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A spatial decomposition-based framework for building last-mile connectivity to urban public transit systems: Defining feeder networks for the metro rail in Bengaluru, India

Murari Srinivasa
Decision Sciences
Indian Institute of Management Bangalore
murari.srinivasa20@alumni.iimb.ac.in

Rajluxmi V Murthy
Decision Sciences
Indian Institute of Management Bangalore
rajluxmi.vmurthy@iimb.ac.in

Reshma Chandrasekharan
Decision Sciences
Indian Institute of Management Bangalore
reshma.chirayil@iimb.ac.in

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A spatial decomposition-based framework for building last-mile connectivity to urban public transit systems: Defining feeder networks for the metro rail in Bengaluru, India

Murari Srinivasa[a], Rajluxmi V. Murthy[a], Reshma Chandrasekharan[a]

[a]*Decision Sciences, Indian Institute of Management Bangalore, Bengaluru, 560076, KA, India*

Abstract

Urban passenger transit is multimodal in nature, and connectivity at the last-mile with the dominant public transit system in a city is critical. In this paper we develop and demonstrate a replicable framework that comprehensively defines a last-mile universe by quantifying coverage, identifying potential last-mile stops and the associated last-mile feeder network for any urban geography where the public transit network is known and associated spatio-demographic information is available. The methodology is based on spatial decomposition techniques from computational geometry using principles of tessellations, Voronoi diagrams, and Delaunay triangulations from computational geometry.

We demonstrate the proposed framework utilizing publicly available data for an urban agglomeration in India (Bengaluru) over its planned metro rail infrastructure. We find that the proposed long-term metro rail network covers about 43% of the current population of 8.4 million within a walking distance of 1 km from the nearest station, spread over 32% of the urban area. The methodology identifies 245 last-mile stops and sub-zones within the administrative region and recommends a feeder network structure serving 92 stations. These can be used to deploy last-mile feeder systems which can potentially bring 93% of the city's population under walkable coverage of a multimodal metro plus last-mile setup, spanning 89% of the area.

Keywords: urban public transit, last-mile connectivity, spatial analytics, computational geometry, feeder networks

1. Introduction

Rapid urbanization over the last few decades has driven growth in urban passenger mobility systems, and emerging economies like India are at the forefront of such development. 54% of the world's population lives in cities and accounts for 80% of world GDP. India's own urban population is projected to increase to 0.8 Bn by 2050 (UN-DESA, 2019). The associated increase in population density in the expansion of megacities such as Chennai, Bangalore, Hyderabad will present unique and diverse challenges in passenger mobility. We are also witnessing the development of modern public shared transit systems in urban agglomerations via metro rail projects. The urban metro rail infrastructure has seen a significant push from the Government of India with investments more than INR 2 Tn across more than 20 cities (Appendix Table A.1) under the NUTP (National Urban Transport Policy) , as per which the stated objective is to build and deploy mass rapid transit systems in all cities of population 1 Mn or more (Kanuri et al., 2019).

1.1. The Last-Mile Problem

Last-mile connectivity refers to the challenge of reaching public transit stops, such as a metro station, from one's source and then from the station to the final destination. A recurrent phenomenon across the globe is that public transit systems necessarily need strong, tightly-coupled last-mile connectivity for adoption and continued patronage (Chandra et al. (2013); Tilahun et al. (2016); Stiglic et al. (2018)). However, inadequacies at the last mile are well documented in the developed world (K˚aresdotter et al. (2022); Zuo et al. (2020)). Recent research in India as well (Mukherjee et al., 2023) has highlighted poor access to metro rail systems as a key contributing factor to under-utilization and low ridership. While there has been no consistent approach to deploying last-mile services at metro stations, experiments on improving last-mile connectivity in India have yielded encouraging results, within a restricted scope (Kathuria et al., 2019). This represents a significant gap in practice which needs to be addressed.

In this context, the Last-mile Problem (LMP) - known variously in literature as the Firstmile Last-mile (FMLM) problem (Grahn et al., 2021), or the First and Last-mile (FLM) problem (Lu et al., 2021) - may be broadly defined as the design and operation of services facilitating travel from a root public transportation node to a point which is conveniently close to the passenger's final destination. The generic last-mile structure is illustrated in Fig. 1 as represented by Wang (2019). Passenger source/destinations here typically represent homes or workplaces which are walkable from the common proximal last-mile stop of feeder service operations to the metro station. Each metro station serves a catchment area consisting of multiple such last-mile stops on the road network, which are beyond walking distance from each other and the metro station.

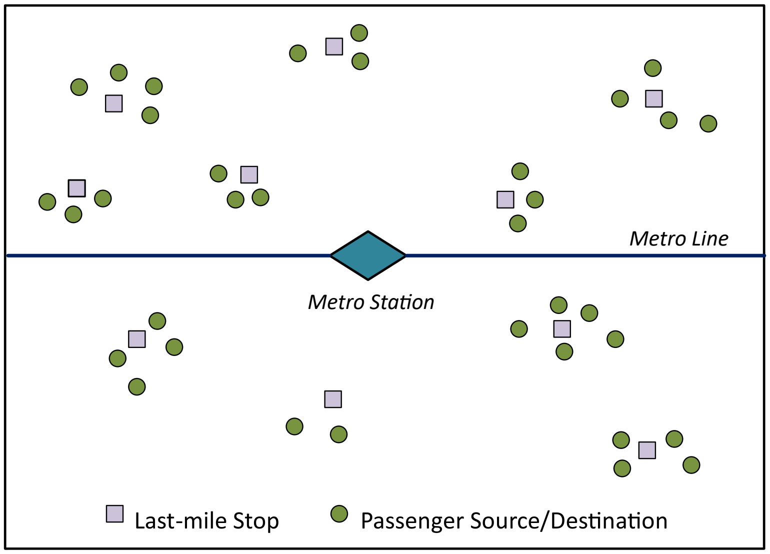

Fig. 1. Generic Last-mile structure

2. Literature Review

Last-mile connectivity as a research area has evolved with advances in multimodality of passenger transport, within which we focus on network design and optimization as the theme of interest. The Feeder Network Design Problem introduced by Kuah and Perl (1989) developed a generic mathematical programming model to design a system connecting existing bus and rail networks. Shrivastav and Dhingra (2001) developed solutions for connectivity between the existing suburban rail and bus networks in Mumbai, India using heuristic approaches. Verma and Dhingra (2005) used genetic algorithms to develop feeder bus route networks for the rail network in the Thane suburb of the Mumbai Metropolitan region. Dou et al. (2017) proposed a schedule coordination method for transfer problems between a generic urban rail transit service and its feeder bus service. Maheo et al. (2019) designed a hub-and shuttle public transit system (HSPTS) for the Canberra urban region, as an optimization problem using a Bender's decomposition approach on a Mixed Linear Integer Programming (MILP) formulation.

Urban passenger transit has seen much recent innovation around demand-responsive paradigms, and hence last-mile research has also been based around the dynamic nature of demand. Wang and Odoni (2016) originally defined the LMP as a provision of travel service from a public transportation node to a home or a workplace or vice versa, and modelled the supply side of the problem as spatially distributed queuing systems. Wang (2019) addresses routing and scheduling aspects of a generic on-demand Last-mile Transportation System (LMTS) by formulating an exact Mixed Integer Programming (MIP) optimization model for routing and scheduling decisions. Shehadeh et al. (2021) propose stochastic programming and distributionally robust models for fleet-sizing and dynamic allocation of an on-demand LMTS. Growth of ridesharing and ridesourcing platforms has further spurred research in the area of integrated planning of public transit with ride-hailing services (Uber, Ola, Lyft etc.) and microtransit (Bridj, Chariot, Via etc.). Steiner and Irnich (2020) developed a holistic model which integrates mobility-on-demand into an existing public transit network, with the objective of minimizing overall costs while guaranteeing a minimum passenger level of service and demonstrate results for the German city of Gottingen.

Tracing the above evolution of last-mile literature, we observe that recent research has focussed more on operations over a given last-mile structure for demand-responsive paradigms suited for evolved urban transit markets as per the framework by Jones (2014). However, studies such as (Mukherjee et al., 2023) indicate that the last-mile problem can potentially be viewed from a more fundamental perspective in many emerging urban contexts where seamless multimodality of transport is not the norm. In fact, there is a body of recent research strongly suggesting that urban transportation policies can be better customized to local conditions (Akbar et al., 2023). Current research, such as Cui et al. (2025) modelling complex interstation dependencies affecting ridership, has additionally highlighted the role of comprehensively planned feeder services in expanding metro network coverage.

3. Research Opportunity

We see a research gap in providing a structural definition of the last-mile universe of a public transit system, while accommodating the spatial and demographic characteristics of an urban geography. Extant literature, such as Zuo et al. (2018) look at identifying catchment areas from the perspective of non-motorized transport only. Arguably, a comprehensive framework that systematically identifies and structures a last-mile universe complementing the public transit systems will be of immense use to transit planners in many countries like India, where metro rail systems are now an integral part of urban planning (MoHUA, 2017), and need to be supplemented by strong feeder subsystems.

Given the spatial maps, demographic distribution of population, and metro rail infrastructure in an urban geography, we specifically seek to

- Quantify the demographic coverage of a public transit system, and the gap in last-mile access,
- Develop a replicable approach to identify a set of last-mile stops associated with the public transit network to improve passenger access,
- Structure these stops into a feeder network that can be further developed into fixed routes for a generic last-mile service operator.

