GIS and Gravity Model-Based Accessibility Measure for Delhi Metro

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Abstract

Metro is a rapid transit mode that helps in fast and efficient movement of the public. To make metro journey more convenient and attractive, from origin to destination, accessibility of metro must be good. In this study, tri-level analysis is carried out for the study area of Delhi. Traffic congestion and environmental condition of Delhi are degrading continuously, and to improve the situation, a sustainable Multi Modal Transport System (MMTS) with high accessibility must be explored. In this paper, policy to improve zone to zone metro accessibility for work purpose is discussed and the relation between multimodal transport system with accessibility is studied using GIS (ArcGIS), macrosimulation software (VISUM) and gravity model. It was observed that by the addition and extension of metro lines, transport accessibility is greatly improved. This study shows that percentage of zones in Delhi with higher accessibility level could increase from 5 to 13.88% with the implementation of phase IV of metro. In addition, the implementation of phase IV metro could reduce the average travel time between zones and metro stations. It will also reduce the travel time between metro stations substantially (for the zones covered in this study the average travel time is reduced by 23.63% and for the station covered in this study the average travel time is reduced by 17.73%). Further, it was found that ‘out vehicle travel time’ (OVTT) is having a major impact on the accessibility of metro. Lastly, it was concluded that with the higher level of metro accessibility, people will prefer the multimodal transport system with metro as the main mode. Travel time isochrones for public and private trips for the estimated MMTS model are also presented in this paper to depict the changes in accessibility for different scenarios. This will further help in improving private transport accessibility by reducing congestion on roads. Thus, planning for transport accessibility helps in developing the city in a sustainable manner in the future.

Keywords Accessibility · Metro · Multimodal transport system · Isochrones · Macrosimulation · GIS

1 Introduction

Transport system helps the commuters to reach the desired location for different purposes. People generally prefer their private travel mode due to the advantage of it being more convenient, comfortable, safer, and faster compared to public transport. To make commuters shift from private vehicle to public transport (bus, metro, etc.), it is required to improve the connectivity of the mass transit system. According to PTEG (PTEG 2010), connectivity for work, education,

business, etc. through public transport depends upon four main factors. The first factor is the availability of public transport that is public transport should be available in nearby place for a commuter. Second comes the accessibility that defines the measure of ease for reaching the destination (Farber and Fu 2017). The third is the affordability, i.e. fare system of public transport, and the last one is the acceptability of public transport over private transport.

Even though it is difficult to provide public transport services in very close vicinity, the effort can be made to make it more reachable by planning for the higher level of accessibility. Especially in the case of metro, it is required to provide the services which make metro more accessible for the public. Since the congestion and environment condition of Delhi are worsening, thus it is required to promote the metro over private transport for the sustainable development of the transport system. It is required to improve the

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services to access the metro and reach the destination with less travel time.

According to Hansen (1959), accessibility is defined as the potential of opportunities for interaction. Accessibility is an assessment to check if the area is highly accessible w.r.t. time, cost and effort. If reaching the desirable destination requires more time, cost and effort, the area is said to have low accessibility. Accessibility depends upon factors like the quality of transport system such as travel time, travel cost and the land use pattern (Handy and Niemeier 1997). Economic growth is directly related to the accessibility as time saved in travel will be invested in the growth of an individual and in turn will help in increasing the growth rate of the country. To realise the full potential of improved transport accessibility for every individual, the method of transportation planning should be modified.

Planning should be done in a way, so as to allow one to reach from origin to destination with greater ease and mobility. Three ways in which accessibility can be improved are: by increasing (a) mobility, (b) connectivity and (c) proximity. The major issue is how to make facilities accessible in a sustainable manner. Most of the time, transport planning is done according to future forecasting and estimating the congestion level and does not take “accessibility” into consideration. This planning method has its disadvantages as it recommends expanding the road-network to decrease congestion and accommodate more vehicle traffic. Instead of only focusing on the vehicle traffic, accessibility-based planning takes into account the different public-transit modes as well as non-motorised modes in the planning process. With the rapid increase in demand, it is imperative to shift our transport planning approach, from planning for mobility to planning for accessibility (Straatemeier 2008). An accessible transport system also boosts the policy for equal access of disabled (Department for Transport 2018) and other vulnerable groups.

According to Chen et al. (2011), accessibility is directly related to ridership which in turn depends upon external and internal factors affecting public transit. Some of these exogenous and endogenous factors are employment, population, vehicle ownership, urban density, economic condition, reliability of service, frequency, comfort, fare, safety, etc. By considering these different parameters, many studies have been carried out. Accessibility measures were developed with different needs-based on time, cost, gender, vulnerable group, etc. by using different models. Gravity model-based Hansen equation is one of the widely used and readily understood method for estimating transport accessibility (Bocarejo and Oviedo 2012). Researchers have used Hansen equation in different ways according to their viewpoint for studying accessibility by considering the different factors.

