EXAMINATION ON THE INFLUENCE AREA OF TRANSIT-ORIENTED DEVELOPMENT: CONSIDERING MULTIMODAL ACCESSIBILITY IN NEW DELHI, INDIA

By

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ABSTRACT

Transit oriented development (TOD) is a land use and transport integrated urban planning strategy that is highly acclaimed for promoting sustainable city development. The catchment or influence area of transit stations is a key factor in TOD planning. This research aims to identify the problems regarding adoption of TOD influence zone standards/ guidelines formulated by developed countries in developing countries and the necessity of conducting adaptability studies on TOD influence areas.

As Indian cities adopt the concept of transit-oriented development (TOD), concerns have arisen regarding the applicability of TOD standards formulated in developed countries in the Indian context. The existing studies show that the size of the influence area varies among different cities and travel modes. Accordingly, no single size influence zone is suitable for all cases. This study aims to estimate the TOD influence areas in New Delhi by examining the last mile connectivity patterns of passengers on the Delhi Metro Railway (DMR) across the city and at specific stations. The literature review highlights the necessity of carefully considering the spatial extent of influence areas and modes other than walking as access or egress mode in the Indian context. Questionnaire surveys conducted on the last mile connectivity reveals use of various access modes for metro stations in India, although current research only considers walking and cycling to be universal forms of access. Therefore, this study focuses on the DMR's multimodal accessibility to investigate the last mile distance of each mode. In order to offset the rounding errors of reported distance, a heaping model and multiple imputation (MI) were employed to improve the accuracy of the reported distance. Afterward, distance decay analysis and receiver operating characteristic (ROC) curves were used to determine the thresholds of last mile distances. The findings show that the influence area differs across station types and travel modes; increasing in the order of walking, informal transit, buses, and private transport, respectively. The study highlights that the current TOD influence zone standards adopted are conservative when compared to the actual distances walked by commuters to transit stations, and the distance is considerably high when other modes are included.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 - INTRODUCTION

1.1 Need for study

Transit oriented development (TOD) is a concept focusing on station area development linking transit, land use and community living and was popularized by Peter Calthrope in his book “The New American Metropolis” (Calthrope, 1993; Carlton, 2007). TOD as a planning strategy was derived in North America where large cities have experienced low-density sprawl, which has worsened traffic congestion and degraded the quality of the environment in the 1990’s (Sung, 2011).Cities in Europe and Asia have historically been transit oriented with mixed land use, pre dominance of pedestrians and cyclists, and transit services (Renne, 2009; Thomas et al., 2018).

TOD has multiple definitions, and various cities in the developed world have adopted guidelines and standards for its planning and implementation. The influence area is a major element in the TOD. There have been many studies on TOD’s influence area in developed nations. According to Cervero et al. (1994), Bernick and Cervero (1997) and Guerra et al. (2012), the extent of an influence area is usually based on one’s willingness to walk. Researchers have put forward various distances; most range from 400 to 800 m (Untermann, 1984; Calthrope, 1993; Dittamar & Ohland, 2004). Guerra et al. (2012) says that even though 1/2 mile (800 m) has been adopted as the de facto standard for TOD influence areas in the US, “The half-mile transit catchment area, whether radial or network-based is more an artifact of historical precedent than a statistical or analytical construct,” raising doubts about the feasibility of adopting this standard. Limited research exists on this regard but show that people are willing to walk or cycle longer than the half mile standard (Zhao et al., 2003; Martens, 2004; Agrawal et al., 2008; El-Geneidy et al., 2014; Flamm & Rivasplata, 2014; Park et al., 2015; Chia & Lee, 2015). Those research results give different distance values with each other indicating that the transit catchment area may vary among cities, travel modes (both last mile and transit mode), types of area (urban or sub-urban) and trip purposes. Meanwhile, those studies focused only on walking

(Guerra et al., 2012; Chia & Lia, 2015; Agrawal et al., 2008; El-Geneidy et al., 2014) and cycling (Martens, 2004; Flamm & Rivasplata, 2014) as the access modes. However, there is lack of consensus among researchers on whether this is a correct practice.

Furthermore, in recent years, cities in developing countries, such as India, have started adopting the TOD as part of their city planning strategies. The government of India published the National Transit Oriented Development Policy and corresponding guidelines to assist their cities in the adoption of TOD. Based on research from developed countries, India's national TOD policy (MoUD, 2015) defines an influence area as being "in the immediate vicinity of the transit station, i.e., within a walking distance, having high density compact development with mixed land use to support all basic needs of the residents." Furthermore, it specifies the influence zone of transit stations as falling within a walking distance of 500–800 m (i.e., a 10–12 min walk). However, it is necessary to establish whether such measurements apply to Indian cities, since their travel patterns and population densities differ significantly from those of developed states. According to Park et al. (2015), these distances may be suitable for American cities, but they may not be suited for cities in Europe and Asia. This is corroborated by Sung and Oh (2011) whose research showed that TOD planning factors need to be carefully implemented in high density metropolises such as Seoul, South Korea

1.2 Study objectives

There is a dearth of data and research regarding last mile mobility and TOD influence zone research in India. The conventional TOD influence area standards cannot be applied in India. Existing studies show that the influence areas can be extended to a larger area than specified in the policy and the TOD influence areas need to be examined according to urban and travel characteristics of India. There is a need find a link between actual mobility patterns to the TOD policies and guidelines in the country.

This research examines the extent of influence zones for transit stations based on relevance of various last mile connectivity modes and existing mobility patterns in Indian cities. The objectives of the research are:

1. To determine whether the "half mile radius" influence circle commonly assigned to

TOD is applicable in Indian cities or not (walking).