Accordingly, the framework developed in this paper is presented in Fig. 2. The rest of the paper demonstrates the implementation of successive stages of the proposed framework to identify the last-mile universe of the metro rail system in the city of Bengaluru (Karnataka, India). Section 4 outlines the computational environment and the spatio-demographic analysis of the study area. Section 5 covers the core methodology in detail through the Coverage and Proximity Analysis, Access Benchmarking, and the Spatial Decomposition phases. We discuss results and implications in Section 6 and conclude with Section 7.

Our contribution to research and practice in the area of last-mile connectivity is multifold. We provide a consistent structural basis for addressing the last-mile problem by comprehensively defining the last-mile universe and its components. Our unique methodology makes effective use of techniques from computational geometry based on spatial tessellations, Voronoi diagrams, and Delaunay triangulations that have not been applied in prior work[1] in the literature. In addition, we ensure replicability of the framework over geographies, administrative regions, and last-mile service paradigms and work with reliable, publicly available demographic and spatial information of standard urban administrative setups.

4. Data and Preprocessing

The study uses the most recent publicly available data on block-level area, population and spatial boundaries from Census 2011 and *Bruhat Bengaluru Mahanagar Palike* (BBMP) sources, in conjunction with latest spatial data on current and future Metro Rail stops and routes made available by the Bengaluru Metro Rail Corporation Limited (BMRCL). Spatial data on bus stops and locations are sourced from Bengaluru Metropolitan Transport Corporation (BMTC) databases. Bengaluru road network data is sourced from NextGIS Inc.

All geospatial computations and visualizations have been carried out over *WGS 84* Coordinate Referencing System (CRS) standards (Szabova and Duchon, 2016) using the *sf* and *ggplot2* libraries respectively, in *R* (version 4.3.1) under *RStudio* (version 2024.04.1) on a system running a 1.6 GHz Intel core-i5 processor with eight cores and 20GB RAM. Geo-spatial layers corresponding to some of the metro lines and stations were identified and isolated using Google Maps and *QGIS* (version 3.32.1). Basic preprocessing on data was needed as demographic and spatial information were drawn from independent sources. The sets were merged to create a single joint data set carrying all relevant information for the study.

[1] The interested reader is referred to Boots et al. (1999), Preparata et al. (1988) and Hjelle and Dæhlen (2006) for detailed theoretical discussions on these concepts from computational geometry and their applications in spatial analytics research.

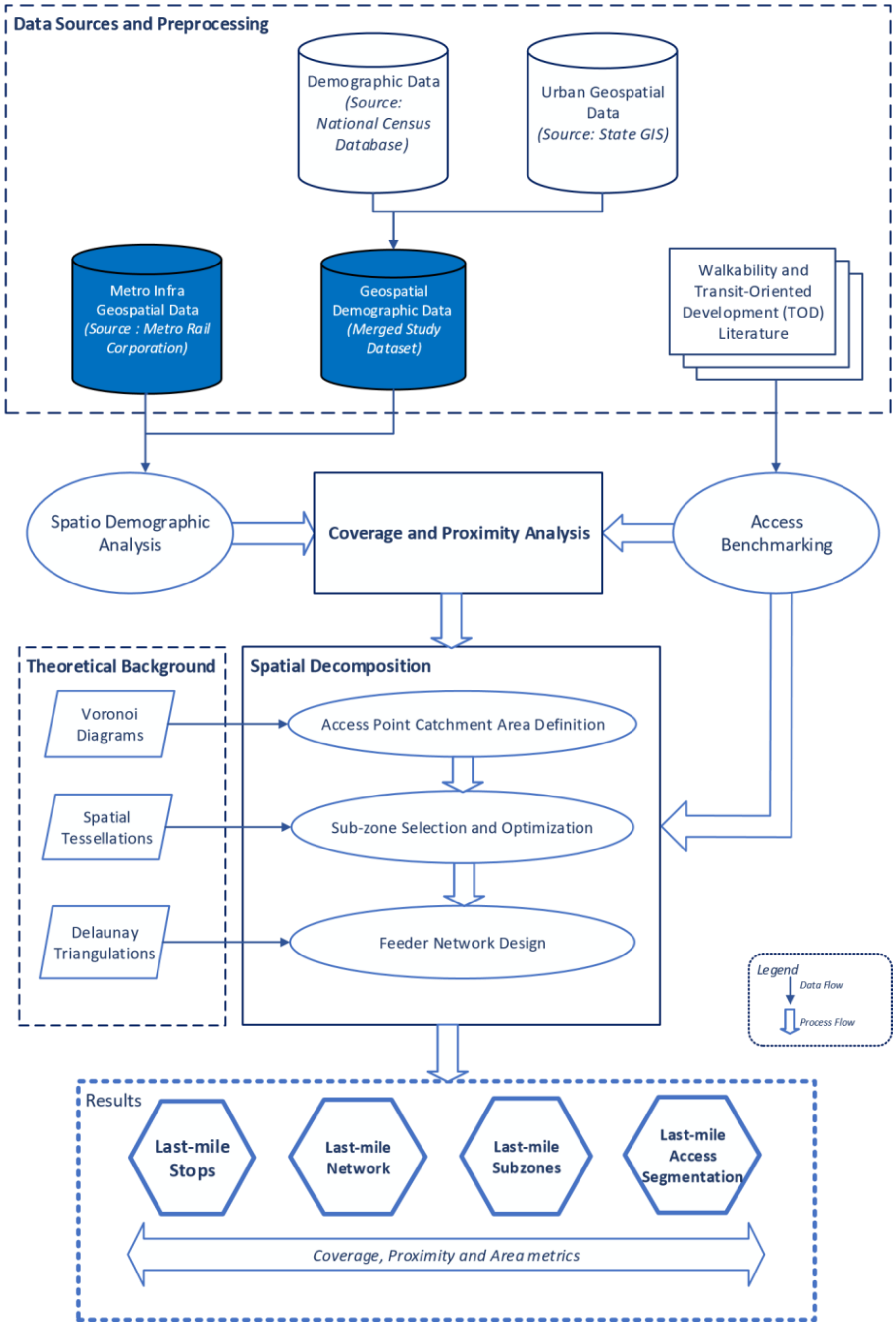

Fig. 2. Proposed framework for building last-mile connectivity to public transit systems

Distances are calculated according to Euclidean principles, as the study area is small enough to not be significantly affected by the earth's curvature. We assume a constant conversion rate of about 110 km per degree of latitude and longitude on account of the proximity to the equator, as per CRS specifications. For computational simplicity, we assume that populations are uniformly distributed within the wards.

4.1. Study area Demographics and Transit Infrastructure

Bengaluru (formerly Bangalore) is the third largest metropolitan region in India, and the capital of southern state of Karnataka. It is located at $12^\circ 59'$ N and $77^\circ 57'$ E at an average altitude of 920 m above sea level, with population of about 8.4 Million (Census 2011). Current population estimate (as of 2024) stands at about 11 Million and at current growth rates, the figure is expected to touch 15 Million by 2036 (WPR, 2023). The metropolitan region is governed by the municipal corporation known as the *Bruhat Bengaluru Mahanagar Palike* (BBMP). The BBMP handles local administration over an area of 709 sq. km., having a population density of 11,905 per sq. km. The BBMP administrative area is divided into 198 contiguous geographical units which serve as administrative zones called "wards", with an average population of about 42,645 per ward (Fig. 3).

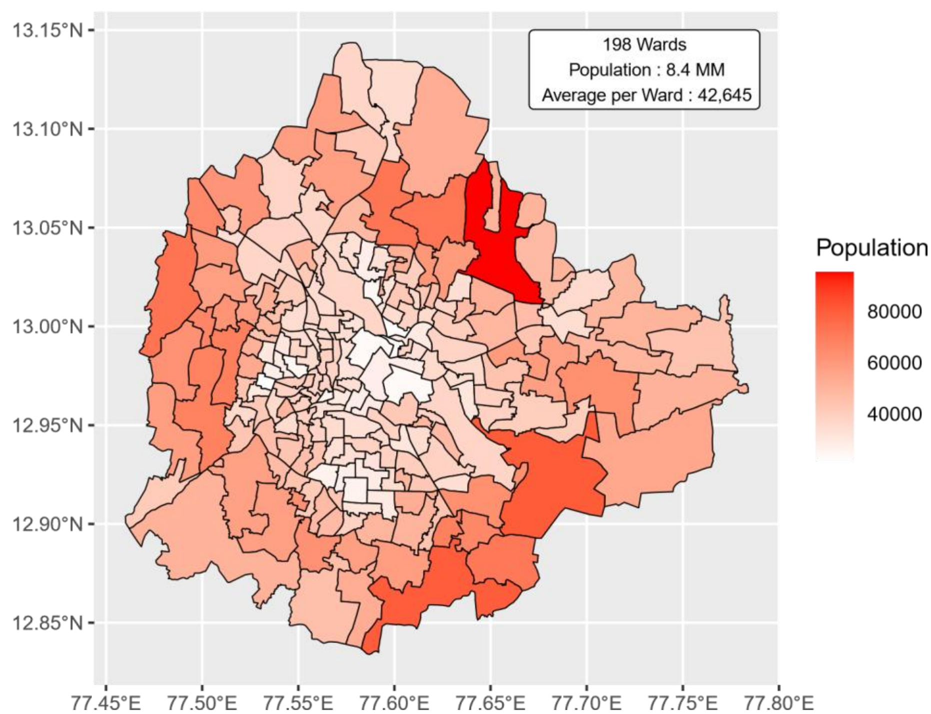

Fig. 3. Bengaluru Metropolitan Region - Population Distribution

Bengaluru is the second most dense city in terms of vehicular traffic in India after Delhi with a total of 11 Million registered vehicles as per official Karnataka state transport figures in 2023. Public transit via local bus services, metro rail and suburban rail accounts for only about 48% of the overall daily trips (Pai, 2010) and the city is known to be facing acute problems of traffic congestion due to high private vehicle ownership and usage. Average vehicular traffic speeds in peak hours are estimated to be about 15 kmph (Sync, 2020), and are significantly below national benchmarks for large cities.