Delhi traffic is at saturation level (Minal and RaviSekhar 2016). One of the most effective way to reduce traffic on

roads is by encouraging people to shift towards public transport and use a multimodal transport system (MMTS). This can be realised by providing a lucrative public transit facility to the commuters. Lack of proper accessibility to public transport is the main reason behind the reluctance to use public transit. For a throbbing transit oriented development of urban spaces, public transport accessibility must be inclusive in the planning process. It will lead to commuters conveniently, safely and comfortably changing the modes in their journey and thus helps in shifting public towards MMTS.

This study is carried out in the National capital of India, Delhi for measuring the metro accessibility. With the increasing traffic congestion and rush to further widen the roads, the most lucrative solution is to attract commuters from private modes to public transit like metro and boost MMTS. Metro system plays a major role in MMTS. Metro is a highly sustainable mode with the efficiency to transfer higher number of passengers with higher travel time reliability with less greenhouse gas emissions (DMRC 2015, 2016). It was observed that currently metro ridership is reduced by 8% from 2017 to 2018 (DMRC 2018) and facing the problem of lower ridership (Roy and Shah 2018). One of the reasons for lower ridership of Delhi metro is poor accessibility to reach metro stations. For e.g. the location of bus stops are not well integrated with metro stations entry and exit gates. The parking lots provided at metro stations should be planned strategically so as to boost ‘park and ride’ trips. Thus, this study investigates the accessibility of metro for the propagation of public transit and MMTS. The study was performed in three stages. Firstly, zone to zone metro accessibility is analysed for work purpose using macrosimulation software VISUM, Gravity model and ArcGIS using five parameters: journey time, journey distance, direct distance, out vehicle travel time and impedance. In the second stage, policy for accessibility is studied. In the last stage, the relationship between accessibility and MMTS is explored. These three stages of the study are carried out to make the policy for accessibility of metro which will help in reducing the share of private transport on roads.

In this research, the main objective is to compare the different parameters of accessibility and to find the most influencing parameter which can be easily understood and implemented by the planners. Further, a policy for improving metro accessibility for establishing MMTS in a metropolitan city of a developing country is also explored and discussed. This paper proceeds with a literature review and description of the study area, data collection method and study parameters. Further, the results from the analysis are discussed and policy simulation for MMTS system is evaluated.

2 Literature Review

Various studies have been done in transport accessibility by considering different factors such as trip length, trip rate, land use, trip purpose, group-based, and socioeconomic factor. Accessibility can be measured in different ways depending upon the availability of data and requirement (Black and Conroy (1977), Kwan (1998), Yigitcanlar et al. (2007), Langford et al. (2012), Ford et al. (2015), etc.). It can be measured using a network that is number of links and nodes (Shimbel 1953), by considering the mode of transport and land use (Hansen 1959). Another way of measuring accessibility is based on the number of trips and travel cost (Saviegar 1967). There are many other ways to measure accessibility, some of the measures of accessibility and factors which affect the accessibility are discussed in this section.

Hansen (1959) introduced the gravity-based approach to find the zone accessibility by summing up the opportunity available in each zone with the difficulty in reaching the zone by different modes. Generalised equation is given as Eq. (1)

$$A_{ijm} = \sum_j B_j f(C_{ij}) \quad (1)$$

where A_{ijm} is accessibility of zone i to zone j for the purpose using mode m . B_j is the attractiveness of zone j for a given purpose. $f(C_{ij})$ is the function to represent the travel cost from zone i to j .

Similar to Hansen, many researchers have given different approaches to find the accessibility by considering different parameters for the function ' f ', that is by considering different parameters as utility function (Wachs and Kumagai 1973; Frost and Spence 1995). Dalvin and Martin (1976) analysed the sensitivity between zone to zone accessibility using Hansen accessibility measure for private vehicle users. The different attractiveness parameter used were as follows: total employment, retail employment, household and population. The study concluded that accessibility parameter is highly sensitive to the choice of attractor variable. Al-Sahili and Aboul-Ella (1992) used descriptive measure rather than quantitative analysis to examine the zone accessibility for the public facility for a location by considering circular buffer zones of maximum walking distance around each facility. Through the study, they have shown that accessibility can be measured by using simple technique instead of using a complex one.

O'Sullivan et al. (2000) developed an effective set of desktop GIS tool with which isochrones map for accessibility analysis of public transport can be produced. Chang and Lee (2008) have done accessibility analysis of high speed rail by expanding Hansen method to GIS-based mapping audit along with ANOVA. This study was done to plan the priority that has to be given for the development of the area to

increase the ridership for the high speed rail. According to Curtis (2008) for sustainable accessibility, the key principle is to integrate land use with transport along with inclusion of population and employment for the location of the region. Straatemeier (2008) pointed out the limitations of traditional transport planning and depicted how planning for accessibility is more advantageous than planning for mobility.