2. To study the various access/ egress modes (informal transport, bus, private modes) in Indian cities to estimate the suitable influence area considering multimodal accessibility
3. To understand how the extent of influence area changes according to the locational differences of transit stations

The study focuses on empirical findings (rather than on methodology) which can support TOD policy and city planning in Indian cities. Different existing methods have been used to arrive at findings/outputs to support identification of influence areas for TOD. Current planning practices may be reviewed to take into consideration of actual environments around stations and the travel behavior of commuters. The guidelines given can be used as initial reference. It should also be noted that these distances will vary across cities and within the zones of a city, depending on the type of main transit mode, access/ egress mode and station area characteristics.

1.3 Dissertation framework

With the given background, the research focuses on New Delhi, which is one of the first cities in India to adopt TOD into its City Master Plan. The city is taken as the case study for this research and data used pertains to the last mile connectivity patterns of commuters of metro rail. New Delhi can be an interesting case to explore the extent of influence areas for TOD, as the city has already initiated TOD in its growth and has a mass transit system in place since many years, with commuters having well established last mile patterns. This research expects to study the access/ egress culture and use of many modes in Indian cities to determine the suitable influence area in an Indian context. The graphical representation of the research framework is given in Figure 1.

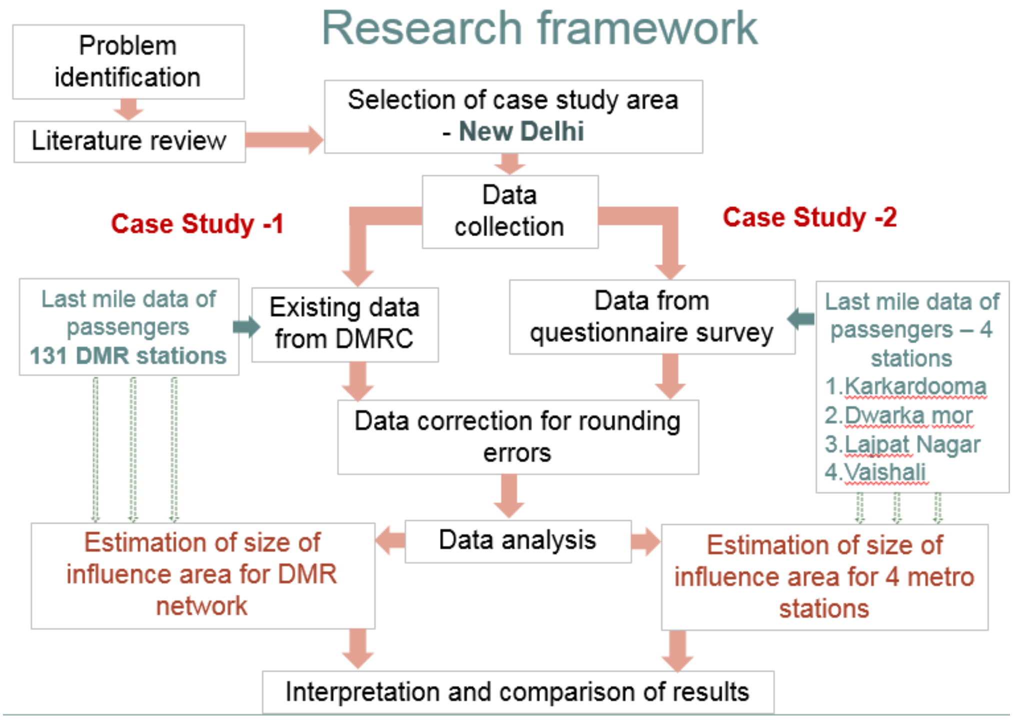


Figure 1 Research framework

Chapter 2 provides a detailed overview of literature regarding TOD influence areas. The chapter discusses the inconsistencies regarding extent of influence areas and looks at various studies that have been carried out to estimate influence areas. Chapter 3 provides information regarding New Delhi, the case study city and discusses the data used for the study. The rounding errors encountered during the analysis have also been discussed in detail. Chapter 4 explores the extent of influence zones for DMR network in New Delhi using secondary data collected from DMRC. Multiple imputation process used to remove rounding and heaping bias is described in detail in the chapter. The particulars on distance decay analysis carried out for walking, informal modes, bus and private modes and ROC analysis is given in this Chapter. Chapter 5 discusses the analysis on last mile distances and results for the four selected transit stations. The deliberation on the comparisons of the results between station types is also given. Chapter 6 presents an overview of lessons learned from the research, and offers concluding remarks.

CHAPTER 2 - LITERATURE REVIEW

2.1 Definitions of TOD

The TOD has no universal definition. Some of the definitions found in literature are given below:

i. "A mixed-use community within an average 2,000-feet (or 10-minute) walking distance of a transit stop and core commercial area. TOD mixes residential, retail, office, open space, and public uses in a walkable environment, making it convenient for residents and employees to travel by transit, bicycle, foot, or car" (Calthrope, 1993)

ii. "Development within a specified geographical area around a transit station with a variety of land uses and a multiplicity of landowners" (Salvensen, 1996)

iii. "The practice of developing or intensifying residential land use near rail stations" (Boarnet & Crane, 1998)

iv. "A mixed-use community that encourages people to live near transit services and to decrease their dependence on driving" (Still, 2002)

v. "Mix of uses, at various densities, within a 1/2-mile radius around each stop" (Dittamar & Ohland, 2004)

vi. "An approach to expansion that aims to encourage the development of mixed use and compact, increasing the number of passengers of public transport and creating more livable communities" (Arrington & Cervero, 2008)

vii. "Concentrated mix of moderately dense and pedestrian friendly development around transit stations to promote transit riding, increased walk and cycle travel and other alternatives to use of private cars" (Cervero, 2009)

viii. "A planning technique that aims to reduce automobile use and promote the use of public transit and human-powered transportation modes through high density, mixed-use, and environmentally friendly development within areas of walking distance from transit centers" (Sung, 2011)