Delimitation of wards is reviewed and restructured by the BBMP periodically to accommodate long-term population and infrastructural growth. Wards are the smallest administrative units across urban agglomerations in India for which geospatial and demographic information is made available reliably and have been considered the ideal unit of analysis further in this study. Wards are usually irregular and non-convex in nature, and areas vary between 0.3 to 28.6 sq. km. Wards in the core of the city are smaller in area and denser in population than those in the periphery, with significant variations in population densities at a standard deviation of 19,731 per sq. km (Fig. 4). Our methodology accommodates variations in population density between the wards, while assuming uniform distribution within the ward area.

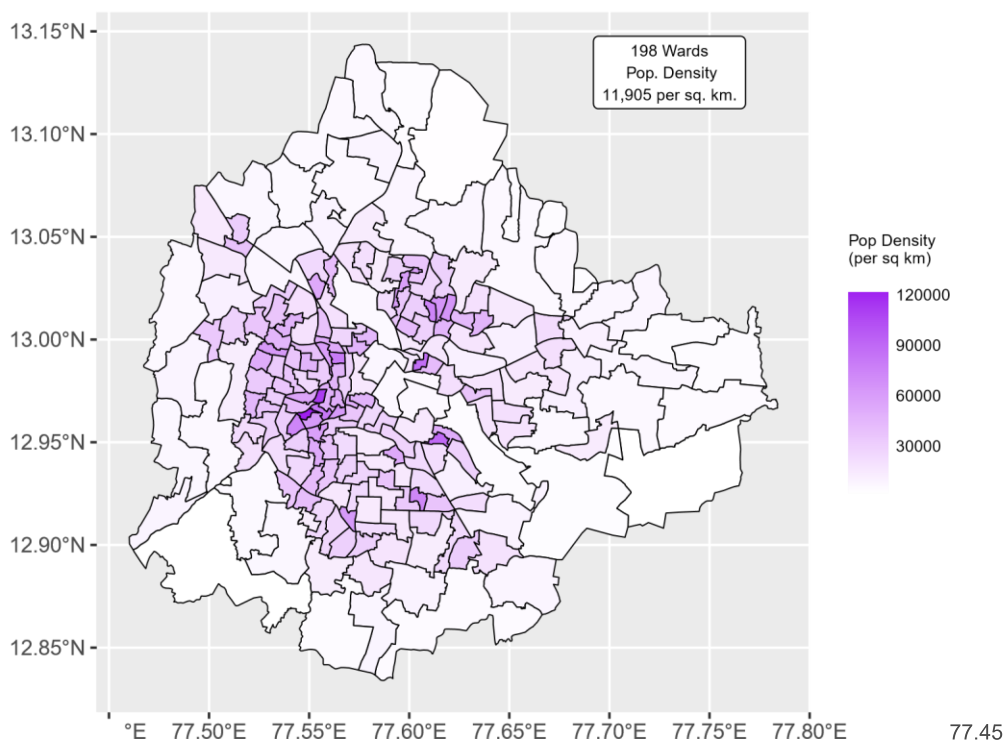

Fig. 4. Bengaluru Metropolitan Region - Population Density Map

The Metro Rail in Bengaluru managed by the Bengaluru Metro Rail Corporation Ltd. (BMRCL) is the most widely used public transit format in the city after the bus service operated by the Bengaluru Metropolitan Transport Corporation (BMTC). The current daily ridership estimate is around 700,000 passengers per day (Mukherjee et al., 2023) over two operational lines covering 74 km. The proposed network under further phases covering five lines, would run over 170 kms and forms the basis for our study. The metro lines and station locations are overlaid on to the ward map to visualize the overall extent of coverage (Fig. 5).

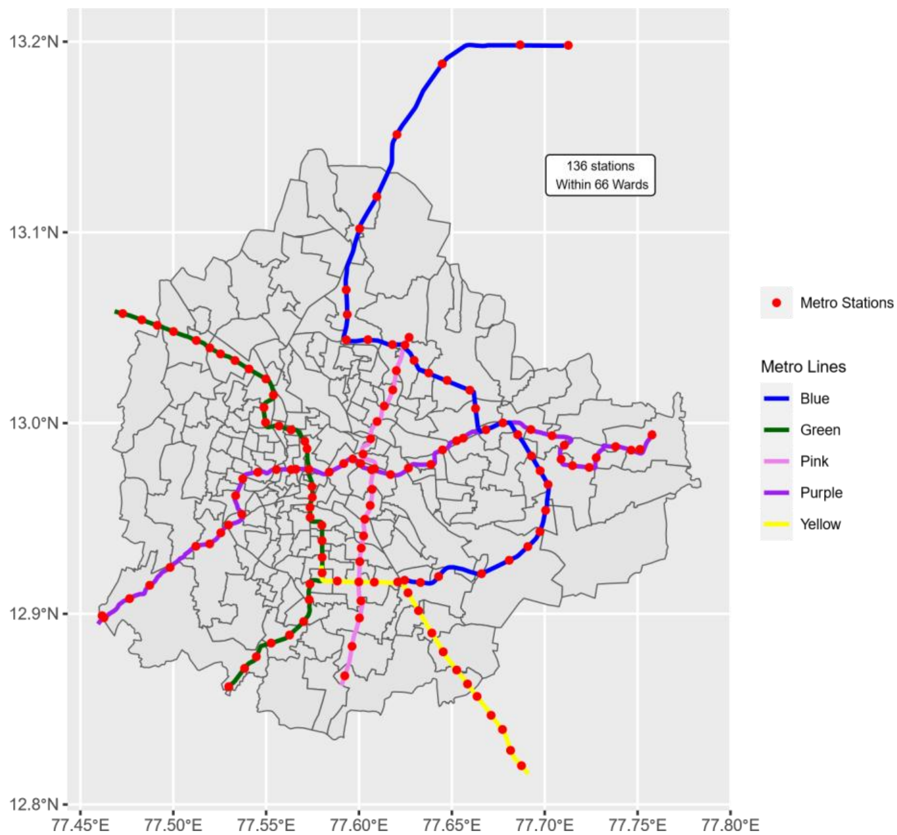

Fig. 5. Bengaluru Metropolitan Region - Metro rail lines and stations

The current and proposed metro lines connect a network of 136 stations spread throughout the study area. These stations are located within 66 out of the 198 wards. 12 stations fall outside the BBMP area and cannot be assigned to a ward. Successive stations on the same line are usually about 2 km apart on all lines, except the Blue line which connects to the airport, where the inter-station separation gradually increases to more than 5 kms.

5. Methodology

5.1. Coverage and Proximity Analysis

The 66 wards within which the metro stations are located account for about 36.0% of the BBMP population (Fig. 6), providing a base estimate for the population with some proximal metro access within the vicinity of the ward.

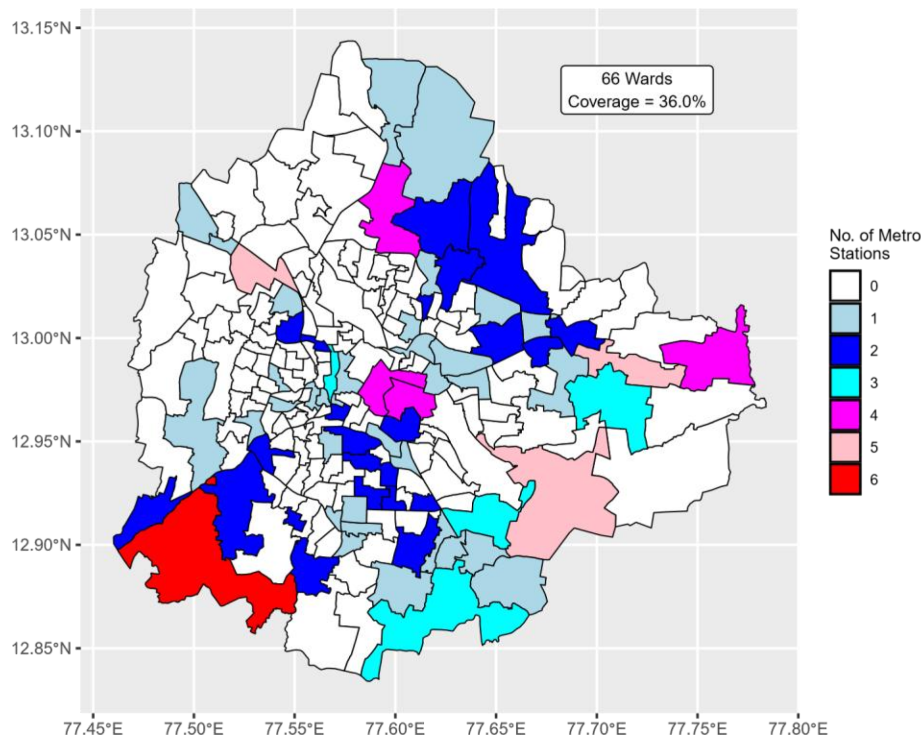

Fig. 6. Metro Stations Distribution over Wards

To estimate access in wards which do not have a metro station, we calculate the distance of the ward centre from each ward to its nearest metro station. Fig. 7 shows a heatmap of the city based on these distances. Ward centres are located, on an average about 1.39 km away from the nearest metro station. While this may seem like good proximal access, the wide disparities between ward shapes and areas mean that the distances range from 0 to 5.5 kms. Wards in the periphery being larger and further away from metro stations, mean that the overall distances travelled by passengers are much higher.