Prasertsubpakij and Nitivattananon (2012) studied metro accessibility for different users to develop multi-dimensional assessment of metro accessibility. It was suggested to balance the access for different groups, provide cost efficient feeders, safe access for individuals, and proper connectivity to metro. This will help the public to prefer public transport safely and comfortably. Bocarejo and Oviedo (2012) used characteristics of time and income spent for accessing work as input in function ' f ' to measure real accessibility by using Hansen equation. Kumar, et al. (2013) have done study of multimodal transport system performance by considering travel time ratio, level of service, interconnectivity ratio, passenger waiting index, running index as parameters for analysing performance. They concluded that multimodal transport system is attractive when the access and egress distance is not large. Access and egress travel time can be reduced by providing proper access and egress facilities as parking facilities, feeder modes, pedestrian walking environment, cycle tracks, etc. Liu et al. (2018) proposed a model to see the station level ridership growth with expansion of rail network. According to the research, expansion in rail network not only helps in improving accessibility but also motivates the surroundings for the development which will increase the ridership. Xia et al. (2018) measured accessibility by estimating travel cost and related potential population flow using Gravity-Radiation model for population flow estimation, and Google Maps API for travel costs. The new estimated potential traveling population (EPTP) weighted travel costs showed strong correlation with the resident population.

Bivina et al. (2019) studied the accessibility of metro for pedestrian; as a result, it was found that walk accessibility to metro station is highly affected by safety and security, and mobility and infrastructure. Yang et al. (2019) focus on evaluating access to public transport service at stations, considering walking time to stations and waiting time for services at stations using Degree Centrality and Gravity Model in Wuhan. By modeling public transport operation, configuration and surroundings of stations, a comprehensive public transport service accessibility index (CPTAI) is formulated to quantify accessibility and shows significant statistical association with trips by public transport. Düring et al. (2019) developed a toolbox for spatial accessibility analysis adapted for data-poor environments and through three different case studies

demonstrated the positive effect of improved accessibility on mobility patterns for multimodal transport, access to jobs and pedestrian frequency potentials.

Raju et al. (2020) carried out an accessibility analysis for healthcare centres using gravity model and geospatial techniques in Tiruchirappalli city. The study calculated spatial accessibility index using Floating Catchment Area, emergency factors travel time and travel impedance function. The study concluded that majority of hospitals are located near to the city centre and the periphery of the city shows very low spatial access to healthcare facilities. Wang et al. (2020) investigated the Accessibility and Gravity Model linkage to Regional Traffic and Economy for Hengyang, China, to realise different patterns of connections between districts of the study area.

Li et al. (2021) examined the time-varying accessibility to senior centres by public transit in Philadelphia and found that accessibility to senior centres declines from the downtown to the suburbs. It was also observed that neighbourhoods with higher shares of older adults tend to have lower accessibility to senior centres. The study suggested measures for transit authorities to better accommodate the diverse travel needs of older adults.

From the literature review, it is clear that many researchers have used Hansen equation for accessibility analysis by considering different parameters. Chang and Lee (2008) have used reduced form of Hansen equation by omitting the attraction factor. However, Dalvin and Martin (1976) have used Hansen equation for analysis of private transport by considering different attraction factors. On the other hand, Bocarejo and Oviedo (2012) used time and income both as the utility function in Hansen equation.

This research is based on relationship between metro system-based MMTS and accessibility. To measure the accessibility of the metro, different utility function based on time has been used in the analysis to get the most influential parameter. This study explores the effect of different measurement parameters like journey time, journey distance, direct distance, out vehicle travel time and impedance on the measure of accessibility for Delhi metro system. Further, the study explores how accessibility approach of transport planning can help in boosting MMTS and thus lead the way to sustainable transportation of the Delhi. To develop a transport model for accessibility measure and the policy that can be applied in developing city like Delhi in efficient manner has been explored.

3 Study Area and Data Collection

In this study, Delhi, the national capital of India, has been considered as the study area for the accessibility analysis of metro rail. For this study, primary data are

taken from the Household survey which was conducted by Central Road Research Institute, New Delhi. The dataset consists of household information, socioeconomic data, trip information, and vehicle information. The secondary data consist of bus routes, headway information, metro routes, schedule of metro train and frequency. The information was collected from Delhi Transport Corporation (DTC) and Delhi Metro Rail Corporation (DMRC) site for Bus and Metro, respectively. The total study area was divided into pockets with 360 internal zones and 8 external zones and around 5100 samples were obtained. South Delhi region contains major commercial centres, educational institutions, markets and residential colonies and so approximately 3100 samples were collected from this region. The remaining 2000 samples were collected from North, East and West Delhi region. Figures 1 and 2 depict the Delhi metro phase II which was completed in 2011 and metro phase III (which is currently underway), respectively. Phase III of Delhi Metro was expected to be completed by the end of 2020 but construction was delayed due to the COVID-19 pandemic. Delhi Metro is one of the most disable-friendly mode in India. All the stations have ramps from the street and lifts have lower level of control panel for the accessibility of disabled people. Further, Delhi metro has all the facilities like a separate coach for women, reserved seats for the vulnerable groups, to make the metro accessible for women, senior citizen and other vulnerable group of people for their safe and convenient journey.