One of the main learnings gained from the review of these definitions is that the TOD is typically defined as a highly dense and mixed-use development around the transit station where the benefit of proximity to the station would promote transit usage rather than simply a planning strategy. The practice or the strategy itself can also be called TOD; moreover, it can be regarded that the term TOD can be synonymous with planning strategy, design, and development. The basic objective of the TOD is to reduce car dependence by reducing trip lengths as well as promoting the use of mass transit and sustainable modes, such as walking and cycling. The benefits that were achieved through the implementation of successful TOD projects include reduced traffic congestion, improved air quality, and affordable housing. Moreover, livable communities were created, sustainable transport was achieved, and the use of transit and non-motorized transport (NMT) as well as opportunities to live, work, shop, and relax increased (Cervero & Kockelman, 1997; Cervero & Murphy, 2002; Shastry, 2010; Cervero & Ewing, 2014). The aforementioned definitions provide the basic features that are essential for developing the TOD. A variety of factors and their combinations are typically utilized to define and explain the TOD. These factors include the proximity to a transit station (based on distance or time), density levels, mixed land use, walking and cycling accessibility, effect of reducing car use, main travel mode, and the availability of public spaces to build communities (Cervero, 1997; Cervero et al., 2002; Lund et al., 2004). Based on these definitions, a definition for the TOD is suggested in this review: *an urban planning strategy that aims to promote sustainable transport by creating more affordable housing and job availability by means of increased densification around mass transit stations. This especially developed area will have a mixed land use that supports a vibrant community life, and its extent will be determined by the types of mobility modes serving first or last-mile connectivity and area characteristics*.

2.2 Influence areas of TOD

The general definition of an influence area is given by “an area polarized by a center for a set of relations (influence area of a city) or a category of relations (area of cultural or commercial influence, trading area)” (Rodrigue, 2017); moreover, it is often described as the use of access distance and access time (or both) to transit. Andersen and Landex (2008) defines influence area of public transit as a "vicinity of a stop or station of a public transport line" and the "area is where most of the non-transferring passengers at the particular stop or station come from". Influence area of a transit station, therefore is an area around a transit which serves as the customer base for transit services. It is also the area that receives the maximum benefits of transit. Often these influence areas are based on distances people are willing to travel to transit in a specified time. These specifications are further based on the various travel modes that are used for last-mile connectivity; often by walk. For this study, influence area is defined as the area around a transit station from where commuters access transit station via various modes.

The various means reported in literature to specify the influence area of the TOD are discussed further in this section. In literature, this area has been specified based on access distance, which directly provides the geographic extent of the TOD. A distance of 2000 ft (600 m)[1] was introduced by Calthorpe (1992, 1993). Untermann (1984) and Dittamar and Ohland (2004) determined the distance as 1/2 mi (800 m). These aforementioned distances have been specified based on the walking distance that people prefer to transit (Cervero et al., 1994; Bernick & Cervero, 1997; Guerra et al., 2012). Guerra et al. (2012) raised doubts about the feasibility of adopting 1/2 mi (800 m) as the de facto standard for TOD in the United States as it is "more an artifact of historical precedent than a statistical or analytical construct". To determine the extent of TOD influence areas, some literature refer to a single distance, whereas it is reported that others use a distance range as basis. Guerra et al. (2012) and Flamm and Rivasplata (2014) emphasized that in the U.S, the radius of influence area can vary between 1/4 and 1/2 mi (400—800 m); consequently, various cities have adopted different radii for the TOD. In California, ordinances support the extent of the TOD projects to radii of 1/4, 1/3, and 1/2 mi (400, 550, and 800 m, respectively) around the transit station (Cervero et al., 1994). Portland has adopted a 1/4-mi radius (400 m); Washington County, Oregon has adopted 1/2 mi (800 m); San Diego has adopted 2000 ft (600 m), which is approximately 1/3 mi (550 m) (Community Design + Architecture, 2001). These distances have also been expressed in terms of time. Researchers defined the extent of the TOD based on the

[1] The conversion is not precise, but rounded values are used hereafter.

distance that transit stations can be accessed by people within a specified time. Bernick and Cervero (1997) suggest that a 5-min walk corresponds to a 1/4-mi (400 m) distance. On the other hand, Calthrope (1993) assumed that a 10-min walk is equivalent to a 1/2-mi (800 m) distance. For this study, distance is used to define influence area, as it gives a better understanding in context of planning for TOD.

Few researchers have attempted to establish these distances based on empirical analysis. The results are summarized in Table 1. Most of these studies focused on walking as access mode (Agrawal et al., 2008; Guerra et al., 2012; El-Geneidy et al., 2014; Chia & Lee, 2015), whereas a few focused on cycling (Martens, 2004; Flamm & Rivasplata, 2014). Guerra et al. (2012) conducted a study that used secondary data from across 20 US transit agencies; they also built station-level direct demand models of transit ridership based on regression modeling. Chia and Lee (2015) used the walking time decay function to determine the willingness of people to walk. Zhao et al. (2003) combined both regression and distance decay methods to determine the accessibility levels around transit stations. In other cases, simple statistical methods, such as the mean or median (or both) distances and percentile distances were calculated to determine the influence areas of transit stations (Agrawal et al., 2008; El-Geneidy et al., 2014; Flamm & Rivasplata, 2014). When a particular catchment area is applied around a land use based on the mean or 85th percentile rule it assumes that for the extent of this whole area, people who walk or cycle are equally distributed; but according to Larsen et al. (2010), the distribution of demand follows a distance decay curve. Distance decay offers a better understanding of demand over this area and has been used to understand the demand for transit and transport accessibility (Zhao et al., 2003; Kimpel et al., 2007; Chia & Lee, 2015).

