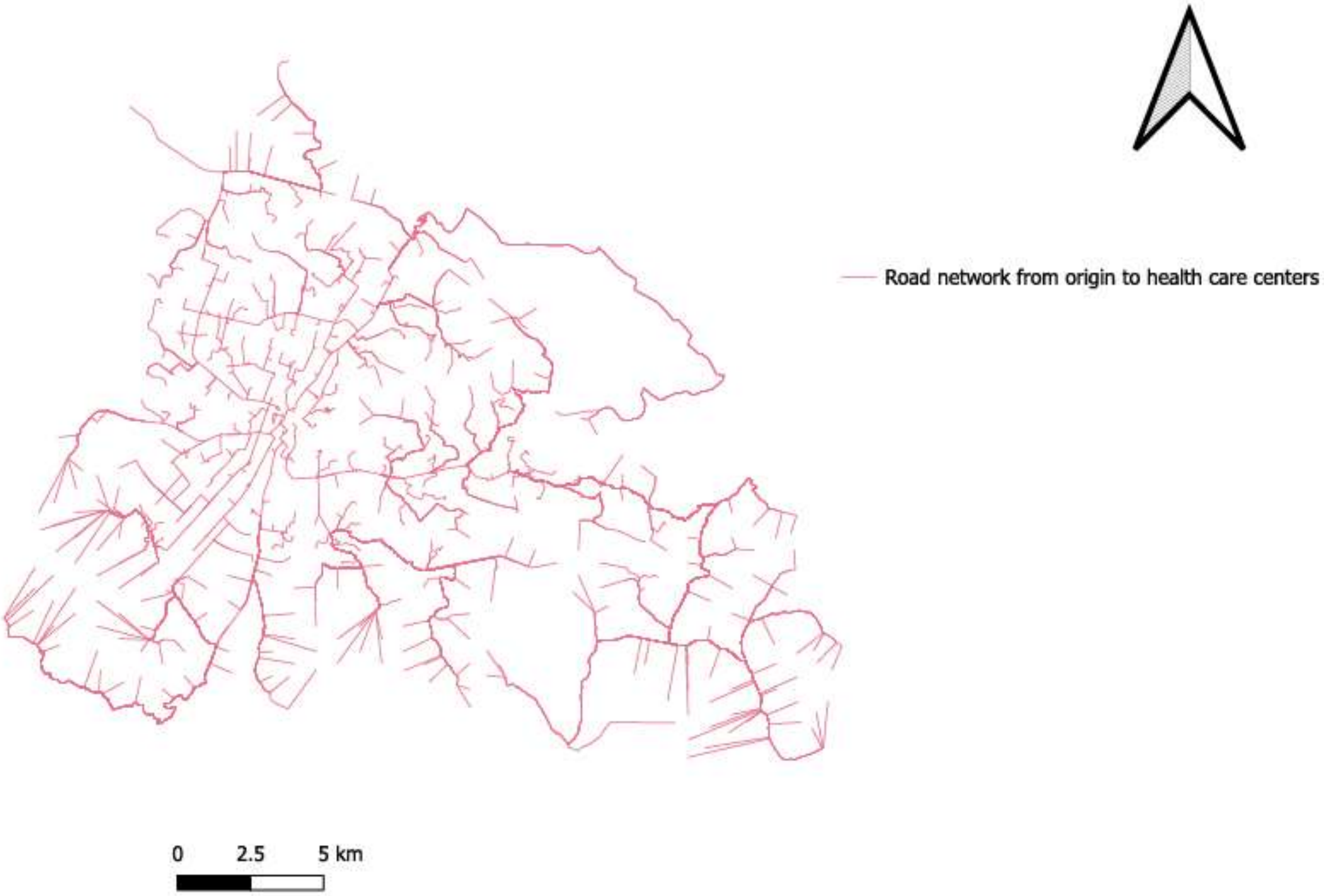
Appendix C: Grid cells



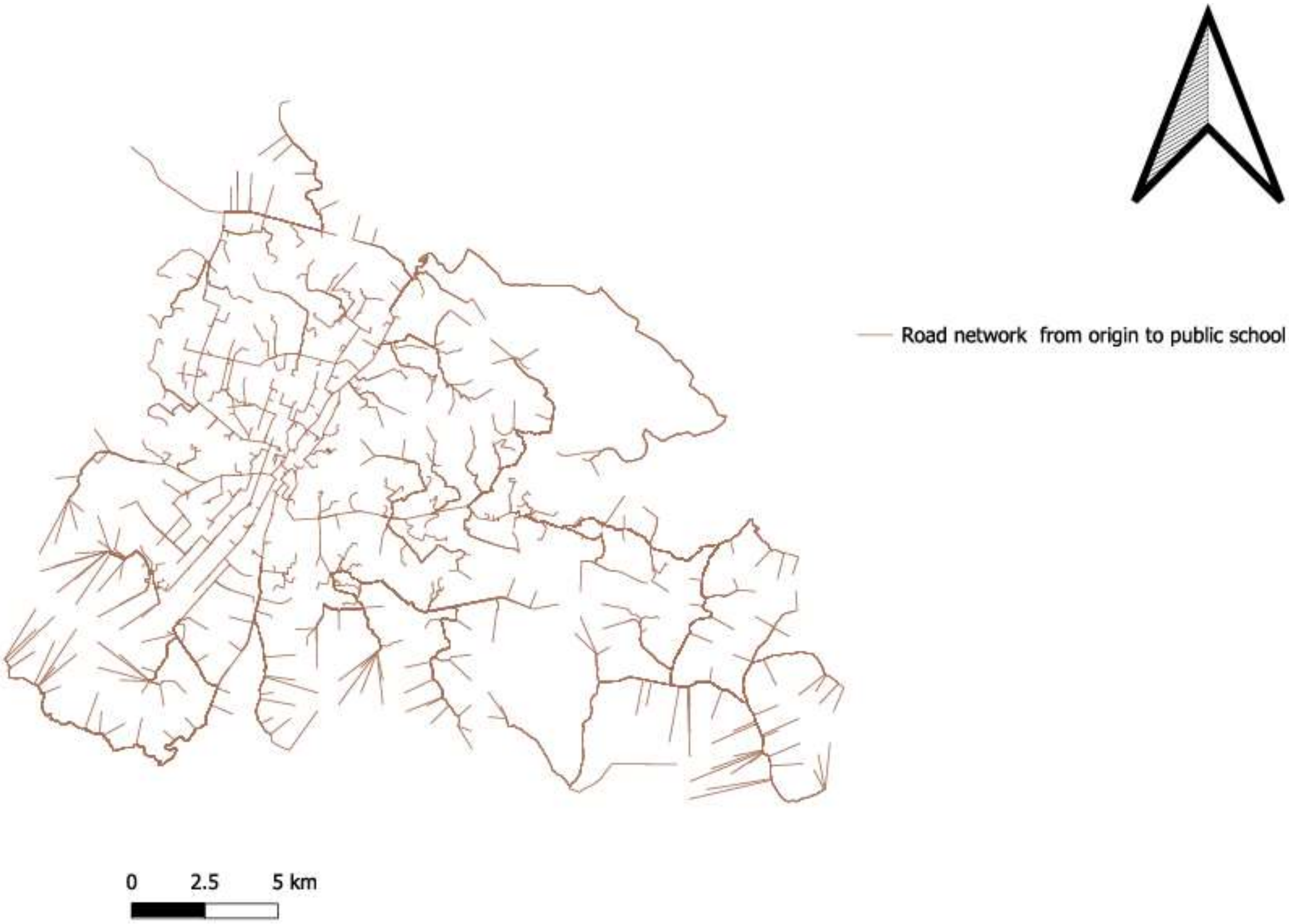
Appendix D: Taxi routes



Appendix E: Road network residential area to public health care



Appendix F: Road network residential area to public school



Appendix G: Fastest path from origin to primary school

Origin id	Destination	Entry cost	Network cost	Exit cost	Total cost	Total cost (min)	Gravitational accessibility	Residential
1	63	0	3276	0	3276	55	0.025	residential
2	63	0	667	0	666.69	11	0.084	residential
3	63	0	1763	0	1763.3	29	0.043	residential
4	23	0	5061	0	5061.1	84	0.018	residential
5	63	0	285	0	285.19	5	0.146	residential
7	36	0	857	0	857.43	14	0.074	residential
9	63	0	1752	0	1752.2	29	0.064	residential
10	42	0	2139	0	2139.2	36	0.046	residential
11	36	0	603	0	602.71	10	0.096	residential
12	42	0	1584	0	1584.1	26	0.058	residential
13	36	0	821	0	821.47	14	0.083	residential
14	17	0	1608	0	1608.2	27	0.056	residential
15	42	0	633	0	632.98	11	0.174	residential
16	36	0	1190	0	1189.7	20	0.082	residential
17	17	0	470	0	470.06	8	0.146	residential
18	46	0	3299	0	3298.8	55	0.031	residential
19	101	0	14277	0	14277	238	0.006	residential
20	81	0	12653	0	12653	211	0.008	residential
21	81	0	9772	0	9772	163	0.011	residential
24	101	0	8500	0	8499.5	142	0.011	residential
25	101	0	11850	0	11850	198	0.008	residential
26	81	0	13763	0	13763	229	0.007	residential
27	81	0	7354	0	7353.9	123	0.015	residential
28	81	0	6667	0	6667.5	111	0.017	residential
29	81	0	12371	0	12371	206	0.008	residential
32	101	0	6076	0	6076.1	101	0.015	residential
33	101	0	10484	0	10484	175	0.009	residential
34	53	0	2809	0	2808.8	47	0.037	residential
35	73	0	2917	0	2917.4	49	0.04	residential
36	73	0	3666	0	3665.7	61	0.032	residential
37	81	0	2680	0	2680.1	45	0.043	residential
39	101	0	2069	0	2069.2	34	0.034	residential

42	101	0	2252	0	2251.7	38	0.031	residential
43	101	0	2622	0	2621.7	44	0.034	residential
44	53	0	1996	0	1996.3	33	0.051	residential
45	53	0	1627	0	1626.8	27	0.056	residential
46	73	0	658	0	657.69	11	0.068	residential
47	53	0	2921	0	2920.7	49	0.032	residential
48	79	0	530	0	529.85	9	0.08	residential
51	101	0	5541	0	5540.7	92	0.016	residential
52	101	0	2560	0	2559.9	43	0.03	residential
53	101	0	2943	0	2943.1	49	0.027	residential
54	101	0	6016	0	6016	100	0.015	residential
55	101	0	6071	0	6071.3	101	0.014	residential
56	53	0	4031	0	4031.5	67	0.027	residential
57	53	0	2938	0	2937.6	49	0.034	residential