3.1 Study Parameters

In this study, primary data are used to develop the travel demand four stage model. The output from four stage model is further used to measure accessibility. Since our study is based on metro accessibility, thus we have extracted the metro skim matrix based on five internal factors. First, journey time (JRT) is the time between the departure from origin to arrival to the destination zone. The second parameter is journey distance (JRD), the distance covered between origin and destination zone. Third, direct distance (DID) is the direct distance between origin and destination. Fourth, out vehicle travel time (OVTT) includes the access time, egress time and transfer waiting time. Last one impedance consists of travel distance and travel time. These factors are related to convenience and comfort by public transport thus considered as internal factors. Further employment data of different zones were considered as attraction factor for the accessibility analysis.

Fig. 1 Delhi Metro phase II

Fig. 2 Delhi Metro phase III

4 Methodology

In this study, we have analysed the accessibility at three levels. Firstly, the zone to zone accessibility of Delhi metro for work trip by considering five different parameters is compared. The analysis is carried out by considering one parameter at a time to find the most influential parameter. Accessibility is analysed on the basis of JRT, JRD, DID, OVTT and Impedance with the help of ArcGIS and through macrosimulation in VISUM software. The Metro network of phase II and phase III (Figs. 1, 2) form the basis of further analysis of extracting the study parameters. With the help of primary data and secondary data, four stage modelling is performed in macrosimulation software and the metro skim matrix of JRT, JRD, DID, ACT (Access time), EGT (Egress time), TWT (Transfer waiting time) and Impedance were extracted. Since ACT, EGT and TWT are the out vehicle time, thus they are considered together as OVTT parameter for the study. In the accessibility analysis, we have considered distance and time spent by the public inside the metro and outside the metro. For the accessibility measure, we have used Hansen formula (Eq. 1) which is based on the gravity model, to measure the opportunity which is available in each zone to travel to other zone using the metro as the main mode to derive zone to zone accessibility presented in Eq. (2).

$$A_{ijm} = \sum_j B_j f(C_{ij}) \quad (2)$$

where A_{ijm} is the accessibility of zone i to zone j for the work using metro. B_j is the attractiveness of zone j for a work purpose. $f(C_{ij})$ is the function to represent the travel cost from

zone i to j . $f(C_{ij}) = 1/C$, where C is the value of OD metro skim matrices for JRT, JRD, DID, OVTT and Impedance.

In this study, we have considered B_j as the attractiveness of zone j for work that is the employment in the zone j . Skim matrix of various parameters for metro is used as travel cost function. Further, the results of accessibility level are analysed using ArcGIS and comparison is done between the different parameters that affect the zone to zone accessibility by using metro as the main mode.

In the second level of study, policy for a higher level of accessibility is discussed. For the study, isochrones time for PuT was drawn for the Delhi metro using VISUM software. Isochrones time for zone to stop and metro stop to stop were drawn. The analysis was carried out for phase II and Phase III. The further policy is implemented in the form of Phase IV Delhi metro plan, by considering the horizontal year 2021 study. And again accessibility level is measured with the help of Hansen equation and GIS software after implementing Phase IV.

At last, to analyse the importance of accessibility and to explore the relationship between accessibility and MMTS, the third stage of analysis is carried out. For this study, south Delhi region is considered as study area which is divided into 55 zones, 51 internal zones and 4 external zones. Traditional four stage traffic assignment and multimodal traffic assignment (MMTA) was carried out in macrosimulation software VISUM for the base year 2018. MMTA is done with metro as the main mode (obligatory) and rest modes as the feeder for the metro service. Further isochrones time for private (PrT) for the four stage traffic assignment and MMTA were drawn.