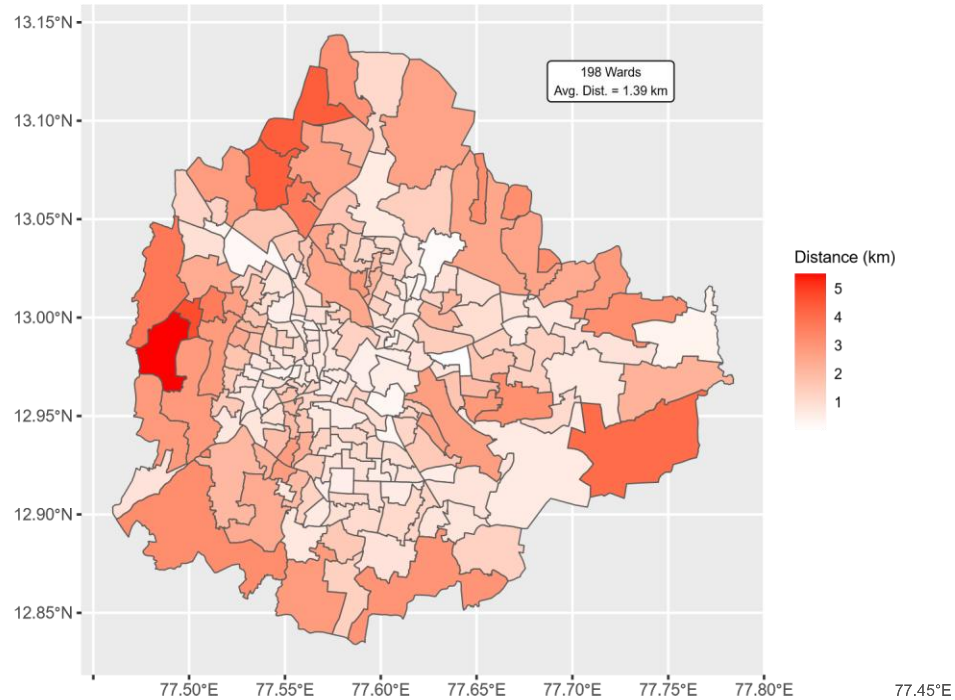

Fig. 7. Wards and Proximal Metro Access

A more granular analysis of the nature of ward geometries reveals the extent of variation across shapes, orientation and distance metrics. Fig.8 (Gandhinagar) and Fig.9 (Rajarajeshwari Nagar) highlight typical cases from different parts of the city.

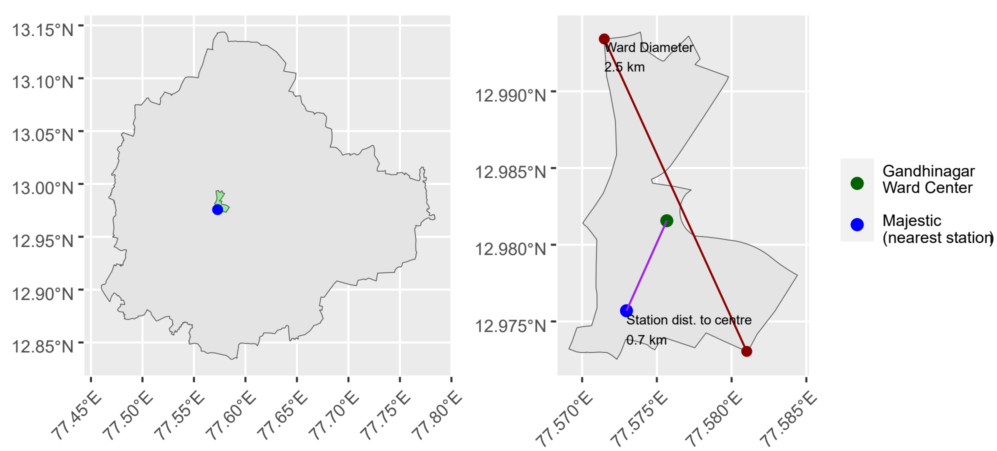

Fig. 8. Gandhinagar Ward - Geometry

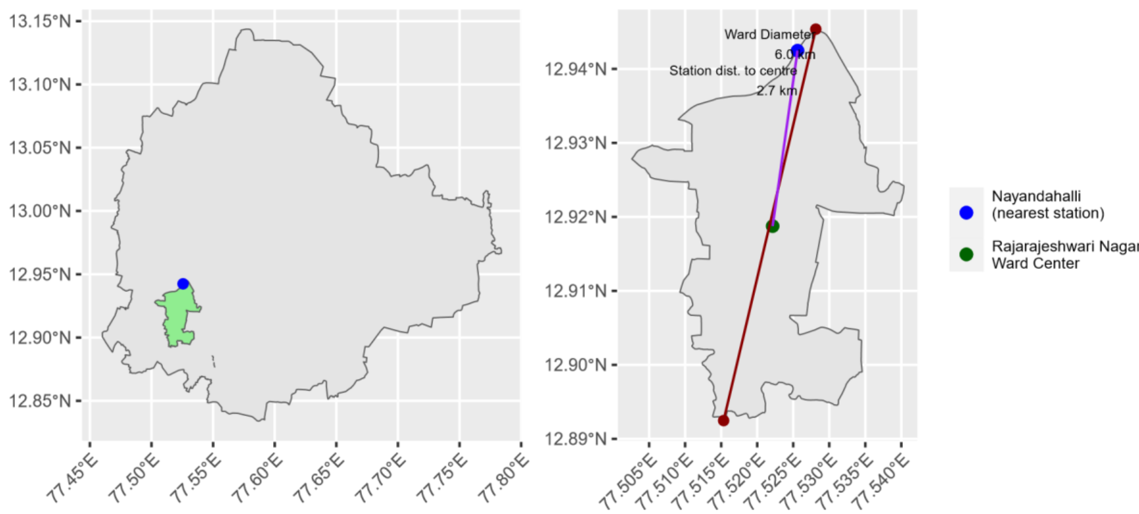

Fig. 9. Rajarajeshwari Nagar Ward - Geometry

These variations need to be accounted for while devising spatial decomposition techniques, and more rigorous benchmarks need to be derived to quantify and segment overall access with greater accuracy.

5.2. Defining Access Benchmarks

To arrive at a stronger estimate of coverage, benchmarks on walkable distances of access to a public transit system need to be established first. Distance benchmarks in developed countries like the Netherlands with good walkability indices are around 600m (Krygsman et al., 2004). More recently, the "half-mile radius" has been proposed by Guerra et al. (2012) as a good benchmark for households in the catchment areas of public transit stops. In India, estimates of last-mile travel times preferred by passengers lie between 6 to 20 minutes by different modes of transport in a similar city such as Delhi (Goel and Tiwari, 2016). We use a typical walking distance to a metro station of 1 km from preliminary surveys in Bengaluru, consistent with literature (Tiwari and Jain, 2023).

We also need to define segment(s) in the potential catchment area for the metro network where a passenger is likely to use motorized transport for access/egress. Recent studies tends to suggest a 5-km radius for this in Bengaluru (Mukherjee et al., 2023). The BBMP area was segmented through the commonly used GIS-based circular buffer approach (Andersen and Landex, 2009) of delineating transit-point access. The segments are computed as the spatial set union of circular units of a given radius – in this case 1 km and 5 km, respectively. The segments are then overlaid with demographic data to compute coverage. Fig. 10 shows the three segments for the BBMP area.