58	53	0	1037	0	1037.1	17	0.073	residential
59	53	0	760	0	759.97	13	0.083	residential
60	53	0	717	0	716.6	12	0.1	residential
61	83	0	1112	0	1112.2	19	0.074	residential
63	101	0	8917	0	8916.9	149	0.01	residential
64	101	0	6157	0	6157	103	0.015	residential
65	101	0	5804	0	5803.7	97	0.016	residential
66	101	0	4251	0	4251.2	71	0.021	residential
67	53	0	14613	0	14613	244	0.007	residential
68	101	0	9877	0	9876.7	165	0.009	residential
69	53	0	6196	0	6196.3	103	0.018	residential
70	53	0	3314	0	3313.9	55	0.031	residential
71	53	0	3426	0	3426.4	57	0.029	residential
72	53	0	673	0	672.93	11	0.107	residential
73	81	0	1287	0	1287.3	21	0.08	residential
74	86	0	1515	0	1514.6	25	0.074	residential
81	100	0	2304	0	2304.2	38	0.011	residential
82	53	0	11419	0	11419	190	0.009	residential
83	53	0	6500	0	6500	108	0.017	residential
84	53	0	3825	0	3824.6	64	0.029	residential
85	53	0	5656	0	5655.7	94	0.02	residential

86	50	0	889	0	888.94	15	0.1	residential
87	86	0	375	0	375.23	6	0.189	residential
88	86	0	1020	0	1020	17	0.09	residential
95	100	0	11673	0	11673	195	0.007	residential
96	99	0	11088	0	11088	185	0.008	residential
97	53	0	8654	0	8654.1	144	0.013	residential
99	53	0	1760	0	1759.9	29	0.059	residential
100	104	0	772	0	772.34	13	0.043	residential
101	49	0	1417	0	1416.8	24	0.035	residential
102	49	0	919	0	919.04	15	0.051	residential
103	93	0	1421	0	1420.9	24	0.039	residential
107	100	0	11889	0	11889	198	0.007	residential
108	99	0	11522	0	11522	192	0.008	residential
109	99	0	6815	0	6814.5	114	0.014	residential
110	99	0	3650	0	3650.2	61	0.015	residential
111	53	0	7615	0	7614.6	127	0.015	residential
112	93	0	2988	0	2987.6	50	0.039	residential
113	89	0	337	0	337.3	6	0.108	residential
114	93	0	1363	0	1363.4	23	0.044	residential
115	93	0	941	0	941.13	16	0.047	residential
118	100	0	12898	0	12898	215	0.006	residential
119	100	0	12898	0	12898	215	0.006	residential
120	99	0	8503	0	8503.4	142	0.011	residential
121	99	0	4116	0	4116	69	0.022	residential
122	99	0	2857	0	2857	48	0.029	residential
123	93	0	3353	0	3353	56	0.032	residential
124	93	0	2675	0	2675	45	0.036	residential
125	93	0	2255	0	2255	38	0.036	residential
128	93	0	18517	0	18517	309	0.005	residential
129	93	0	14907	0	14907	248	0.006	residential
130	99	0	10264	0	10264	171	0.009	residential
131	99	0	3990	0	3990	67	0.024	residential
132	99	0	2524	0	2524	42	0.035	residential
133	93	0	4352	0	4352	73	0.023	residential
134	93	0	1903	0	1903	32	0.046	residential