Table 1 Number of zones in different accessibility level for parameters for current scenario (2018)

A_i (accessibility-levels)	JRT	JRD	DID	OVTT	Impedance
1	0	0	0	18	1
2	12	0	0	32	15
3	15	12	3	53	16
4	27	31	19	76	39
5	48	78	57	62	56
6	66	74	82	63	73
7	89	92	96	38	92
8	67	40	76	13	46
9	33	25	22	3	21
10	3	8	5	2	1

5 Results and Discussions

5.1 Accessibility Measure

Analysis for zone to zone accessibility for work purpose through metro was done with the help of modifying Hansen equation. The gravity-based model has been developed using derived travel demand parameters JRD, JRT, DID, OVTT and Impedance, and results were analysed by using GIS. Table 1 depicts the number of zones that are lying within a particular accessibility level for the different parameters using Hansen equation. Accessibility level is defined from 1 to 10, with 1 as the lowest accessible, 5 as average and 10 as highest accessible level. Figure 3 depicts the pictorial view to show the difference between various parameters for accessibility measure.

It can be seen from Table 1 and Fig. 3 that accessibility, according to JRT, JRD, DID and Impedance, is equal and above than average, i.e. equal to level of accessibility 5 and

above for most of the zones, whereas, according to OVTT, accessibility is less than average for most of the zones. Based on distance, zone to zone accessibility is above average but when accessibility is measured on the basis of access time, egress time and transfer waiting time then accessibility is poor for most of the zones. For a city like Delhi, accessibility is much more dependent upon time than the distance. Since Delhi has 1749 km of road length per 100 km², has one of the highest road densities in India, still facing the congestion on roads (Centre of Science and Environment 2017). Accessibility not only depends upon ‘In vehicle travel time’ by metro but also depends upon other three parameters of time. First, the time taken to reach the metro station from origin, i.e. access time. Second, the time spent to transfer from one mode to other mode, i.e. transfer waiting time. Third, the time taken to reach the destination after completing the journey from metro, i.e. egress time (Moyano et al. 2018; Kujala et al. 2018).

Figure 4a–e are the extracted results from GIS, showing accessibility heat map for different zones with a different shade. With the help of GIS output heat map, it was observed that accessibility in the inner zones is higher as compared to the outer zones in North Delhi, West Delhi, East Delhi, and South Delhi region. This result can be explained with the help of Delhi metro routes. In Fig. 2, we can see that in the central part of the Delhi, connectivity of the metro lines with the central area is better than the outer region. Due to the higher level of connectivity in the central part, zones in central Delhi have lesser OVTT for metro, i.e. less access, egress and transfer waiting time as compared to outer zones in North, West, East and South Delhi.

To understand how accessibility is varying across different zones, we have carried out a detailed exploration by listing out the zones on the basis of the highest score on the accessibility scale. Table 2 consists of 5 most accessible zones (in descending order) according to different parameters in the accessibility analysis. In Table 2, we can see that

Fig. 3 Graph between accessibility level and number of zones for current scenario (2018)

Fig. 4 **a** Heat map of zonal accessibility based on journey distance for current scenario (2018), **b** Heat map of zonal accessibility based on journey time for current scenario (2018), **c** Heat map of zonal accessibility based on direct distance for current scenario (2018), **d**

Heat map of zonal accessibility based on out vehicle travel time for current scenario (2018), **e** Heat map of zonal accessibility based on Impedance for current scenario (2018)

most of the zones are different for the different parameter. For JRT and Impedance parameter, 3 of the zones out of 5 are same, it is because impedance is combined parameter in which JRT is one of the parameter and according to other parameters zones are almost different.

These zones are listed as the most accessible zones due to the balance in opportunity and connectivity. Sufficient

connectivity is present in these regions to fulfill the public needs of travel for the purpose of work through metro service.

From the above result, it can be concluded that by considering different parameters in accessibility measure, different results are obtained. From these parameters, we need to choose the parameter which affects our region of study

Table 2 List of most accessible zones for different parameters for current scenario

Rank	Parameter				
	JRT	JRD	DID	OVT	Impedance
1	Janta Colony	Bazar Sita Ram	Idgah Road	Samaypur Badli	Janta Colony
2	Dharam Pura	Jama Massjid	Model Basti	Baird Place, Khyber Lines	Rajouri Garden
3	Rajouri Garden	Shastri Nagar	Ram Nagar	Shiv Vihar	New Ranjit Nagar
4	New Ranjit Nagar	Qasabpura	Kuncha Pandit	East Of Kailash	Baljit Nagar
5	Baljit Nagar	Janta Colony	Nimri Colony	Shakarpur	Wazirpur

Table 3 Isochrones time PuT(metro) from zone Nizamuddin

Station	Phase II	Phase III
Mundka	1 h 32 min 17 s	1 h 16 min 41 s
Huda City	1 h 33 min 47 s	1 h 14 min 54 s
Rithala	1 h 38 min 17 s	1 h 17 min 54 s
Azadpur	1 h 10 min 47 s	58 min 54 s
Hauz khas	52 min 47 s	33 min 54 s
INA	42 min 17 s	23 min 54 s
ISBT	47 min 17 s	30 min 24 s
Botanical Garden	53 min 17 s	30 min 41 s
Welcome	1 h 1 min 17 s	40 min 24 s
Noida Sector 15	47 min 17 s	24 min 41 s

the most. In a developing city like Delhi with good transport infrastructure and large road network, the only reason left for not using MMTS is accessibility for public transport in terms of time. Therefore, it can be concluded from the measure of accessibility result that OVTT is the most affecting parameter. Thus to help the planner to escape from the complexity of study for the large network, it is required to find the parameter which is more important and which affects the region of study the most for accessibility.