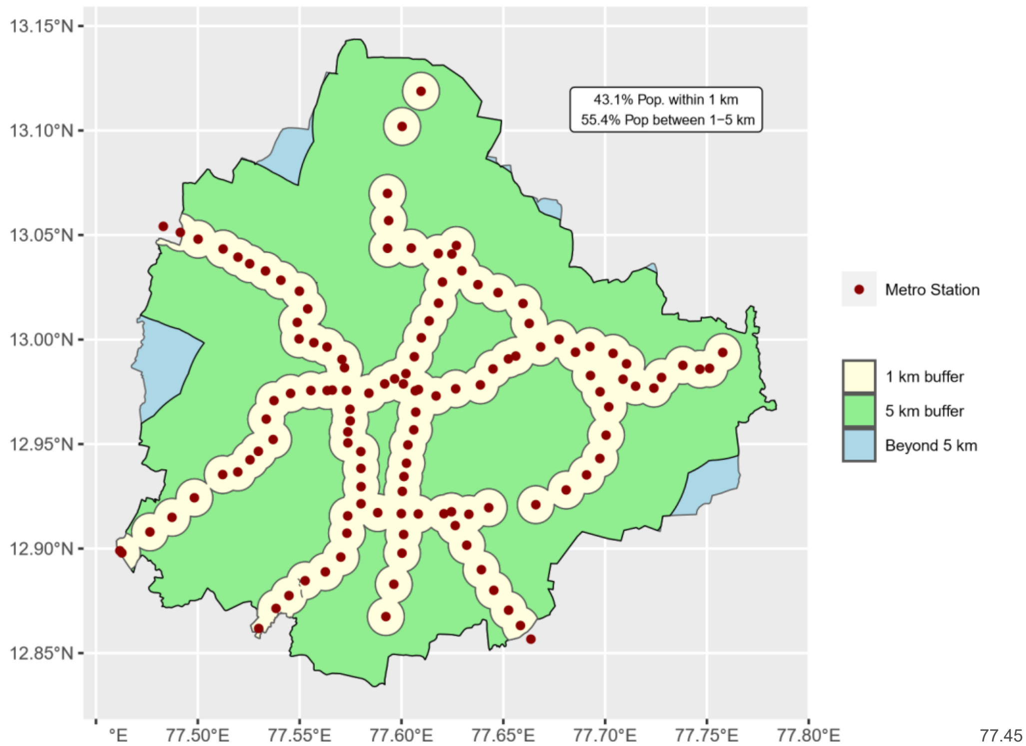

Fig. 10. Metro Access Segmentation - Circular Buffer Approach

An estimated 43.1% of the population resides within the primary walkable buffer (shaded yellow) within a radius of 1 km of the metro station. A further 55.4% of the population is located within the green 1-5 km buffer area. With these two segments covering almost all of the metropolitan region, we define 1-5 km as the relevant secondary segment for analysis. It is also noteworthy to mention that this segment is much more widespread – spanning almost twice the walkable buffer area, thus amplifying the coverage challenges arising from population density variations discussed in Section 4.1. These segments serve as basis for some of the results obtained from spatial deconstruction carried out in Section 5.3, and associated population benchmarks computed in this section have been used as robustness checks on coverage results.

5.3. Spatial Decomposition

The spatial decomposition of the study area is carried out in multiple stages beginning with the definition of the catchment areas of the access points. The catchment areas are further divided into sub-zones, and then structured to finally arrive at a last-mile network for each station.

5.3.1. Defining catchment areas and sub-zones

To define the catchment areas of the metro stations, the concept of Voronoi diagrams (Voronoi, 1908) from computational geometry, is applied to the set of points representing all the metro stations. Transit Voronoi diagrams have been routinely used in transportation literature to model urban road and transit networks (Chen et al., 2022). Voronoi diagrams have also been widely used in spatial analytics to map service coverage areas in variants of the Vehicle Routing Problem (VRP) (Fang et al., 2013). Recent literature on electric vehicle (EV) routing has also employed this technique (Chen et al., 2021). Public transit focussed research such as (Deepa et al., 2022) has made used Voronoi diagrams to identify a restricted coverage map of transit systems. We use it here to identify station catchment areas and first compute the Voronoi diagram of the stations over a larger rectangular area. The map is then cut off at the borders of the BBMP area to reveal the Voronoi map with 127 regions (Fig. 11), each corresponding to a metro station.

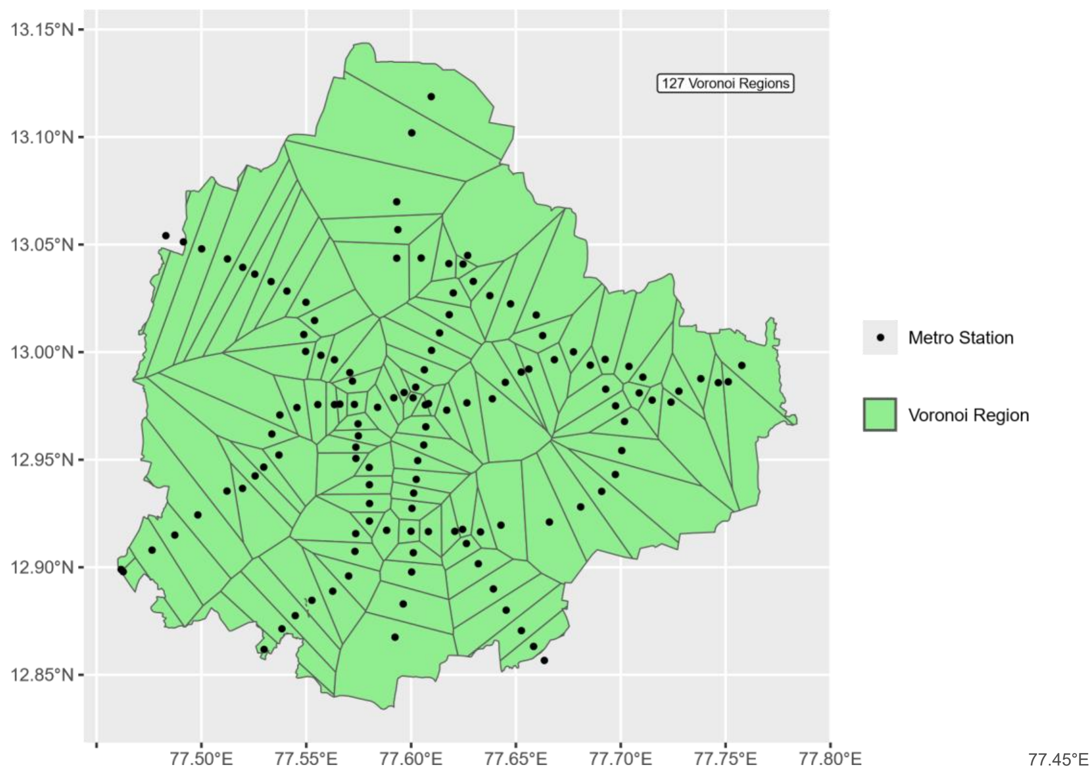

Fig. 11. Bengaluru Metro Voronoi Map

Each Voronoi region here represents the geographical area for which the particular metro station located within it is the nearest metro connection - in effect, the catchment area for the metro station based on the principle of proximity. As a next step, the Voronoi map is overlaid on the ward structure to compute the spatial intersection of the two geometry collections, identifying a total of 821 sub-zones over the BBMP area. Each of these subzones is associated with a single metro station as its access point to the Metro rail network, and located entirely within a ward. This subdivision is then segmented along the access benchmarks from Section 5.1 (Fig.12) by computing the distances of the respective centroids from the nearest metro station.

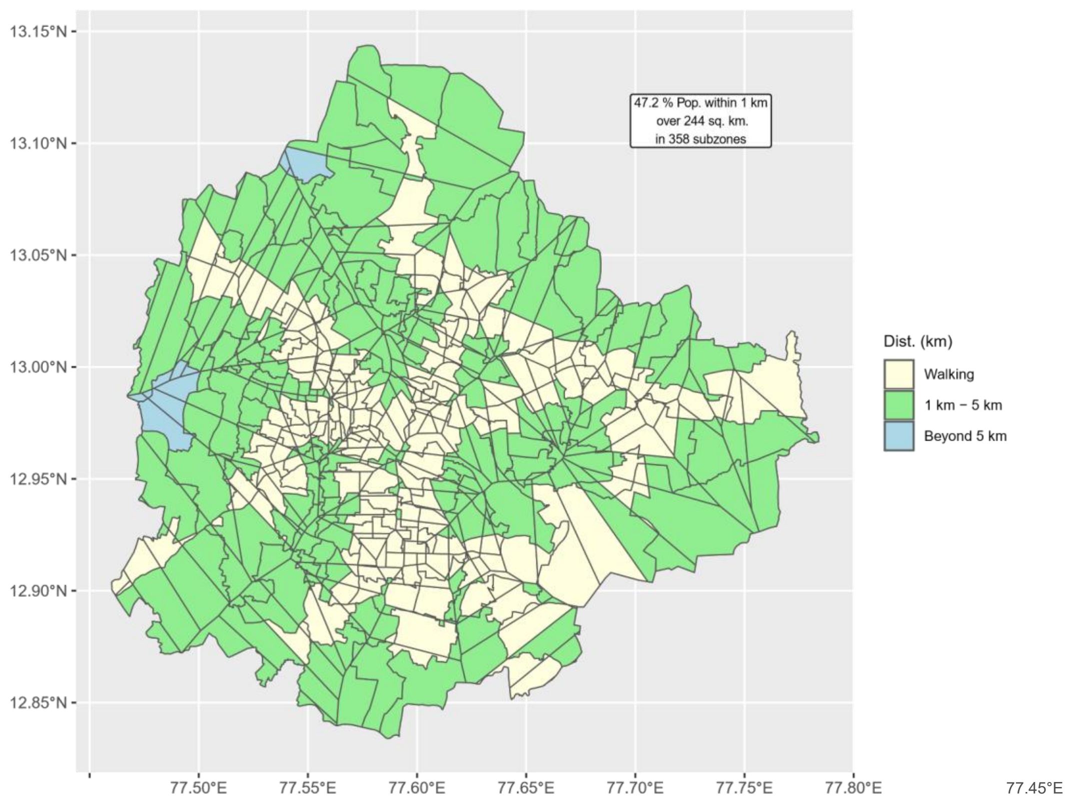

Fig. 12. Potential Last-mile sub-zones

It is reasonable to expect that the residents within a sub-zone would prefer to access the metro network via the nearest station. Under this assumption, 47.1% of the population is found to be located within 358 sub-zones, whose geometric centres are within 1 km from the nearest metro station and can be treated as sub-zones within average walking distance from the metro station. The remaining 463 sub-zones located beyond 1 km from the metro station are spread over 467 sq. km. and represent the opportunity to be addressed by a last-mile feeder service. These sub-zones are further investigated for locating the last-mile stops.