135	93	0	3449	0	3449	57	0.027	residential
141	99	0	4344	0	4344	72	0.022	residential
142	93	0	3823	0	3823	64	0.026	residential
143	93	0	2257	0	2257	38	0.041	residential
144	93	0	5426	0	5426	90	0.018	residential
145	93	0	6447	0	6447	107	0.015	residential
153	64	0	8819	0	8819	147	0.009	residential
160	64	0	5784	0	5784	96	0.014	residential
161	64	0	7175	0	7175	120	0.011	residential
169	24	0	783	0	783	13	0.028	residential
170	24	0	4365	0	4365	73	0.009	residential
178	63	0	8104	0	8104	135	0.012	residential
180	24	0	5458	0	5458	91	0.011	residential
184	17	0	14280	0	14280	238	0.007	residential
185	17	0	13214	0	13214	220	0.007	residential
188	63	0	4385	0	4385	73	0.021	residential
189	23	0	6521	0	6521	109	0.014	residential
190	23	0	5255	0	5255	88	0.017	residential
191	23	0	6107	0	6107	102	0.015	residential
192	23	0	5348	0	5348	89	0.017	residential
193	17	0	6925	0	6925	115	0.015	residential
194	17	0	10119	0	10119	169	0.01	residential
195	17	0	11468	0	11468	191	0.008	residential
198	23	0	2564	0	2564	43	0.031	residential
199	23	0	2838	0	2838	47	0.029	residential
200	17	0	4027	0	4027	67	0.025	residential
201	17	0	5995	0	5995	100	0.017	residential
202	17	0	11739	0	11739	196	0.008	residential
207	17	0	3701	0	3701	62	0.027	residential
208	17	0	2923	0	2923	49	0.034	residential
209	17	0	4871	0	4871	81	0.021	residential
210	17	0	6633	0	6633	111	0.015	residential
211	17	0	14690	0	14690	245	0.006	residential
215	17	0	1663	0	1663	28	0.054	residential
217	17	0	5793	0	5793	97	0.018	residential

218	17	0	8533	0	8533	142	0.012	residential
219	17	0	9408	0	9408	157	0.011	residential
222	17	0	1280	0	1280	21	0.068	residential
223	17	0	3332	0	3332	56	0.03	residential
225	46	0	13759	0	13759	229	0.007	residential
226	17	0	13443	0	13443	224	0.007	residential
229	17	0	3913	0	3913	65	0.026	residential
230	17	0	6657	0	6657	111	0.015	residential
232	46	0	10589	0	10589	176	0.009	residential
236	46	0	882	0	882	15	0.095	residential
237	46	0	889	0	889	15	0.091	residential
238	46	0	2129	0	2129	35	0.045	residential
239	46	0	2503	0	2503	42	0.039	residential
240	46	0	5172	0	5172	86	0.02	residential
241	46	0	8007	0	8007	133	0.013	residential
245	47	0	1040	0	1040	17	0.089	residential
246	47	0	1659	0	1659	28	0.058	residential
247	47	0	944	0	944	16	0.092	residential
248	46	0	5035	0	5035	84	0.021	residential
249	46	0	4351	0	4351	73	0.024	residential
250	46	0	8420	0	8420	140	0.012	residential
251	15	0	4864	0	4864	81	0.007	residential
252	46	0	14894	0	14894	248	0.006	residential
253	46	0	17031	0	17031	284	0.005	residential
254	9	0	5202	0	5202	87	0.021	residential
255	9	0	1516	0	1516	25	0.065	residential
257	9	0	1947	0	1947	32	0.038	residential
258	9	0	3418	0	3418	57	0.022	residential
259	15	0	3431	0	3431	57	0.011	residential
260	15	0	4066	0	4066	68	0.008	residential
261	15	0	6870	0	6870	115	0.006	residential
264	9	0	4536	0	4536	76	0.024	residential
266	9	0	2266	0	2266	38	0.026	residential
267	9	0	3630	0	3630	61	0.021	residential
268	9	0	6586	0	6586	110	0.013	residential

269	16	0	3711	0	3711	62	0.008	residential
270	16	0	10638	0	10638	177	0.004	residential
272	9	0	5370	0	5370	89	0.021	residential
275	9	0	2612	0	2612	44	0.025	residential
276	9	0	3484	0	3484	58	0.021	residential
277	16	0	1948	0	1948	32	0.011	residential
278	16	0	4440	0	4440	74	0.006	residential
281	9	0	8576	0	8576	143	0.013	residential
282	9	0	3618	0	3618	60	0.031	residential
286	9	0	7813	0	7813	130	0.011	residential
288	16	0	6802	0	6802	113	0.005	residential
291	64	0	5175	0	5175	86	0.019	residential
293	42	0	2543	0	2543	42	0.051	residential
294	47	0	839	0	839	14	0.096	residential
295	93	0	4933	0	4933	82	0.019	residential
305	93	0	7696	0	7696	128	0.013	residential
306	93	0	9395	0	9395	157	0.01	residential
309	9	0	13516	0	13516	225	0.007	residential
310	9	0	7542	0	7542	126	0.015	residential
311	9	0	2538	0	2538	42	0.045	residential
313	9	0	9421	0	9421	157	0.011	residential
315	10	0	7620	0	7620	127	0.011	residential
316	16	0	8825	0	8825	147	0.004	residential
323	7	0	3929	0	3929	65	0.009	residential
324	9	0	10654	0	10654	178	0.01	residential
325	5	0	5404	0	5404	90	0.019	residential
328	10	0	6360	0	6360	106	0.007	residential
329	10	0	4160	0	4160	69	0.009	residential
330	10	0	16647	0	16647	277	0.004	residential
331	10	0	20253	0	20253	338	0.004	residential
332	10	0	22510	0	22510	375	0.003	residential
335	103	0	1003	0	1003	17	0.023	residential
336	103	0	3410	0	3410	57	0.009	residential
337	103	0	7394	0	7394	123	0.006	residential
338	7	0	5071	0	5071	85	0.008	residential