5.2 Policy for Higher Accessibility

As discussed earlier, that accessibility is much more dependent upon the OVTT that is the access time, egress time and transfer waiting time; a reduction in this component should lead to increase in the zone to zone accessibility. With this intention, analysis and comparison of change in accessibility due to the expansion of metro from Phase II to Phase IV are done.

In phase III as shown in Fig. 2, two new metro lines were introduced: Magenta line (from Botanical Garden to Janakpuri West) and Pink line (from Majlis park to Shiv vihar) along with the extension of Red, Yellow, Green, Violet lines. Table 3 shows the difference in travel time due to the introduction of phase III metro plan from Nizamuddin zone to other important metro stations, situated in different regions of Delhi. Nizamuddin is located in south Delhi,

having denser population, surrounded by Nizamuddin Dargha and railway station which is one of the 5 main railway stations in Delhi, connecting all the major cities. Figure 5a, b show the isochrones time for PuT from Nizamuddin zone to all the metro station with the column over various metro stations, showing the travel time for phase II and phase III, respectively. From this result, we observed that travel time from Nizamuddin zone to other metro stations was reduced after the implementation of phase III plan. Similarly, for other zones, the same results were observed. We have observed this from Figs. 1 and 2 that in phase III, connectivity between various stations with Nizamuddin zone is improved due to the introduction of a pink line from Nizamuddin zone with the addition of Nizamuddin metro station in phase III. Due to this, travel time between stations were reduced.

Similarly, in Table 4, isochrones time PuT from Lajpat nagar metro station to other important metro stations were shown for phase II and phase III. Lajpat nagar is a major commercial and residential area. Figure 6a, b show the isochrones time PuT from Lajpat nagar metro station to other metro stations with a column over metro stops showing travel time to various metro stations from Lajpat nagar metro station. It was observed that ‘In vehicle travel time’ is reduced from Lajpat nagar metro stops to other stops after the implementation of phase III metro. From Figs. 1 and 2, we can observe that in addition of a violet line, the pink line is also introduced, passing through Lajpat nagar metro station and nearby magenta line is also introduced. Due to this, travel time is reduced from the Lajpat nagar metro station to the other stops. Similarly, for other zones and stops, travel time is reduced.

From the above results, it can be concluded that due to the extension and introduction of the new metro line, travel time is reduced between zones and metro stops to other metro stops. Further, new metro stations were introduced in phase III; this improves the accessibility of zones as less access and egress distances need to travel for metro. In current scenario, service frequency of metro is increased which helps in reducing transfer wait time as in peak hour frequency is 2 min to 3 min and in off-peak hour it is 4 min to 6 min.

a Isochrones of travel time from Nizamuddin zone (phase II)

b Isochrones of travel time from Nizamuddin zone (phase III)

Fig. 5 a Isochrones of travel time from Nizamuddin zone (phase II), b Isochrones of travel time from Nizamuddin zone (phase III)

Table 4 Isochrones time PuT(metro) from Lajpat Nagar metro stop point

Metro stops	Phase II	Phase III
Mundaka	1 h 18 min	1 h 6 min 30 s
Huda City Centre	1 h 19 min 30 s	54 min 30 s
Rithala	1 h 24 min	57 min 30 s
Azadpur	56 min 30 s	38 min 30 s
Hauz Khas	38 min 30 s	13 min 30 s
INA	28 min	3 min 30 s
ISBT	33 min	24 min
Botanical Garden	39 min	24 min 17 s
Welcome	47 min	34 min
Noida Sector 15	33 min	18 min 17 s

Figure 7 shows the metro phase IV which is going to be completed in 2025. In Phase IV, two new metro lines are going to be constructed. First, moss green line from Tughlakabad to T1 IGIA and Lajpat nagar to Saket G block and second aqua line from Inderlok to Indraprastha. Further extension of red, pink and magenta line is going to take place.

Accessibility analysis was carried out after taking phase IV metro construction in consideration, and results were extracted for the same parameters as shown in Table 5 and Fig. 8

Figure 9a–e show GIS result for different parameters after considering phase IV metro plan. From the comparison between accessibility analysis for the current scenario and accessibility after implementation of phase IV metro, it was observed that according to JRT parameter, zones having lower accessibility shift towards average accessibility level. For JRD parameter, not much difference was observed and for DID parameter no change was observed. The great effect is observed in accessibility for OVTT parameter. Earlier, around 179 zones out of 360 were in lower accessibility category but after implementation of phase IV, number of zones in the lower accessibility category reduced to 112 zones. Similarly according to impedance factor around 20 zones shift towards average accessibility level and approx. 15 zones shift to an above average level.