5.3.2. Sub-zone selection and optimization

The sub-zones marked in green and blue in Fig. 12 represent segments lying beyond 1 km from the respective proximal metro stations. An empirically determined minimum area of 0.3 sq km is used to cut-off sub-zones of very small size from further analysis. There is still a fairly large variation in areas of these sub-zones and the selection can be further optimized using a hexagonal tessellation based approach. Hexagons are the most compact regular polygons that tile the plane, and hexagonal cells exhibit unambiguous uniform adjacency (Stough et al., 2020). Recent studies in transportation research such as Soza-Parra et al. (2023) have used hexagonal tessellations over an urban geography to simulate travel demand.

The entire BBMP region is tessellated into contiguous hexagonal blocks of about 1.1 sq. km in area. All hexagonal blocks which lie entirely within a single sub-zone are marked to be added. Small sub-zones whose centroids lie within the same hexagonal block are marked as superfluous - only the point corresponding to the hexagonal block is considered to avoid duplication. These are computed through appropriate successive spatial union, intersection and difference operations. The aforementioned computations yield a final set of 245 last-mile sub-zones which are located entirely within an administrative ward, and whose centres lie beyond walking distance from the proximal metro station (Fig. 13).

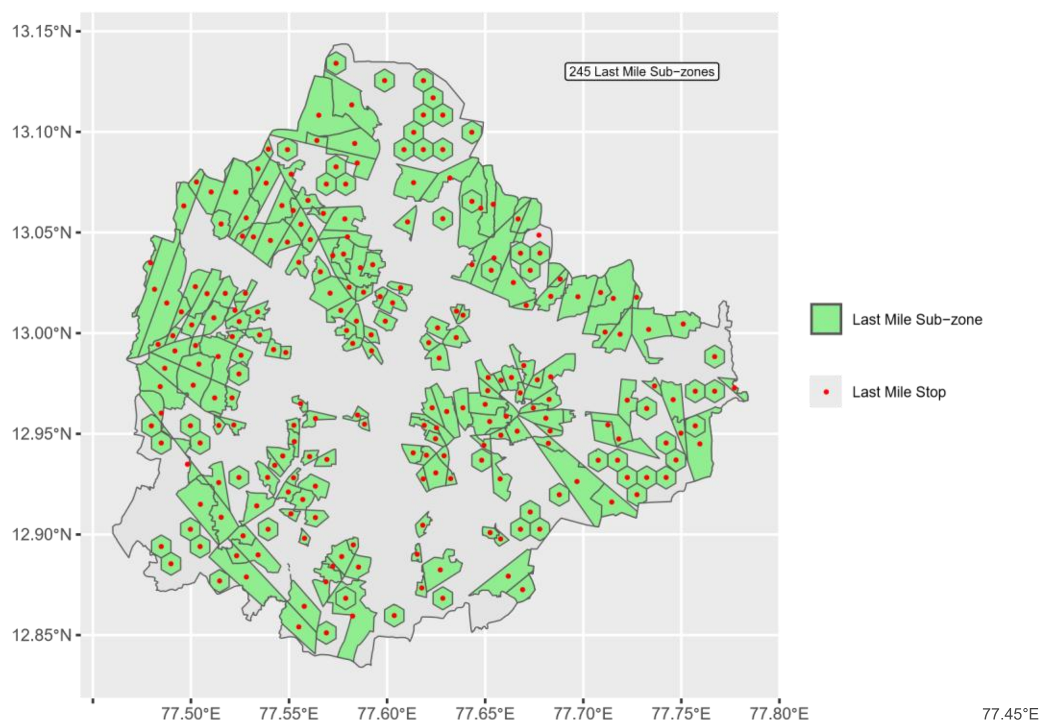

Fig. 13. Last-mile Sub-zones - Recommended

The population represented by each sub-zone is calculated as a percentage of the ward population based on the assumption of uniform distribution within the ward.

5.3.3. Computing the last-mile stops

As a first step, the geometric centres (centroids) of these last-mile sub-zones are computed. These centroids are about 359 meters from the nearest BMTC bus stop on the road network, as shown in Fig. 14.

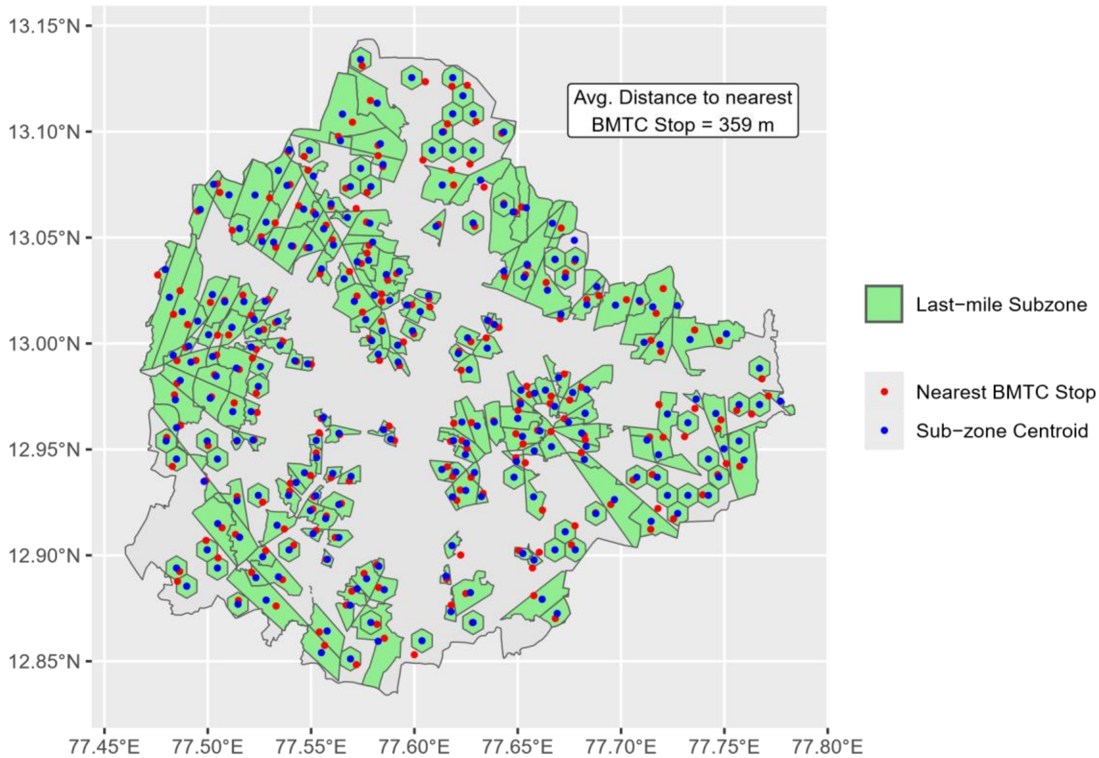

Fig. 14. Last-mile Sub-zones versus BMTC Stops

Visualizations show that some of the nearest bus stops are outside the corresponding sub-zone as well. We consider the map of the road network of the BBMP area with a filtered set of 9,336 motorable public roads from an original universe of 141,287 mapped streets in the BBMP area. The nearest point on the sub-zone road network to the sub-zone centroid is found to be at a distance of 177m on an average and is recommended as the final last-mile stop corresponding to the subzone (Fig. 16).