339	7	0	3314	0	3314	55	0.01	residential
340	7	0	1377	0	1377	23	0.022	residential
341	5	0	2046	0	2046	34	0.04	residential
344	10	0	2372	0	2372	40	0.01	residential
347	10	0	21456	0	21456	358	0.003	residential
348	10	0	24580	0	24580	410	0.003	residential
351	103	0	6421	0	6421	107	0.006	residential
352	103	0	7496	0	7496	125	0.006	residential
353	5	0	13119	0	13119	219	0.007	residential
355	5	0	6856	0	6856	114	0.013	residential
356	5	0	2208	0	2208	37	0.032	residential
357	5	0	4476	0	4476	75	0.019	residential
363	10	0	24821	0	24821	414	0.003	residential
364	10	0	29686	0	29686	495	0.002	residential
370	5	0	11536	0	11536	192	0.008	residential
371	5	0	8266	0	8266	138	0.011	residential
372	5	0	5077	0	5077	85	0.017	residential
373	5	0	2022	0	2022	34	0.03	residential
374	2	0	5515	0	5515	92	0.012	residential
379	3	0	78778	0	78778	1313	0.001	residential
386	5	0	15550	0	15550	259	0.006	residential
387	5	0	7728	0	7728	129	0.011	residential
388	5	0	2843	0	2843	47	0.024	residential
389	3	0	5316	0	5316	89	0.016	residential
401	5	0	11224	0	11224	187	0.008	residential
402	4	0	3467	0	3467	58	0.012	residential
403	3	0	4109	0	4109	68	0.017	residential
404	3	0	2174	0	2174	36	0.014	residential
408	10	0	16984	0	16984	283	0.004	residential
414	3	0	2743	0	2743	46	0.014	residential
415	3	0	1705	0	1705	28	0.017	residential
419	3	0	57815	0	57815	964	0.001	residential
423	3	0	6077	0	6077	101	0.008	residential
424	3	0	6272	0	6272	105	0.008	residential
425	3	0	13915	0	13915	232	0.004	residential

431	3	0	8670	0	8670	145	0.007	residential
442	3	0	49959	0	49959	833	0.001	residential
451	3	0	49507	0	49507	825	0.001	residential
452	3	0	47992	0	47992	800	0.001	residential
461	3	0	51223	0	51223	854	0.001	residential
462	3	0	38979	0	38979	650	0.002	residential
538	3	0	74551	0	74551	1243	0.001	residential
540	93	0	9401	0	9401	157	0.011	residential
541	93	0	5929	0	5929	99	0.017	residential
543	93	0	5104	0	5104	85	0.021	residential
546	93	0	9948	0	9948	166	0.01	residential
548	93	0	7996	0	7996	133	0.013	residential
549	93	0	12890	0	12890	215	0.007	residential
550	103	0	6407	0	6407	107	0.008	residential
554	103	0	4247	0	4247	71	0.009	residential

Appendix H: Fastest path from origin to secondary schools

Origin id	Destination	Entry cost	Network cost	Exit Cost	Total cost	Total cost (min)	Gravitational accessibility	Residential
1	43	0	4588	0	4588	76	0.009	residential
2	43	0	1593	0	1593	27	0.025	residential
3	43	0	2690	0	2690	45	0.016	residential
4	43	0	6796	0	6796	113	0.006	residential
5	43	0	1597	0	1597	27	0.025	residential
7	43	0	1991	0	1991	33	0.023	residential
9	43	0	1533	0	1533	26	0.026	residential
10	28	0	2027	0	2027	34	0.022	residential
11	43	0	1736	0	1736	29	0.026	residential
12	43	0	1798	0	1798	30	0.025	residential
13	43	0	1607	0	1607	27	0.027	residential
14	43	0	2620	0	2620	44	0.018	residential
15	43	0	220	0	220	4	0.164	residential
16	43	0	1388	0	1388	23	0.031	residential
17	43	0	1482	0	1482	25	0.03	residential
18	45	0	4056	0	4056	68	0.012	residential
19	71	0	15106	0	15106	252	0.002	residential
20	66	0	11360	0	11360	189	0.003	residential
21	66	0	8479	0	8479	141	0.004	residential
24	71	0	9329	0	9329	155	0.004	residential
25	71	0	12679	0	12679	211	0.003	residential
26	66	0	12470	0	12470	208	0.003	residential
27	66	0	6061	0	6061	101	0.006	residential
28	66	0	5375	0	5375	90	0.007	residential
29	66	0	11078	0	11078	185	0.003	residential
32	71	0	6905	0	6905	115	0.006	residential
33	71	0	11313	0	11313	189	0.003	residential
34	71	0	2182	0	2182	36	0.02	residential
35	66	0	2261	0	2261	38	0.02	residential
36	66	0	3009	0	3009	50	0.015	residential
37	66	0	1387	0	1387	23	0.025	residential
39	71	0	2898	0	2898	48	0.015	residential

42	71	0	3198	0	3198	53	0.014	residential
43	71	0	2705	0	2705	45	0.016	residential
44	71	0	1369	0	1369	23	0.031	residential
45	71	0	1000	0	1000	17	0.039	residential
46	66	0	1990	0	1990	33	0.023	residential
47	71	0	3214	0	3214	54	0.015	residential
48	66	0	2269	0	2269	38	0.021	residential
51	71	0	6370	0	6370	106	0.007	residential
52	71	0	3389	0	3389	56	0.013	residential
53	71	0	3772	0	3772	63	0.011	residential
54	71	0	6845	0	6845	114	0.006	residential
55	71	0	7018	0	7018	117	0.006	residential
56	71	0	3404	0	3404	57	0.013	residential
57	71	0	2310	0	2310	39	0.018	residential
58	71	0	552	0	552	9	0.068	residential
59	52	0	1166	0	1166	19	0.045	residential
60	52	0	922	0	922	15	0.051	residential
61	66	0	2049	0	2049	34	0.027	residential
63	71	0	9746	0	9746	162	0.004	residential
64	71	0	6986	0	6986	116	0.006	residential
65	71	0	6633	0	6633	111	0.006	residential
66	71	0	5080	0	5080	85	0.008	residential
67	71	0	13823	0	13823	230	0.003	residential
68	71	0	10823	0	10823	180	0.003	residential
69	71	0	5406	0	5406	90	0.008	residential
70	71	0	2524	0	2524	42	0.016	residential
71	52	0	3278	0	3278	55	0.014	residential
72	52	0	446	0	446	7	0.09	residential
73	52	0	1693	0	1693	28	0.034	residential
74	43	0	1122	0	1122	19	0.036	residential
81	71	0	13134	0	13134	219	0.003	residential
82	71	0	10629	0	10629	177	0.004	residential
83	71	0	5710	0	5710	95	0.007	residential
84	71	0	3035	0	3035	51	0.014	residential
85	71	0	4866	0	4866	81	0.009	residential