The receiver operating characteristic (ROC) curve has been widely used in health and medical field for diagnostic testing. ROC curve is a plot that illustrates the trade-off between the true positive rate (sensitivity on the Y axis) and false positive rate (1-specificity on the X axis) across a series of cut-off points. ROC analysis is finding application in the field of transportation; researchers have used ROC curves to calculate the threshold distances for people who walk/ cycle (active transport) against the passive users (other modes) (Chillon et al., 2015; Rodríguez-López, et al., 2017; Chillon et al., 2016). In this case, sensitivity, is the proportion of commuters correctly identified by the test as meeting the condition of walking (proportion of commuters who walk). Specificity on the other hand, is the proportion of commuters correctly identified by the test as not meeting the condition of walking (proportion of commuters who use other modes for access and egress). These two indices are then used to predict the dichotomous outcome of the test. Every point on the ROC curve represents a sensitivity – specificity pairing for a particular distance threshold.

The threshold values are determined from the ROC curve using Youden index, highest Sensitivity + Specificity and the closest-to-(0, 1) (distance to corner) criterion for threshold selection. According to Gonen (2010) and Krzanowski and Hand (2010), the cut-off point can be obtained by realizing the point on the curve with the highest Youden index. Youden's index is the maximum vertical distance (J) from the ROC curve to the line of equality. The effectiveness of the analysis can be determined by calculating the area under the curve (AUC) (ranging from 0 to 1). The closer the AUC is to 1, the more discriminatory the analysis is (Chillon et al., 2016, Rodríguez-López et al., 2017). An area of 1 represents a perfect test and tests with area of 0.5 below should be rejected. Youden Index is the maximum vertical distance from the ROC curve to the line of equality (diagonal line from (0,0) to (1,1)) and is illustrated in Figure 2. In order for the test to be accurate, the curve should follow the left-hand border and the top border of the graph. The curve also needs to be away from the 45-degree diagonal.

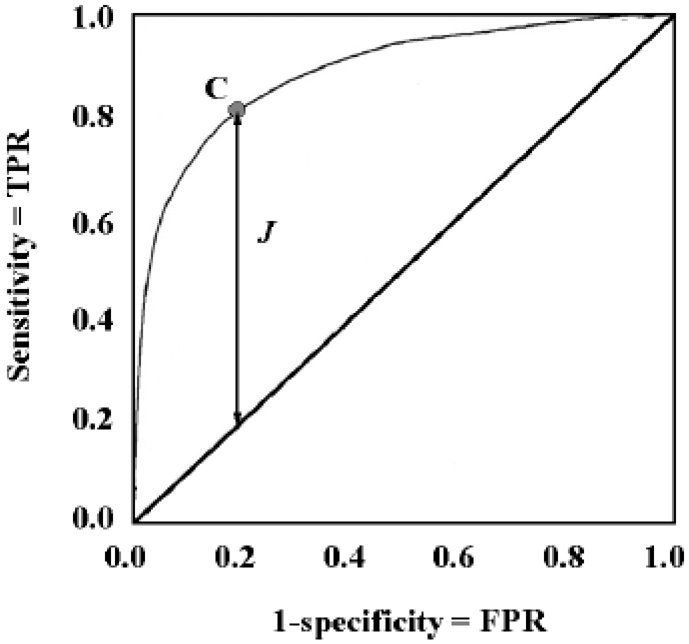


Figure 2 ROC curve and Youden index (J).

(Image source: Bozikov & Lijana, 2010)

Table 1. Studies on determining influence or catchment areas.

Study	City/area	Main mode	Access mode	Trip purpose	Data on distance	Methodology	Result
Zhao et al. (2003)	Southeast Florida, USA	Public transit	Walking	All	Based on questionnaire, addresses were assigned to streets using GIS to calculate shortest distance	Regression analysis; distance decay method was employed; GIS was used to calculate walking distances from route map	No noticeable increase in accessibility was observed after 800 m; drops were noticed at 1800 ft (550 m) and at 2700 ft (820 m)
Martens (2004)	Netherlands, Germany, the United Kingdom	Bus, metro rail, tram, train	Cycling	All	Based on results and secondary data from other studies[2]	Compared travel behavior of bicycle riders and commuters in Netherlands, Germany, and UK based on other studies	Faster main modes attract bicycle and ride users from distances of up to 4–5 km; slower modes attract users from no more than 2–3 km
Agrawal et al. (2008)	California and Oregon, USA	Rail transit	Walking	All	Based on questionnaire, distances walked reported by respondents and route were entered into GIS database	Simple statistics; reported and actual mapped distances were compared	Mean distance was 0.5 mi (800 m)

[2] Van Goeverden and Egeter (1993) for Netherlands; Bickelbacher (2001) for Germany; Taylor (1996) for UK.

Guerra et al. (2012)	20 transit agencies, USA	Heavy rail, light rail, bus rapid transit	Walking	All	Based on secondary data; model used distance bands to estimate direct demand models for 1449 high-capacity American transit stations; population and number of jobs within these bands were estimated	Regression modeling was used to predict average weekday boarding and alighting using a variety of radial transit catchment buffers of 1/4- mi width (400 m)	Half-a-mile (800 m) catchment in residential areas and 1/4 mi (400 m) for work trips; for estimating station-level transit ridership, the radius only had a minor influence on the model's predictive power
El-Geneidy et al. (2014)	Montreal, Canada	Bus, commuter rail	Walking	All	Data on 2003 transit users in Montreal; OD survey was used in which trip-ends are geocoded and routes were also recorded	Multi-level regression, geocoding applied on OD data	For bus transit, 524 m; for commuter rail, 1259 m
Flamm & Rivasplata (2014)	Philadelphia and San Francisco, USA	Bus, light rail, heavy rail, ferry	Cycling	Work and non-work	Based on questionnaire; distances were based on estimates given by cyclists; to cross-check these distances, origin–destination distances were calculated using Google maps	Simple statistics	Average of 2.8 mi (4500 m) and 5.4 mi (8700 m) for Philadelphia and San Francisco, respectively
Chia & Lee (2015)	South East Queensland, Australia	Public transit	Walking	All	Secondary data were obtained from 2009 South East Queensland Travel Survey (SEQTS), in which self-reported distances are available	Walking time decay function; one-way analysis of variance used to differentiate among user groups	Two major drops where people were willing to walk were observed: 268 m (4 min) and 670 m (10 min)