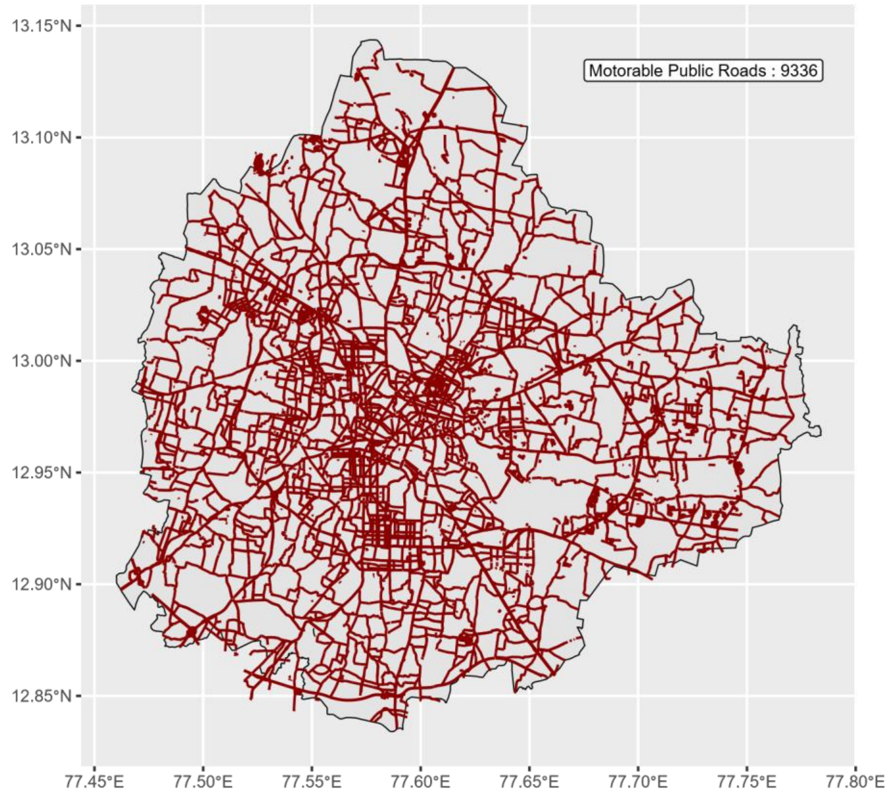

Fig. 15. BBMP Road Network

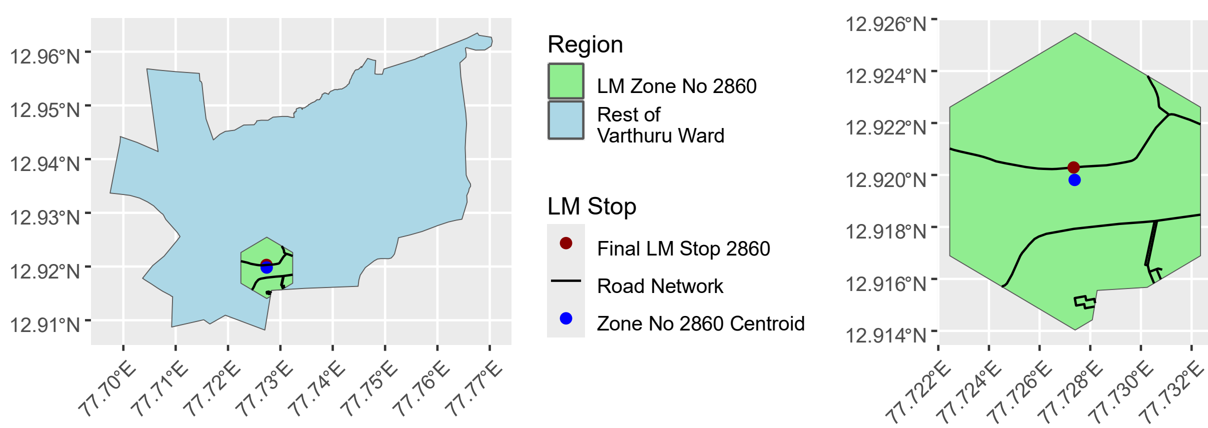

Fig. 16. Last-mile Stop computation - Subzone 2860 (Varthuru Ward)

5.3.4. Station feeder network design

The distributed approach ensures that the final set of 245 stops is spread across the metropolitan area and also uniformly over the Voronoi regions of the applicable stations (Fig. 17). 92 of the 127 stations in scope have one or more stops associated with them, with no station having more than eight. A typical example with five stops is highlighted in Fig. 18.

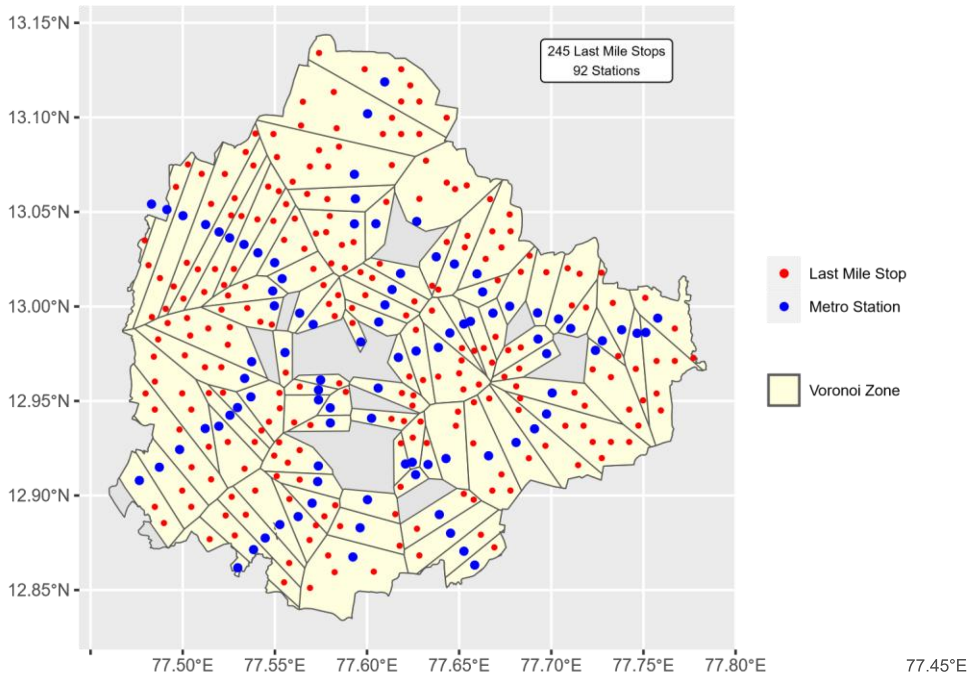

Fig. 17. Last-mile Stops - Recommended

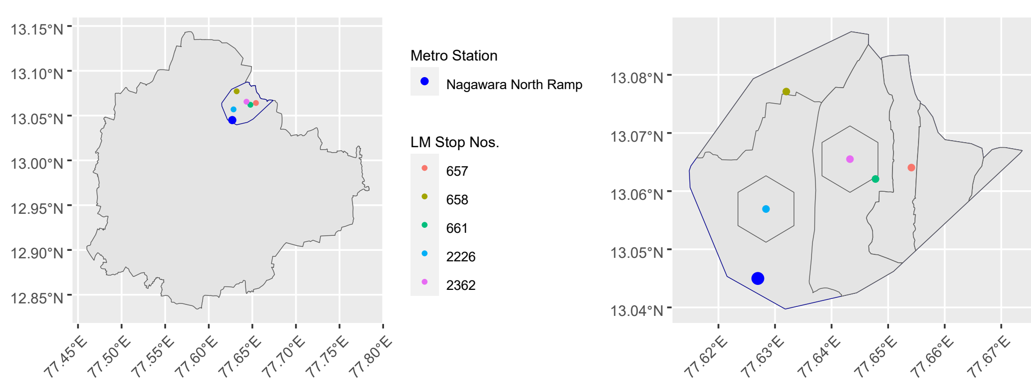

Fig. 18. Nagawara North Ramp - Last-mile Stops

There are 29 stations with a single stop associated with them, and can be treated as trivial networks that do not need further computation. The remaining 216 stops need to be structured into appropriately defined feeder networks. To achieve this, we compute the

Delaunay triangulation (Delaunay et al., 1934) for the set of points represented by each station and the associated last-mile stops within the station's Voronoi zone. Delaunay triangulations are seen to form a reasonable approximation of the transportation road network between spatially distributed points (Musin, 2004), and are widely used in spatial analysis as a robust way to map and measure road networks where intersections are known (Chambers, 2020). These operations finally yield 63 stations each with a network of least two last-mile stops. The last-mile network is represented as a weighted, connected, undirected graph (Fig. 19) with its nodes as the station and the last-mile stops.

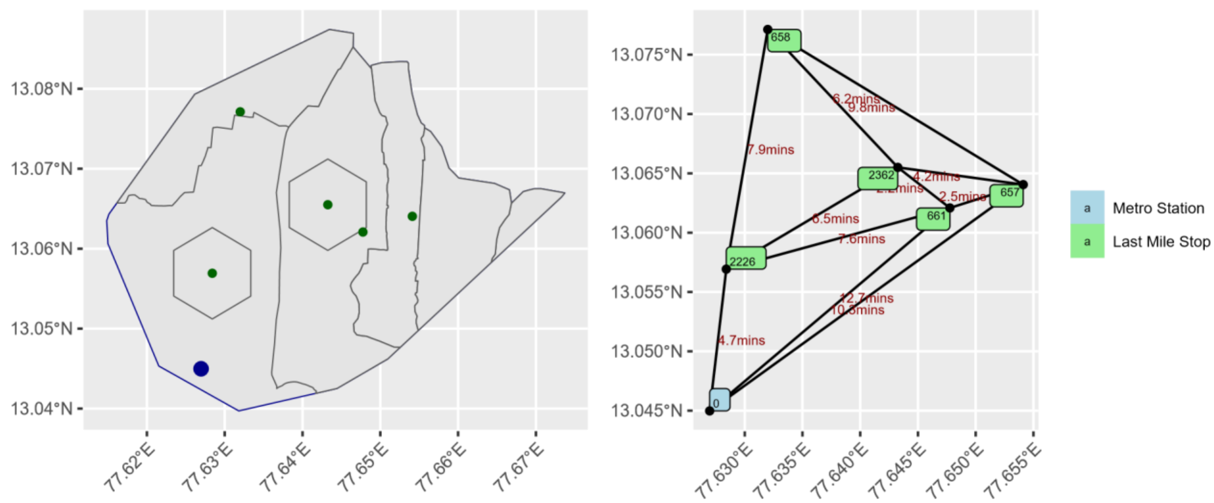

Fig. 19. Nagawara North Ramp - Last-mile Network

The edges are those identified in the Delaunay triangulation above, with edge weights representing the expected travel time between the nodes, calculated as a function of the Euclidean distance and the prevailing average peak hour traffic speed in the city (Sync, 2020).

6. Results and Discussion

The spatial decomposition procedure described in Section 5.3 finally yields the structural definition of the city's last-mile universe with three major components

6.1. Last-mile Transit Stops

The methodology uniquely identifies the last-mile universe of stops spread uniformly over the metropolitan region (Fig. 17). Each of these last-mile stops is characterized by spatial and demographic variables such as location, area, access distance, population covered etc. represented by the last-mile sub-zone of which it is the center (Appendix Table B.2). An appropriate seamless last-mile feeder service operating over the network would take the overall multimodal coverage upto 93% (Appendix Fig. C.21), in line with benchmarks from developed cities (Murray, 2001), spanning 89% of the metropolitan area. The completeness of area coverage also ensures that long-term population growth will be supported over an urban sprawl.