86	51	0	660	0	660	11	0.082	residential
87	52	0	322	0	322	5	0.139	residential
88	43	0	1318	0	1318	22	0.038	residential
95	71	0	14339	0	14339	239	0.002	residential
96	71	0	11842	0	11842	197	0.003	residential
97	71	0	7864	0	7864	131	0.005	residential
99	71	0	970	0	970	16	0.041	residential
100	71	0	4178	0	4178	70	0.01	residential
101	92	0	3422	0	3422	57	0.009	residential
102	92	0	2482	0	2482	41	0.012	residential
103	92	0	1149	0	1149	19	0.023	residential
107	71	0	14554	0	14554	243	0.002	residential
108	97	0	12231	0	12231	204	0.003	residential
109	97	0	7524	0	7524	125	0.006	residential
110	97	0	7647	0	7647	127	0.006	residential
111	71	0	6825	0	6825	114	0.006	residential
112	71	0	2291	0	2291	38	0.02	residential
113	92	0	3141	0	3141	52	0.01	residential
114	92	0	1203	0	1203	20	0.025	residential
115	92	0	1169	0	1169	19	0.024	residential
118	71	0	15563	0	15563	259	0.002	residential
119	71	0	15563	0	15563	259	0.002	residential
120	71	0	9257	0	9257	154	0.005	residential
121	97	0	4825	0	4825	80	0.01	residential
122	71	0	3739	0	3739	62	0.013	residential
123	71	0	3093	0	3093	52	0.016	residential
124	92	0	2515	0	2515	42	0.018	residential
125	92	0	2095	0	2095	35	0.018	residential
128	92	0	18356	0	18356	306	0.002	residential
129	92	0	14747	0	14747	246	0.002	residential
130	97	0	10974	0	10974	183	0.004	residential
131	71	0	4460	0	4460	74	0.011	residential
132	97	0	2950	0	2950	49	0.017	residential
133	92	0	4191	0	4191	70	0.01	residential
134	92	0	1743	0	1743	29	0.025	residential

135	92	0	3289	0	3289	55	0.012	residential
141	97	0	4769	0	4769	79	0.01	residential
142	92	0	3663	0	3663	61	0.012	residential
143	92	0	2096	0	2096	35	0.021	residential
144	92	0	5266	0	5266	88	0.008	residential
145	92	0	6286	0	6286	105	0.006	residential
153	43	0	11236	0	11236	187	0.003	residential
160	43	0	8200	0	8200	137	0.005	residential
161	43	0	9592	0	9592	160	0.004	residential
169	43	0	15572	0	15572	260	0.002	residential
170	43	0	13321	0	13321	222	0.003	residential
178	43	0	9031	0	9031	151	0.004	residential
180	43	0	10481	0	10481	175	0.004	residential
184	43	0	15292	0	15292	255	0.002	residential
185	43	0	14227	0	14227	237	0.003	residential
188	43	0	5311	0	5311	89	0.008	residential
189	43	0	8256	0	8256	138	0.005	residential
190	43	0	6990	0	6990	117	0.006	residential
191	43	0	7841	0	7841	131	0.005	residential
192	43	0	7083	0	7083	118	0.006	residential
193	43	0	7937	0	7937	132	0.005	residential
194	43	0	11132	0	11132	186	0.004	residential
195	43	0	12480	0	12480	208	0.003	residential
198	43	0	4299	0	4299	72	0.011	residential
199	43	0	4573	0	4573	76	0.01	residential
200	43	0	5039	0	5039	84	0.009	residential
201	43	0	7007	0	7007	117	0.006	residential
202	43	0	12751	0	12751	213	0.003	residential
207	43	0	4713	0	4713	79	0.01	residential
208	43	0	3936	0	3936	66	0.012	residential
209	43	0	5883	0	5883	98	0.008	residential
210	43	0	7645	0	7645	127	0.006	residential
211	43	0	15702	0	15702	262	0.002	residential
215	43	0	2675	0	2675	45	0.017	residential
217	43	0	6805	0	6805	113	0.006	residential

218	43	0	9545	0	9545	159	0.004	residential
219	43	0	10420	0	10420	174	0.004	residential
222	43	0	2292	0	2292	38	0.02	residential
223	43	0	4345	0	4345	72	0.011	residential
225	45	0	14516	0	14516	242	0.003	residential
226	43	0	14455	0	14455	241	0.003	residential
229	43	0	4925	0	4925	82	0.009	residential
230	43	0	7670	0	7670	128	0.006	residential
232	45	0	11346	0	11346	189	0.004	residential
236	45	0	1558	0	1558	26	0.032	residential
237	45	0	1646	0	1646	27	0.031	residential
238	45	0	2886	0	2886	48	0.017	residential
239	45	0	3261	0	3261	54	0.015	residential
240	45	0	5930	0	5930	99	0.008	residential
241	45	0	8764	0	8764	146	0.005	residential
245	45	0	217	0	217	4	0.149	residential
246	45	0	1561	0	1561	26	0.026	residential
247	45	0	872	0	872	15	0.044	residential
248	45	0	5792	0	5792	97	0.008	residential
249	45	0	5108	0	5108	85	0.009	residential
250	45	0	9177	0	9177	153	0.005	residential
251	8	0	16302	0	16302	272	0.002	residential
252	45	0	15652	0	15652	261	0.002	residential
253	45	0	17788	0	17788	296	0.002	residential
254	45	0	5209	0	5209	87	0.009	residential
255	45	0	1522	0	1522	25	0.029	residential
257	8	0	3081	0	3081	51	0.016	residential
258	8	0	4553	0	4553	76	0.009	residential
259	8	0	12782	0	12782	213	0.003	residential
260	8	0	15504	0	15504	258	0.002	residential
261	8	0	18309	0	18309	305	0.002	residential
264	45	0	4542	0	4542	76	0.01	residential
266	8	0	1132	0	1132	19	0.02	residential
267	8	0	4765	0	4765	79	0.009	residential
268	8	0	7720	0	7720	129	0.005	residential