2.3 Need for quality data

Data availability and the accuracy of the data used are crucial in performing such studies. Data regarding access and egress are not collected or are limited in most countries (Rietveld, 2000). In addition, the distances reported by commuters often do not match the actual distances travelled. This was highlighted by Agrawal et al. (2008) and accordingly, their study also included a spatial analysis to measure the actual distances. Typically, commuters tend to round distances to some extent when responding to surveys. To overcome this drawback, route mapping with the use of geographic information system (GIS) is an effective approach. In cases where origin–destination data were available, these data may be geocoded and validated to obtain more accurate distances (El-Geneidy et al., 2014). Otherwise, methods such as multiple imputation can be used to correct the rounded data (Heitjan & Rubin, 1990; Drechsler & Kiesl, 2016).

Studies on the survey data often face such rounding and heaping problems, and have employed various techniques to overcome them (Heitjan & Rubin, 1990; Kimpel et al.,2007; Yamamoto et al., 2018). Heitjan and Rubin (1990) proposed a multiple imputation (MI) method to correct for heaped age values. According to their study, the imputation task mainly consists of two steps: a modelling task, i.e., creating and estimating a heaping model, to predict missing values from the observed values and model parameters; and an imputation task which formulates the posterior distribution according to the estimation results of the heaping model to draw missing values. Heitjan and Rubin (1990) proposed an ordered probit regression heaping model and a simple acceptance rejection procedure for the imputation task to adjust for the missing age data. In their research, they performed a Monte Carlo experiment to verify the estimation and imputation task. Drechsler and Kiesel (2016) discussed the potential bias form rounding for income data and indicate that analysing reported data without any adjustment to account for the rounding will lead to biased results. They corrected the rounding error through imputation and implemented a repeated simulation design to illustrate that valid inferences can be obtained using the imputed data. Recently, Yamamoto et al. (2018) applied the heaping model developed by Heitjan and Rubin (1990) to solve the heaping issue of reported vehicle kilometres travelled. Since longer vehicle kilometres may raise the probability of higher levels of coarseness, an ordered response model was used to account for the coarseness level of reported vehicle kilometres. Making a comparison with the conventional regression model, they demonstrate that the proposed heaping model is more efficient to investigate the effect of the explanatory variables on vehicle kilometres.

2.4 Issues regarding determination of influence areas

Various researchers have suggested different radii or a range of acceptable distances based on empirical studies (Guerra et al., 2012; Park et al., 2015). The standards for influence areas are based on walking as the access mode; these areas do not represent the catchment area of commuters who cycle, skate, or use informal modes, such as auto rickshaws or pedi-cabs, for their first or last-mile connectivity. Calthrope (1993), Bernick and Cervero (1997), DoT Maryland (2000), DoT California (2001), and Jiang (2012) have explained the TOD and the corresponding influence area using walking as the access mode. The normally accepted radius of 1/2 mi (800 m) and other distances, such as 1/4, 1/3, or 3/4 mi (400, 550, and 1200 m, respectively), have been quoted in these aforementioned works bearing in mind the distance that "most" people are willing to walk to transit (Cervero et al., 1994; Bernick & Cervero, 1997; Guerra et al., 2012). The half-mile (800 m) radius commonly represents the walk shed of pedestrians and has been derived based on the observation that most pedestrians are willing to walk 15 min to access transit stations at an average speed of 2 mi/h (3.2 km/h) (Agrawal et al., 2008). Untermann (1984) adds that this distance is also dependent on whether the environment is conducive and pleasant. This conclusion is based on the travel patterns in American cities; however, it does not necessarily hold true for European and Asian cities, which have distinctly different travel patterns (Park et al., 2015).

There are researchers who have included other mobility options in explaining TODs but it is limited to bicycles. The distances covered by these modes are typically greater than the distances covered by walking. Studies conducted show that cyclists travel longer distances to reach transit stations than people who walk (Hochmair, 2013; Flamm & Rivasplata, 2014; Lee et al., 2016). Flamm and Rivasplata (2014) examined the behavior of cyclists in Philadelphia and San Francisco and found that they travelled an average of 2.8 mi (4500 m) and 5.4 mi (8700 m) on cycle-transit trips, respectively; these indicate larger catchments for bicycle users. Lee et al. (2016) stressed the importance of bicycles to increase the extent of TOD and its benefits. The study estimated the distances accessed by bicycles in Korean cities as 1.96 and 2.13 km for origin (home)-to-station and station-to-work trips, respectively. This indicated that if a bicycle is used for planning the TOD, then 73.7% and 93.6% of the entire area of Seoul would be covered, whereas a conventional walking-only TOD can cover only 29.9% of the area. The catchment range of feeder buses and car (kiss and ride) was estimated in the range, 1.24-3.73 miles (approx. 2000 – 6000 m) and 0.62-4.35 miles (approx. 1000 – 7000 m) respectively (Gil & Read, 2012); increasing the influence area of transit services to a larger extent. Therefore, a walk-based TOD is not always necessary; however, it should include other modes of last mile connectivity.