6.2. Last-mile Network Specification

Based on the principle of proximity, the Voronoi diagram-based decomposition of the city enables a consistent, long-term definition of the catchment area of the station in terms of the set of last-mile stops (Fig. 18), key metrics of station coverage (Appendix Table B.3) and the associated last-mile network model (Fig. 19) for further planning of specific feeder routes and operational capacities, frequencies etc. for last-mile services at such metro stations.

6.3. Last-mile Sub-zone Definition

The approach provides a precise definition of each individual last-mile sub-zone in terms of its spatial boundaries, location within wards, distance to the proximal transit station (Fig. 20) and associated demographic information (Appendix Table B.2).

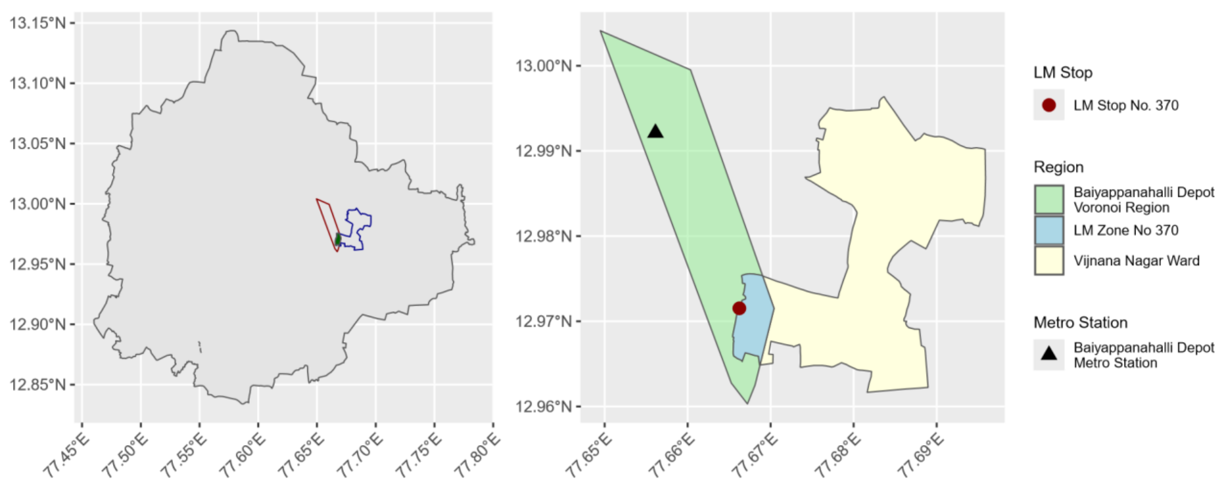

Fig. 20. Sample Last-mile zone in Vijnana Nagar

The sub-zones are relevant from a long-term perspective as the metro infrastructure and passenger adoption grow, as they could serve as traffic planning units. Urban planners can accommodate growth by analyzing the changes in these metrics over the planning horizon. Initiatives to build walkability access within a sub-zone could be focussed on facilitating easy access to the corresponding last-mile stop identified for the sub-zone.

7. Conclusion

The study comprehensively investigates and addresses the structural problem of defining the last-mile for public transit systems in a typical urban geography. We present and discuss metrics, results, and associated implications which can better inform decisions for policy makers, urban mobility planners, and potential businesses as well. To the best of our knowledge, this is the first study to provide a framework which systematically defines a geographic last-mile universe which can be used subsequently for design of complementary feeder services.

Although there are demand-based models of transit ridership that account for spatial heterogeneity (Gan et al., 2019), and to define station catchment areas (Lin et al., 2016), we believe that our contribution lies in looking at the problem from a wider long-term planning perspective, which can accommodate feeder systems of any type. Our methodology overcomes the restrictions imposed by assumptions on the geographic layout and service area considered in studies such as (Quadrifoglio and Li, 2009). We also address limitations in buffer-based approaches to estimating spatio-temporal demand, as highlighted in Yin et al. (2024). The approach based on data from public sources is generic enough to be replicated over other cities with comparable transit infrastructure, geo-spatial layouts and long-term planning horizons. The implementation results can be used to set and compare public transit coverage and access benchmarks across cities to facilitate better policy decision-making.

The nature of the study provides significant avenues for further exploration and extensions. Immediate further work to identify a system of optimal fixed feeder routes over the identified last-mile network is currently underway, based on key results discussed here. Passenger and commuter mobility data within the geographical scope can be incorporated along with demographic growth projections to strengthen methodology and results.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Background

Table A.1. Metro Rail infrastructure in India (2024)

Name	Current Length (km)	Operational Since	Planned Additional (km)	Number of Stations
Delhi Metro	353	2002	118	256
Hyderabad Metro	69	2017	161	57
Chennai Metro	54	2015	235	42
Bengaluru Metro	77	2011	180	74
Kolkata Metro	60	1984	249	50
Mumbai Metro	60	2014	577	53
NOIDA Metro	30	2017	85	22
Kochi Metro	28	2019	70	25
Nagpur Metro	38	2019	112	36
Pune Metro	33	2022	162	28
Lucknow Metro	23	2017	150	21

Appendix B. Metrics

Table B.2. Snapshot of sub-zone metrics

Sub-zone No.	Ward	Station	Dist (km)	Area (sq. km.)	Population
1	Dodda Bidarakallu	Nagasandra	3.9	5.66	32,467
2	Herohalli	Nagasandra	6.2	0.44	3,556
3	Shettihalli	Nagasandra	2.7	2.25	15,350
4	Mallasandra	Nagasandra	1.5	0.06	1,932
5	Bagalakunte	Nagasandra	0.9	2.10	30,820
6	T Dasarahalli	Nagasandra	0.9	0.00	72
7	Chokkasandra	Nagasandra	0.8	1.56	23,065
8	Peenya Industrial Area	Nagasandra	2.6	0.34	3,516
9	Atturu	Dasarahalli	6.1	0.32	1,845
10	Kuvempu Nagar	Dasarahalli	4.9	1.23	6,041
11	Dodda Bidarakallu	Dasarahalli	4.1	0.75	4,278
12	Herohalli	Dasarahalli	5.5	0.44	3,582
13	Shettihalli	Dasarahalli	3.2	4.47	30,430
14	Mallasandra	Dasarahalli	1.3	1.25	39,675
15	Bagalakunte	Dasarahalli	0.9	0.24	3,520

Table B.3. Snapshot of station metrics

Station No.	Station Name	No. of LM Stops	Population Coverage	Area Coverage (sq. km.)
1	Nagasandra	3	51,373	8.4
2	Dasarahalli	7	102,627	10.1
3	Jalahalli	5	74,877	7.0
4	Peenya Industry	3	69,076	4.2
5	Peenya	5	71,593	6.1
6	Yeshwanthpur Industry	2	17,576	2.2
7	Yeshwanthpur	3	39,023	2.8
8	Sandal Soap Factory	1	12,715	2.6
9	Mahalakshmi	2	63,832	1.8
10	Rajajinagar	4	88,424	2.6
12	Srirampura	1	5,711	1.2
13	Sampige Road	3	38,767	2.3
16	KR Market	1	13,312	0.5
17	National College	1	18,039	0.5

Appendix C. Final Coverage Results

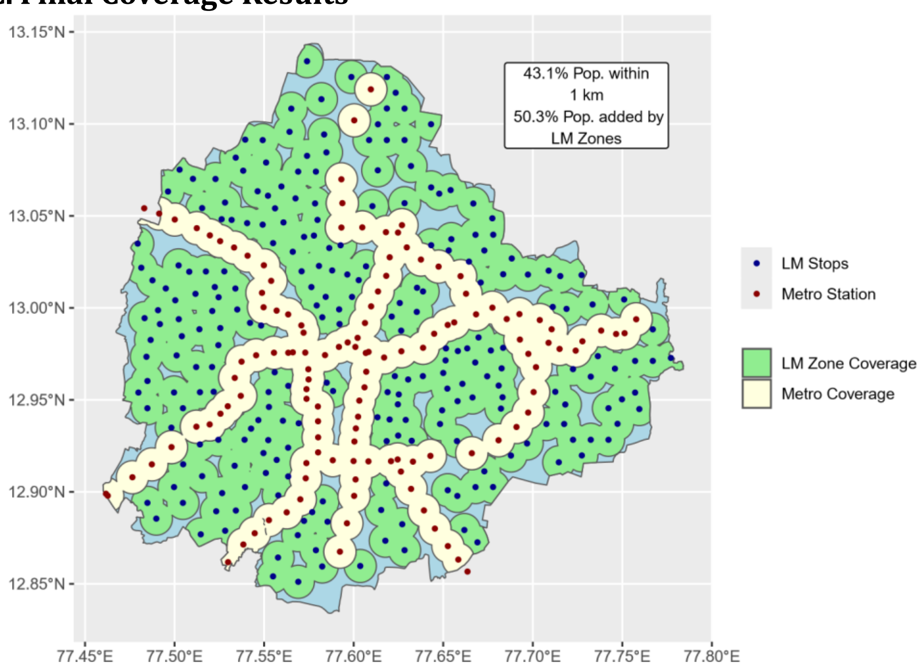

Fig. C.21. Final Coverage - FM/LM and Metro

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