269	8	0	14991	0	14991	250	0.002	residential
270	8	0	25067	0	25067	418	0.001	residential
272	45	0	5376	0	5376	90	0.008	residential
275	8	0	3746	0	3746	62	0.01	residential
276	8	0	4618	0	4618	77	0.008	residential
277	8	0	16377	0	16377	273	0.002	residential
278	8	0	18869	0	18869	314	0.002	residential
281	1	0	8448	0	8448	141	0.005	residential
282	45	0	3625	0	3625	60	0.014	residential
286	8	0	8947	0	8947	149	0.004	residential
288	8	0	21231	0	21231	354	0.001	residential
291	43	0	6042	0	6042	101	0.007	residential
293	43	0	1961	0	1961	33	0.021	residential
294	43	0	1362	0	1362	23	0.034	residential
295	92	0	4772	0	4772	80	0.008	residential
305	92	0	7535	0	7535	126	0.005	residential
306	92	0	9235	0	9235	154	0.004	residential
309	1	0	13389	0	13389	223	0.003	residential
310	1	0	7415	0	7415	124	0.006	residential
311	1	0	1971	0	1971	33	0.022	residential
313	1	0	9294	0	9294	155	0.004	residential
315	8	0	9187	0	9187	153	0.004	residential
316	8	0	23254	0	23254	388	0.001	residential
323	1	0	12359	0	12359	206	0.003	residential
324	1	0	10526	0	10526	175	0.004	residential
325	1	0	4740	0	4740	79	0.008	residential
328	8	0	15957	0	15957	266	0.002	residential
329	8	0	12899	0	12899	215	0.003	residential
330	8	0	20723	0	20723	345	0.001	residential
331	8	0	24329	0	24329	405	0.001	residential
332	8	0	26586	0	26586	443	0.001	residential
335	92	0	11419	0	11419	190	0.003	residential
336	92	0	13826	0	13826	230	0.003	residential
337	92	0	17811	0	17811	297	0.002	residential
338	1	0	13501	0	13501	225	0.002	residential

339	1	0	11743	0	11743	196	0.003	residential
340	1	0	7052	0	7052	118	0.005	residential
341	1	0	1383	0	1383	23	0.022	residential
344	8	0	15857	0	15857	264	0.002	residential
347	8	0	25532	0	25532	426	0.001	residential
348	8	0	28656	0	28656	478	0.001	residential
351	92	0	16837	0	16837	281	0.002	residential
352	92	0	17912	0	17912	299	0.002	residential
353	1	0	12456	0	12456	208	0.003	residential
355	1	0	6193	0	6193	103	0.005	residential
356	1	0	1544	0	1544	26	0.018	residential
357	1	0	3813	0	3813	64	0.008	residential
363	8	0	28898	0	28898	482	0.001	residential
364	8	0	33762	0	33762	563	0.001	residential
370	1	0	10873	0	10873	181	0.003	residential
371	1	0	7603	0	7603	127	0.004	residential
372	1	0	4414	0	4414	74	0.007	residential
373	1	0	1134	0	1134	19	0.021	residential
374	1	0	7275	0	7275	121	0.004	residential
379	1	0	82923	0	82923	1382	0	residential
386	1	0	14887	0	14887	248	0.002	residential
387	1	0	6690	0	6690	112	0.004	residential
388	1	0	1805	0	1805	30	0.014	residential
389	1	0	4557	0	4557	76	0.006	residential
401	1	0	10560	0	10560	176	0.003	residential
402	1	0	7955	0	7955	133	0.004	residential
403	1	0	4548	0	4548	76	0.006	residential
404	1	0	7607	0	7607	127	0.004	residential
408	8	0	24138	0	24138	402	0.001	residential
414	1	0	6887	0	6887	115	0.004	residential
415	1	0	7138	0	7138	119	0.004	residential
419	1	0	61960	0	61960	1033	0	residential
423	1	0	10222	0	10222	170	0.003	residential
424	1	0	10417	0	10417	174	0.003	residential
425	1	0	18059	0	18059	301	0.002	residential

431	1	0	12815	0	12815	214	0.002	residential
442	1	0	54104	0	54104	902	0	residential
451	1	0	53652	0	53652	894	0	residential
452	1	0	52137	0	52137	869	0	residential
461	1	0	55367	0	55367	923	0	residential
462	1	0	43124	0	43124	719	0.001	residential
538	1	0	78696	0	78696	1312	0	residential
540	92	0	9240	0	9240	154	0.004	residential
541	92	0	5768	0	5768	96	0.007	residential
543	92	0	4943	0	4943	82	0.009	residential
546	92	0	9787	0	9787	163	0.004	residential
548	92	0	7836	0	7836	131	0.005	residential
549	92	0	12729	0	12729	212	0.003	residential
550	92	0	12980	0	12980	216	0.003	residential
554	92	0	12319	0	12319	205	0.003	residential

Appendix I: Fastest path from origin to health care centers

Origin id	Destination	Entry cost	Network cost	Exit cost	Total cost	Total cost (min)	Gravitational accessibility	Residential
1	10	0	5181	0	5181	86	0.008	Residential
2	10	0	2648	0	2648	44	0.017	Residential
3	10	0	3744	0	3744	62	0.011	Residential
4	6	0	6517	0	6517	109	0.005	Residential
5	10	0	2878	0	2878	48	0.015	Residential
7	6	0	1673	0	1673	28	0.019	Residential
9	10	0	1567	0	1567	26	0.021	Residential
10	6	0	3449	0	3449	57	0.012	Residential
11	6	0	1418	0	1418	24	0.021	Residential
12	6	0	2922	0	2922	49	0.015	Residential
13	6	0	1289	0	1289	21	0.024	Residential
14	5	0	3057	0	3057	51	0.014	Residential
15	6	0	1344	0	1344	22	0.034	Residential
16	6	0	1246	0	1246	21	0.025	Residential
17	6	0	2257	0	2257	38	0.021	Residential
18	7	0	3141	0	3141	52	0.005	Residential
19	13	0	15340	0	15340	256	0.002	Residential
20	13	0	13011	0	13011	217	0.002	Residential
21	13	0	10207	0	10207	170	0.003	Residential
24	13	0	9563	0	9563	159	0.003	Residential
25	13	0	12913	0	12913	215	0.002	Residential
26	13	0	14198	0	14198	237	0.002	Residential
27	13	0	7789	0	7789	130	0.005	Residential
28	13	0	7102	0	7102	118	0.005	Residential
29	13	0	12806	0	12806	213	0.002	Residential
32	13	0	7139	0	7139	119	0.005	Residential
33	13	0	11548	0	11548	192	0.003	Residential
34	13	0	2416	0	2416	40	0.016	Residential