Currently, remedies are being implemented to resolve this problem. In their policy regarding pedestrian and bicycle mobility improvements (FTA, 2011), the Federal Transit Authority (FTA, USA) proposed 1/2 mi (800 m) and 3 mi (2400 m)[3] for pedestrians and cyclists, respectively. This proposal revises the earlier 1500-ft (400 m) radius that considered only pedestrians. Additionally, the policy mentions that a 1/2 mi (800 m) radius is a conservative measure and the area can be extended assuring that people can walk safely and conveniently to reach the transit. Evidently, adherence to standards is not extremely strict. Hence, policy changes have been implemented in the past based on studies that reflect the last-mile mobility patterns of commuters. The states of Maryland and Oregon explain the TOD areas based on walking, bicycles and automobiles, thus emphasizing multimodal access to transit stations (DoT Maryland, 2000). Gutiérrez et al. (2011) considered the importance of feeder buses for rail transit-based TODs. If modes other than walking can be considered, the distance can be effectively increased. Therefore, the commonly accepted standards may not be appropriate in cities where different access modes other than walking are used.

The use of different modes to access transit stations is especially relevant in urban and suburban areas. Literature also suggests that catchment areas have to be different based on the type of transit used (either in urban or suburban areas). In suburban areas, the

[3] Based on a 15-min travel time, assuming a 1 mi/h average cycling speed

walkable distance in the catchment area has been set to 400–800 m (Ker & Ginn, 2003). Ker and Ginn (2003) indicated that commuters walked shorter distances to suburban stations (800 m) compared with distances covered to reach urban stations (1 km). However, when delineating a catchment area, Cervero (1997) suggests that these areas could be larger than those in suburban areas because of low residential densities and extensive parking spaces. Therefore, it can be deduced that even if people walk shorter distances to transit stations in suburban areas, the catchment areas of these stations are larger than those in the urban areas.

Various studies show that the size of influence zones is also based on the type of transit (main mode). The common understanding is that people walk more to access rail stations (1/2 mi or 800 m) compared with the distance covered to access bus stations (1/4 mi or 400 m) (O'Sullivan & Morrall, 1995; Morrall & O'Sullivan, 1996; Gutierrez & Palomares, 2008; Zielstra & Hochmair, 2011). However, opinions differ among researchers regarding these catchment area sizes. A guide published by Snohomish county indicates that commuters are generally willing to walk more to the rail transit (1/4–1/3 mi or 400–550 m) compared with accessing the bus transit, which is a 1000 ft (300 m) walk; this highlights the difference in catchment areas based on the transit mode. In Ireland, the basic rule is that commuters are willing to walk 1 km to access rail stations (O'Connor & Harrison, 2012). The difference in catchment areas can be observed based on the type of rail transit (APTA, 2009). The APTA[4] standards also indicate that transit ridership decreases as the distance from transit stations increases; the standards adopted by APTA are summarized in Table 2.

Hochmair (2013) suggests that this difference in catchment areas also applies to cyclists and specifies the distance as 1 mi (1600 m) and 2 mi (3200 m) for community hubs and gateway hubs, respectively. Additionally, certain studies show that based on trip purpose, the distance people walk or cycle to access transit stations can vary (Guerra et al., 2012; Lee et al., 2016). Therefore, it can be remarked that a single standard or de facto value cannot be applied for determining the scale of TODs. The various influence areas based on different factors are summarized in Table 3. It emphasizes that the adoption of a single standard for the influence area is not advisable.

[4] American Public Transportation Association

Table 2 APTA specifications for transit catchment areas.
Source: (APTA, 2009)

	Local street transit	Rapid street transit	Semi rapid transit	Regional transit	Rapid transit
Core station area	NA	1/8 mi (200 m)	1/4 mi (400 m)	1/4 mi (400 m)	1/3 mi (550 m)
Primary catchment area	1/8 mi (200 m)	1/4 mi (400 m)	1/2 mi (800 m)	1/2 mi (800 m)	2/3 mi (1100 m)
Secondary catchment area	1/2 mi (800 m)	1 mi (1600 m)	2 mi (3200 m)	5 mi (8000 m)	3 mi (4800 m)

Table 3 Size of influence areas.

Factors used for defining TOD	Quantitative or Qualitative values assigned
Distance	- 1/4 mi or 400 m (Bernick & Cervero, 1997) - 1/2 mi or 800 m (Untermann, 1984; Dittamar & Ohland, 2004; FTA, 2011) - 1/4–1/2 mi or 400–800 m (Cervero et al., 1994; Cervero, 1997; Community Design + Architecture, 2001; Guerra et al., 2012; Flamm & Rivasplata, 2014) - 2000 ft or 600 m (Calthrope, 1992, 1993)
Time	- 5-min walk (Bernick & Cervero, 1997) - 10-min walk (Calthrope, 1993)
Access mode	- Based on walk as access mode, distances vary from 1/4 to 1/2 mi or from 400 to 800 m (Calthrope, 1993,1994; Cervero et al., 1994; Bernick & Cervero, 1997; Cervero, 1997; Untermann, 1984; Dittamar & Ohland, 2004; Community Design + Architecture, 2001; Guerra et al., 2012; Flamm & Rivasplata, 2014 - 3 mi for cyclists (4800 m) (FTA, 2011) - 2.8 mi (4500 m) and 5.4 mi (8700 m) in Philadelphia and San Francisco for cyclists, respectively (Flamm & Rivasplata, 2014) - 1.96 and 2.13 km for home-to-station and station-to-work trips for cyclists, respectively (Lee et al., 2016)
Type of area	- Walkable catchment area in suburban areas, 400–800 m, and in urban areas, 1 km (Ker & Ginn, 2003)
Main mode	- 1/2-mi or 800-m access to rail station (Morrall & O'Sullivan, 1996; Gutierrez & Palomares, 2008; Zielstra & Hochmair, 2011) - 1-km access to rail station (O'Connor & Harrison, 2012). - 1/4-mi or 400-m access to bus station (Morrall & O'Sullivan, 1996; Gutierrez & Palomares, 2008; Zielstra & Hochmair, 2011) - The primary catchment area for local street transit (1/8 mi or 200 m), rapid street transit (1/4 mi or 400 m), semi-rapid transit and regional transit (1/2 mi or 800 m), and rapid transit (2/3 mi or 1100 m) (APTA, 2009)
Trip purpose	- 1/2-mi (800 m) catchment areas for home-based trips of residents and 1/4-mi (400 m) catchment areas for access to work (Guerra et al., 2012) - 1.96 km for origin (home)-to-station and 2.13 km for station-to-work trips for cyclists (Lee et al., 2016) - 500–1000 ft (150–300 m) for external employees and 1 ½ mi (2400 m) for residents (City of Redmond Planning Commission, 2014)