The above results show that to make metro accessible from all the zones, it is needed to consider OVTT and impedance as major parameters in policy making based on the accessibility. But as we know that impedance is the combination of different parameters such as travel distance, travel time, and travel cost and for this study, we are finding a way to measure accessibility with lesser data. Thus, considering OVTT is the better way in policy making based on the accessibility. A similar study by Kumar et al. (2013) concluded that for making multimodal transport system attractive, accessibility for the main mode should be high

with less access and egress time. From this, we can say that OVTT is the major parameter in the accessibility analysis.

Tables 6 and 7 show the result of Isochrones time PuT for current scenario, and after implementation of phase IV, we can observe from above Tables 6 and 7 that zone to stop and stop to stop time is reduced after the construction of Phase IV metro plan.

It can be observed from the above results that as the Delhi metro lines are expanding, accessibility is improving. When phase III was constructed, accessibility increased as compared to earlier. When the phase IV plan was included, then accessibility was further improved as compared to the current scenario. Hence, one of the ways to improve accessibility is by making metro available (Bocarejo and Oviedo 2012). This can be achieved by making policy for transport planning on the basis of accessibility and not on future forecasting.

5.3 Policy Simulation—Accessibility and MMTS

The study is carried out to relate the accessibility of private transport with the MMTS which is further related to the accessibility of PuT. For this isochrones time for private (PrT) for the four stage traffic assignment and MMTA were compared. Accessibility is analysed by observing the shift of private transport user to public transport. Figure 10a shows the isochrones time PrT from the Sukhdev Vihar zone 206 for four stage traffic assignment. If we compare this isochrones time PrT with Fig. 10b showing the isochrones time PrT from the same zone for multimodal traffic assignment, we can see that in the multimodal scenario, time of travel is reduced, i.e. accessibility is increased. This is due to the shift from private transport to public transport in MMTS scenario. Here, we can conclude that if people prefer metro as the main mode and rest the modes as a feeder for the metro service then accessibility will improve and if accessibility for metro is high then people will prefer metro as the main mode for their journey.

People prefer to move with the mode of transport which is more convenient, safe, takes less travel time, and is economic. If a planner wants to shift the people to use public transport system instead of using private than facilities for MMTS should be provided. For that, accessibility to public transport and accessibility by the public transport should be high.

Further, if people use MMTS, then private traffic on roads will reduce which further helps in reducing environmental pollution (both noise as well as air pollution). We can say that planning towards MMTS and making policy based on accessibility will help in the sustainable development of the transport system.

a Isochrones time from Lajpat nagar metro stop point (phase II)

b Isochrones time from Lajpat nagar metro stop point (phase III)

Fig. 6 a Isochrones time from Lajpat nagar metro stop point (phase II), b Isochrones time from Lajpat nagar metro stop point (phase III)

Fig. 7 Delhi metro Phase IV

6 Conclusion and Recommendations

This paper discussed the policy that can be effectively used in Delhi to increase the zone to zone accessibility through metro for work purpose. Using macro-simulation software VISUM, skim matrices of different parameter JRD, JRT, DID, OVTT and Impedance were extracted for metro. These parameters were used in the gravity-based model, Hansen equation to measure zone to zone metro accessibility for work purpose. Finally, this accessibility result was given as input in GIS to get heat maps for a pictorial view of zone-wise accessibility level for different parameters. Further, isochrones time of PuT for Nizamuddin zone and Lajpat

nagar metro station to other important metro stops for Phase II, Phase III and Phase IV were observed. At last, policy for accessibility is compared with the MMTS in VISUM by taking South Delhi as the study area.

From the accessibility level results for different parameters for the current scenario (2018), it was observed that the zones in the central part of Delhi region are having higher accessibility level as compared to other zones. However, after considering phase IV, accessibility level is improved up to a certain level. Further, for the current scenario (2018), it was observed that the accessibility level for OVTT parameter is below the average level for most of the zones whereas for other parameters it is equal to or above average. However, after considering phase IV, accessibility level for OVTT parameter is improved and for other parameters, not much difference was observed. From the isochrones results, it was observed that as the metro line in expanding from Phase II to phase III, travel time is reduced from zone to metro stops and metro station to station, further time is reduced when phase IV is also implemented. Thus, accessibility level results help in finding the accessibility measure and with isochrones result, policy for accessibility was found for the developing a city like Delhi.