35	13	0	2656	0	2656	44	0.015	Residential
36	13	0	3404	0	3404	57	0.011	Residential
37	13	0	3115	0	3115	52	0.014	Residential
39	13	0	3127	0	3127	52	0.012	Residential
42	13	0	3433	0	3433	57	0.011	Residential
43	13	0	2939	0	2939	49	0.013	Residential
44	13	0	1603	0	1603	27	0.024	Residential
45	13	0	1234	0	1234	21	0.032	Residential
46	13	0	2385	0	2385	40	0.017	Residential
47	12	0	2748	0	2748	46	0.012	Residential
48	14	0	1286	0	1286	21	0.023	Residential
51	13	0	6648	0	6648	111	0.005	Residential
52	13	0	3668	0	3668	61	0.01	Residential
53	13	0	4006	0	4006	67	0.009	Residential
54	13	0	5786	0	5786	96	0.006	Residential
55	13	0	7252	0	7252	121	0.005	Residential
56	13	0	3639	0	3639	61	0.01	Residential
57	12	0	2613	0	2613	44	0.014	Residential
58	12	0	713	0	713	12	0.053	Residential
59	12	0	747	0	747	12	0.046	Residential
60	12	0	1041	0	1041	17	0.036	Residential
61	12	0	2358	0	2358	39	0.019	Residential
63	13	0	10025	0	10025	167	0.003	Residential
64	13	0	7265	0	7265	121	0.005	Residential
65	13	0	6867	0	6867	114	0.005	Residential
66	13	0	5315	0	5315	89	0.007	Residential
67	12	0	14276	0	14276	238	0.002	Residential
68	13	0	11058	0	11058	184	0.003	Residential
69	12	0	5872	0	5872	98	0.006	Residential
70	12	0	2990	0	2990	50	0.012	Residential
71	12	0	3753	0	3753	63	0.01	Residential
72	12	0	997	0	997	17	0.04	Residential

73	12	0	1812	0	1812	30	0.023	Residential
74	6	0	2582	0	2582	43	0.02	Residential
81	13	0	13368	0	13368	223	0.002	Residential
82	12	0	11082	0	11082	185	0.003	Residential
83	12	0	6176	0	6176	103	0.006	Residential
84	12	0	3501	0	3501	58	0.012	Residential
85	12	0	5332	0	5332	89	0.007	Residential
86	9	0	905	0	905	15	0.041	Residential
87	9	0	900	0	900	15	0.049	Residential
88	12	0	2140	0	2140	36	0.023	Residential
95	13	0	14617	0	14617	244	0.002	Residential
96	16	0	10014	0	10014	167	0.003	Residential
97	12	0	8317	0	8317	139	0.004	Residential
99	12	0	1436	0	1436	24	0.034	Residential
100	12	0	4656	0	4656	78	0.009	Residential
101	8	0	1419	0	1419	24	0.009	Residential
102	8	0	1475	0	1475	25	0.008	Residential
103	15	0	982	0	982	16	0.025	Residential
107	13	0	14833	0	14833	247	0.002	Residential
108	16	0	10448	0	10448	174	0.003	Residential
109	16	0	5741	0	5741	96	0.005	Residential
110	16	0	5864	0	5864	98	0.005	Residential
111	12	0	7278	0	7278	121	0.005	Residential
112	16	0	2460	0	2460	41	0.019	Residential
113	8	0	1630	0	1630	27	0.007	Residential
114	15	0	924	0	924	15	0.029	Residential
115	15	0	480	0	480	8	0.054	Residential
118	13	0	15842	0	15842	264	0.002	Residential
119	13	0	15842	0	15842	264	0.002	Residential
120	16	0	7430	0	7430	124	0.004	Residential
121	16	0	3042	0	3042	51	0.009	Residential
122	16	0	1911	0	1911	32	0.015	Residential

123	16	0	2245	0	2245	37	0.016	Residential
124	15	0	2236	0	2236	37	0.017	Residential
125	15	0	1816	0	1816	30	0.018	Residential
128	15	0	18091	0	18091	302	0.001	Residential
129	15	0	14481	0	14481	241	0.002	Residential
130	16	0	9191	0	9191	153	0.003	Residential
131	16	0	2306	0	2306	38	0.012	Residential
132	16	0	108	0	108	2	0.365	Residential
133	15	0	3913	0	3913	65	0.009	Residential
134	15	0	1464	0	1464	24	0.026	Residential
135	15	0	3010	0	3010	50	0.011	Residential
141	16	0	2659	0	2659	44	0.01	Residential
142	15	0	3384	0	3384	56	0.011	Residential
143	15	0	1818	0	1818	30	0.021	Residential
144	15	0	4987	0	4987	83	0.007	Residential
145	15	0	6008	0	6008	100	0.005	Residential
153	10	0	12288	0	12288	205	0.003	Residential
160	10	0	9253	0	9253	154	0.004	Residential
161	10	0	10644	0	10644	177	0.003	Residential
169	6	0	15293	0	15293	255	0.002	Residential
170	6	0	13042	0	13042	217	0.002	Residential
178	10	0	10085	0	10085	168	0.003	Residential
180	6	0	10202	0	10202	170	0.003	Residential
184	5	0	12762	0	12762	213	0.002	Residential
185	5	0	11696	0	11696	195	0.002	Residential
188	10	0	6366	0	6366	106	0.006	Residential
189	6	0	7977	0	7977	133	0.004	Residential
190	6	0	6711	0	6711	112	0.005	Residential
191	6	0	7562	0	7562	126	0.004	Residential
192	6	0	6804	0	6804	113	0.005	Residential
193	5	0	5407	0	5407	90	0.005	Residential
194	5	0	8601	0	8601	143	0.003	Residential

195	5	0	9950	0	9950	166	0.002	Residential
198	6	0	3981	0	3981	66	0.008	Residential
199	6	0	4294	0	4294	72	0.008	Residential
200	5	0	2509	0	2509	42	0.009	Residential
201	5	0	4477	0	4477	75	0.006	Residential
202	5	0	10221	0	10221	170	0.002	Residential
207	5	0	1421	0	1421	24	0.016	Residential
208	5	0	1418	0	1418	24	0.016	Residential
209	5	0	3353	0	3353	56	0.007	Residential
210	5	0	5115	0	5115	85	0.005	Residential
211	5	0	13172	0	13172	220	0.002	Residential
215	5	0	4271	0	4271	71	0.006	Residential
217	5	0	4288	0	4288	71	0.006	Residential
218	5	0	7015	0	7015	117	0.004	Residential
219	5	0	7890	0	7890	131	0.003	Residential
222	5	0	1759	0	1759	29	0.019	Residential
223	5	0	3374	0	3374	56	0.009	Residential
225	7	0	13601	0	13601	227	0.001	Residential
226	5	0	11925	0	11925	199	0.002	Residential
229	5	0	4580	0	4580	76	0.007	Residential
230	5	0	6699	0	6699	112	0.004	Residential
232	7	0	10431	0	10431	174	0.001	Residential
236	7	0	643	0	643	11	0.032	Residential
237	7	0	731	0	731	12	0.029	Residential
238	7	0	1971	0	1971	33	0.009	Residential
239	7	0	2346	0	2346	39	0.007	Residential
240	7	0	5015	0	5015	84	0.003	Residential
241	7	0	7849	0	7849	131	0.002	Residential
245	7	0	789	0	789	13	0.028	Residential
246	7	0	1408	0	1408	23	0.014	Residential
247	7	0	692	0	692	12	0.033	Residential
248	7	0	4877	0	4877	81	0.003	Residential