2.5 TOD influence areas in India

The TOD concept is not new to Asian countries; however, the term "TOD" may not have been used (Sung, 2011). Some researchers claim that the TOD in Asia has not been applied on the basis of sustainability; instead, it has been treated as a function of density and land shortage—a function that is yet to be applied to the US or Australian cities (Kachi et al., 2005). In Japan, the concept is explored using the term "compact city" (Kachi et al., 2005). Seoul is another example of an Asian city with dense development characteristics; Hong Kong similarly illustrates such characteristics. Loo et al. (2010) considered two different regression models with different factors and in different combinations to study the rail-based TOD and take into consideration the difference between New York and Hong Kong. The study stressed that place-specific factors should be considered while examining railway patronage in different cities. Therefore, it can be deduced that the direction in which cities approach factors, such as density, diversity, and design, varies according to the character and customs of a city and is essentially reflected in its mobility culture (Wilson, 2013).

In 2015, the Ministry of Urban Development of India gave notification pertaining to the National Transit Oriented Development (TOD) Policy (MoUD, 2015) to promote sustainable urbanization in Indian cities. The cities have been advised to incorporate the TOD in their master and development plans and identify transit influence zones along transit corridors. The central government issued the TOD Guidance Document in May 2016 (MoUD, 2016) to facilitate the planning and implementation of TOD plans in cities. The TOD is also being promoted in the country through the 2017 Metro Policy (MoHUA, 2017a) and the proposed 2017 Green Urban Mobility Scheme (MoHUA, 2017b). Under the policy, the TOD has been made under the Green Urban Mobility Scheme, and the satisfaction of these criteria has been made a priority for receiving financial assistance in the development of metro infrastructures. The TOD guidance document asserts that the priority should not focus on increasing density, but on promoting NMT infrastructures, mixed land uses, and improving the first-and-last-mile connectivity, street-oriented buildings, and parking management. In the document, the mass transit system is not specified as a prerequisite for the TOD because high-quality local bus systems are also included as part of the TOD. Evidently, there is a necessity to adopt the TOD considering the different characteristics of the proposed areas.

The policy defines the influence zone of transit stations as walking distances of 500–800 m (i.e., 10–12-min walking distances) when the transit station spacing is approximately 1 km. When the distance between the transit stations is less than 1 km, then the influence areas of adjacent stations overlap, and the influence zone becomes a delineated zone with a radius of 500 m. The influence zone is defined as “the area in the immediate vicinity of the transit station, i.e. within a walking distance, having high density compact development with mixed land use to support all basic requirements of the residents is called the influence zone of a transit station/ corridor” (MoUD, 2015). The policy calls for these zones to be clearly demarcated by responsible authorities based on supporting principles for its selection and should be verified through master plans and local area plans before implementing the TOD project. The influence area standards adopted for some of the Indian cities are summarized in Table 4.

Table 4 Influence area standards adopted by various Indian cities.

	Influence area	Transit mode	Comments
National Transit Oriented Development (TOD) Policy	500–800 m	Transit mode not specified	Delineated zone of 500 m is specified on either side of transit corridor when distance between transit stations is less than 1000 m
TOD Guidance document	500–800 m, (10-min walk or cycling), Buffer along transit line, 400–1000 m (5–10-min walk around stations), Individual parcel within a 5–10-min walking distance (800–1000 m) from station	MRTS, Public transit including buses	Specifies influence area on corridor and station area level
New Delhi	Intense zone - 300 m, Standard TOD zone - 800 m (10-min walk), TOD transition zone - 2000 m (10-min cycling) (UTTIPEC, 2012), Delhi Master Plan 2021 specifies a belt with a width of approximately 500 m on both sides of MRTS corridor	MRTS, Metro	Buffer on both sides of MRTS line, Different scales for station areas, advises to conduct ped-shed analysis
Naya Raipur	400 m (5-min walk) and 800 m (10-min walk)	Bus Rapid Transit System (BRTS)	Circular buffer around transit station
Ahmedabad	200 m - BRTS 200 m - Metro	BRTS, Metro	200-m buffer on both sides of transit route, local area plans developed
Mumbai	Gateway zone - 250 m Intermediate zone – 500 m Outer zone -1000 m	MRTS-Suburban rail, metro	
Cochin	500-m buffer	Metro	Buffer on both sides of MRTS line, Pedestrian networks drawn for each station; 250-m inner circles for station area