At last relation between MMTS and accessibility is explored with South Delhi as the study area. With the isochrones of PrT time results, it was clear that by using MMTS, congestion on road is reduced. That means accessibility for PrT is improved. Most of the private vehicle users shift towards public transport with metro as the main mode and

Table 5 Number of zones in different accessibility level for parameters after Phase IV metro implementation

A_i	JRT	JRD	DID	OVTT	Impedence
1	0	0	0	7	0
2	7	0	0	11	0
3	11	6	3	35	6
4	31	34	19	59	30
5	60	76	57	62	75
6	92	83	82	75	82
7	85	92	96	61	92
8	47	41	76	41	41
9	25	23	22	7	23
10	2	5	5	2	5

Fig. 8 Graph between accessibility level and number of zones after Phase IV metro implementation

using private vehicle for a short path in their journey. It can be concluded from this study that by measuring accessibility using a major parameter and applying the policy for that, will help in improving the accessibility of a city like Delhi. Further, this improvement in accessibility will help in shifting of people towards public transport which will reduce the load on the roads and further, help in developing the city in a sustainable manner.

From this study of Delhi region, it can be concluded that OVTT is an important parameter in accessibility analysis as compared to other parameters, and to improve the metro accessibility OVTT should be reduced. For that, facilities like Park and Ride, Bike and Ride, sufficient space for parking, feeder services, and integration of feeder services with metro are a pre-requirement. Also, the availability of metro in walkable distance and safe environment for the pedestrian are also needed to improve metro accessibility.

The study is carried out at three different levels: the measure of accessibility, policy for accessibility and at last the relation of accessibility with MMTS. From these results of the study, we can conclude that the use of policy for accessibility for planning a city like Delhi will help in the development of the city in a sustainable manner. Due to increase in population and migration of people from nearby places to Delhi for work, education and business, Delhi roads and environmental condition are becoming worse. To improve accessibility, it is required to make policy revolving around accessibility. This paper discussed the policy that the accessibility will be improved by expanding the metro network and by making metro available in walkable distance. With the improvement in accessibility through metro, air and noise pollution will reduce due to reduced congestion on roads as commuters will prefer MMTS.

Table 6 Isochrones PuT from Nizamuddin to major metro stops for phase III and phase IV

Metro stops	Phase III	Phase IV
Mundaka	1 h 16 min 41 s	1 h 6 min 30 s
Huda City Centre	1 h 14 min 54 s	54 min 30 s
Rithala	1 h 17 min 54 s	57 min 30 s
Azadpur	58 min 54 s	38 min 30 s
IIT	44 min 24 s	32 min 54 s
New Delhi	34 min 41 s	32 min 16 s
Tughlaqabad	51 min 54 s	41 min 49 s
Chirag Delhi	38 min 24 s	24 min 24 s
T1 IGIA	53 min 53 s	42 min 54 s

Apart from this, study fares of the metro can also be considered as one of the reasons for not opting metro. This study can be extended by using fares of the metro as a parameter. Delhi metro fare is high and it will be higher after the execution of phase IV metro plan. This might restrict the lower income group and students to prefer metro.

Table 7 Isochrones PuT from Lajpat nagar metro station to major stops for phase III and phase IV

Metro stops	Phase III	Phase IV
Mundaka	1 h 6 min 30 s	57 min
Huda City Centre	54 min 30 s	45 min 30 s
Rithala	57 min 30 s	56 min
Azadpur	38 min 30 s	36 min 43 s
IIT	23 min	13 min
New Delhi	24 min	22 min 30 s
Tughlaqabad	30 min 30 s	22 min 55 s
Chirag Delhi	17 min	5 min 30 s
T1 IGIA	32 min 29 s	24 min

a Heat map of zonal accessibility based on journey distance after phase IV implementation.

b Heat map of zonal accessibility based on journey time after phase IV implementation.

c Heat map of zonal accessibility based on direct distance after phase IV implementation.

d Heat map of zonal accessibility based on out vehicle travel time after phase IV implementation.

e Heat map of zonal accessibility based on Impedance after phase IV implementation.

Fig. 9 **a** Heat map of zonal accessibility based on journey distance after phase IV implementation, **b** heat map of zonal accessibility based on journey time after phase IV implementation, **c** heat map of zonal accessibility based on direct distance after phase IV implemen-

tation, **d** heat map of zonal accessibility based on out vehicle travel time after phase IV implementation, **e** heat map of zonal accessibility based on Impedance after phase IV implementation

a Isochrones PrT time from Sukhdev vihar zone 206

b Isochrones PrT from Sukhdev vihar zone 206 in multimodal transport system

Fig. 10 **a** Isochrones PrT time from Sukhdev vihar zone 206, **b** Isochrones PrT from Sukhdev vihar zone 206 in multimodal transport system

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Code Availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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