249	7	0	4193	0	4193	70	0.004	Residential
250	7	0	8262	0	8262	138	0.002	Residential
251	4	0	16253	0	16253	271	0.001	Residential
252	7	0	14737	0	14737	246	0.001	Residential
253	7	0	16873	0	16873	281	0.001	Residential
254	7	0	5029	0	5029	84	0.004	Residential
255	7	0	1343	0	1343	22	0.02	Residential
257	4	0	2217	0	2217	37	0.01	Residential
258	4	0	3689	0	3689	61	0.005	Residential
259	4	0	12733	0	12733	212	0.001	Residential
260	4	0	15455	0	15455	258	0.001	Residential
261	4	0	18260	0	18260	304	0.001	Residential
264	7	0	4363	0	4363	73	0.005	Residential
266	4	0	3266	0	3266	54	0.006	Residential
267	4	0	3900	0	3900	65	0.005	Residential
268	4	0	7672	0	7672	128	0.002	Residential
269	4	0	14942	0	14942	249	0.001	Residential
270	4	0	25018	0	25018	417	0	Residential
272	7	0	5197	0	5197	87	0.004	Residential
275	4	0	2751	0	2751	46	0.006	Residential
276	4	0	5525	0	5525	92	0.003	Residential
277	4	0	16328	0	16328	272	0.001	Residential
278	4	0	18820	0	18820	314	0.001	Residential
281	1	0	8169	0	8169	136	0.002	Residential
282	7	0	3445	0	3445	57	0.008	Residential
286	4	0	8899	0	8899	148	0.002	Residential
288	4	0	21182	0	21182	353	0.001	Residential
291	10	0	7082	0	7082	118	0.005	Residential
293	6	0	3150	0	3150	52	0.014	Residential
294	6	0	2242	0	2242	37	0.02	Residential
295	15	0	4554	0	4554	76	0.007	Residential
305	15	0	7374	0	7374	123	0.004	Residential

306	15	0	8956	0	8956	149	0.003	Residential
309	1	0	13109	0	13109	218	0.001	Residential
310	1	0	7136	0	7136	119	0.003	Residential
311	1	0	1692	0	1692	28	0.016	Residential
313	1	0	9015	0	9015	150	0.002	Residential
315	4	0	7921	0	7921	132	0.002	Residential
316	4	0	23205	0	23205	387	0.001	Residential
323	1	0	12538	0	12538	209	0.001	Residential
324	1	0	10247	0	10247	171	0.002	Residential
325	1	0	4919	0	4919	82	0.004	Residential
328	4	0	14692	0	14692	245	0.001	Residential
329	4	0	11633	0	11633	194	0.001	Residential
330	4	0	19458	0	19458	324	0.001	Residential
331	4	0	23064	0	23064	384	0.001	Residential
332	4	0	25321	0	25321	422	0	Residential
335	15	0	11258	0	11258	188	0.003	Residential
336	15	0	13665	0	13665	228	0.002	Residential
337	15	0	17650	0	17650	294	0.001	Residential
338	1	0	13679	0	13679	228	0.001	Residential
339	1	0	11922	0	11922	199	0.001	Residential
340	1	0	7231	0	7231	121	0.003	Residential
341	1	0	1104	0	1104	18	0.021	Residential
344	4	0	14591	0	14591	243	0.001	Residential
347	4	0	24266	0	24266	404	0	Residential
348	4	0	27391	0	27391	457	0	Residential
351	15	0	16676	0	16676	278	0.002	Residential
352	15	0	17751	0	17751	296	0.001	Residential
353	3	0	10477	0	10477	175	0.001	Residential
355	3	0	4215	0	4215	70	0.004	Residential
356	1	0	1281	0	1281	21	0.017	Residential
357	1	0	3674	0	3674	61	0.005	Residential
363	4	0	27632	0	27632	461	0	Residential

364	4	0	32496	0	32496	542	0	Residential
370	3	0	7521	0	7521	125	0.002	Residential
371	3	0	4152	0	4152	69	0.004	Residential
372	3	0	1024	0	1024	17	0.018	Residential
373	1	0	991	0	991	17	0.019	Residential
374	2	0	4710	0	4710	79	0.004	Residential
379	1	0	82929	0	82929	1382	0	Residential
386	3	0	11535	0	11535	192	0.001	Residential
387	1	0	6696	0	6696	112	0.002	Residential
388	1	0	1811	0	1811	30	0.01	Residential
389	1	0	4563	0	4563	76	0.004	Residential
401	3	0	7171	0	7171	120	0.002	Residential
402	1	0	7892	0	7892	132	0.002	Residential
403	1	0	4508	0	4508	75	0.004	Residential
404	1	0	7613	0	7613	127	0.002	Residential
408	4	0	22872	0	22872	381	0.001	Residential
414	1	0	6893	0	6893	115	0.002	Residential
415	1	0	7144	0	7144	119	0.002	Residential
419	1	0	61966	0	61966	1033	0	Residential
423	1	0	10253	0	10253	171	0.001	Residential
424	1	0	10423	0	10423	174	0.001	Residential
425	1	0	18066	0	18066	301	0.001	Residential
431	1	0	12821	0	12821	214	0.001	Residential
442	1	0	54110	0	54110	902	0	Residential
451	1	0	53658	0	53658	894	0	Residential
452	1	0	52143	0	52143	869	0	Residential
461	1	0	55373	0	55373	923	0	Residential
462	1	0	43130	0	43130	719	0	Residential
538	1	0	78702	0	78702	1312	0	Residential
540	15	0	8975	0	8975	150	0.003	Residential
541	15	0	5503	0	5503	92	0.006	Residential
543	15	0	4782	0	4782	80	0.007	Residential

546	15	0	9521	0	9521	159	0.003	Residential
548	15	0	7675	0	7675	128	0.004	Residential
549	15	0	12463	0	12463	208	0.002	Residential
550	15	0	12819	0	12819	214	0.002	Residential
554	15	0	12158	0	12158	203	0.002	Residential