The “half-mile radius” is the de facto standard that is used in TOD plans, especially in the United States (Guerra et al., 2012). Although this standard, which is based on the willingness to walk, might be applicable to North American cities, it is necessary to determine whether it is applicable in the context of developing countries, such as India. In Indian cities, walking has a high share in the overall modal share, and people tend to walk longer distances (Embarq, 2014). Moreover, differences in the average walking distances across various cities should also be considered. However, the lack of adequate data and studies pertaining to Indian cities mainly limits the examination of this walking culture and the access–egress patterns; a few studies could be found to determine the walking or cycling distances in Indian cities. The NMT studies conducted in cities of Mumbai and Tiruchirapalli show that the willingness to walk can be pegged at 910 and 1700 m, respectively, whereas the willingness to cycle was 2724 m in Mumbai, 5200 m in Tiruchirapalli, and 5100 m in Delhi (Arasan et al., 1994; Rastogi, 2011;). Only a few studies have been conducted in cities, such as Mumbai and Delhi, to determine the distances that people walk to access transit stations. Rastogi (2010) performed studies in Mumbai to examine the distances that people have walked and cycled to access suburban rail. The acceptable walking and bicycling distances to reach the transit access environment were found to be 1250 m for 80% of the commuters (Rastogi & Rao, 2003; Rastogi, 2010). Johar et al. (2015) studied the distances walked by commuters from bus stops to various destinations in New Delhi and found that the mean walking distances (based on lognormal distribution) were 677, 660, 654, and 637 m for shopping, recreation, education, and work trips, respectively. Research shows that commuters walk longer distances to access rail transit than reaching the bus transit (O'Sullivan & Morrall, 1995; Morrall & O'Sullivan , 1996; Gutierrez & Palomares, 2008; Zielstra & Hochmair, 2011); therefore, it can be assumed that commuters walk longer distances to reach metro stations in Delhi. These results indicate that the assumed standard of 500 m in the TOD guideline has to be rechecked and it cannot be used as a common standard because the distances that people are willing to walk vary among cities. This can be done by conducting detailed studies on the last-mile-connectivity walking patterns of commuters.

Indian cities also have numerous types of travel modes, such as auto rickshaws, cycle-rickshaws, electric rickshaws, gramin-sevas, and minivans, which are not employed in developed countries; some of these modes are shown in Figure 3. Informal transit is one of the most popular modes, especially for the middle class in Indian cities. Informal transit has been defined as “public transport services that are provided differently as compared to the typical government-provided bus- and rail-based transport in cities” (Kumar et al., 2016). They perform a critical role in urban mobility by helping to reduce the demand-supply gap of public transit. Guillen et al. (2013) highlighted the importance of informal modes in developing countries and found that commuters tend to use these modes even for a short distance. Besides, buses and private modes are also popular access modes to transit stations in Indian cities. This multimodal accessibility is highly different from developed countries, which have simpler transport modes. These informal transport modes (or para transit or intermediate public transport modes) and their systems of operation perform a considerably important function in Indian cities. They frequently provide multiple options in terms of modes, types of services, and fares to meet the mobility requirements of commuters in cities. Studies also show that in developing countries, the commuters habitually tend to use available informal transport modes for distances that could be easily covered by cycling and walking (Guillen et al., 2013); this highlights the convenience of these modes. It has been shown that passengers who use informal transport modes like pedi-cabs tend to travel approximately 1 km longer than people who walk (Fillone & Mateo-Babiano, 2018). Compared with cities in developed countries where walking and cycling are the predominant modes for last-mile connectivity, a considerable size of the population in Indian cities relies on these informal modes to reach transit stations. In such cases, planning and policy making need to include these modes into last mile connectivity and overall planning, and develop adequate infrastructure.

(a) (b)

(c) (d)

Figure 3 Examples of informal modes available in New Delhi: a.) Auto rickshaw, b.) E-rickshaw, c.) Gramin seva, d.) Cycle rickshaw.
(Image source: a.) www.wikipedia.org, b.) www.ndtv.com, c.) www.dailymail.co.uk, d.) www.livemint.com)

However, the standards that have been adopted tend to ignore the multimodal nature of Indian cities. Regarding Indian cities, few studies have examined last mile distances and influence areas of transit stations. The existing research illustrates that when people access transit stations, they are willing to walk or cycle longer distances than are mentioned in the national TOD policy (Arasen et al.,1994; Rastogi & Rao, 2003; Rastogi, 2010, 2011; Johar et al., 2015). Arasan et al. (1994) investigated non-motorized transport (NMT) in the city of Tiruchirapalli, and found willingness to walk and cycle to be 1700 and 5200 m, respectively. This study calculated the maximum walking and cycling distances after which people will consider switching to public transit. Therefore, their result shows large distances compared to other Indian case studies. They also indicate that those distances depend on factors such as journey purposes, socio economic characteristics of the travellers, the available travel modes, residential environment, etc. Rastogi and Rao (2003) scrutinized the multimodal nature of transit access trips and demonstrated that walking is the most preferred mode for distances under 1250 m. For distances longer than 1250 m, various modes (such as walking, bicycling, auto rickshaw, taxi, bus, and car) were competitive. Since 86% of passengers walk less than 1250 m, Rastogi (2010) proposed this figure as the catchment area for suburban rail stations in a case study on Mumbai. In terms of time, Rastogi (2011) suggested a 5–10 min walk to transit stations as the criterion area to be developed in line with NMT. Johar et al. (2015) administered a survey to bus commuters in New Delhi and looked at their walking distances for trips for different purposes. The mean walking distance ranged from 600 to 700 m for diverse reasons such as work, education, recreation and shopping. A report published by Embarq (2014) proposed that a radius of 150–250 m (5-min walk) for the pedestrian priority area (primary area), a radius of 500–700 m for pedestrian and cyclist priority area (secondary area) and the radius of the catchment area will depend on the areas served by informal transport and route lengths of feeder bus services; highlighting the need to include these modes for station area planning. It is necessary to study these modes to understand the functions they perform in access or egress trips and the influence they exert on the TOD.

Evidently, few studies determine whether the TOD standards formulated by developed countries are appropriate for Indian cities. Moreover, the applicability of a common standard has to be verified because each city is different in terms of mobility characteristics. The current walking mobility culture in Indian cities has to be thoroughly examined in relation to the TOD planning. The informal modes have the capacity to ensure better public transit services (Kumar et al., 2016) would therefore facilitate the TODs. The function of informal transport and feeder buses to reach transit stations has to be considered in determining influence zones. This study focuses on the multimodal accessibility of transit users in India to examine the appropriate influence area of TOD using survey data carried out in New Delhi, India. The data set was obtained from a questionnaire survey administered by Delhi Metro Railway (DMR) Corporation (DMRC) to DMR passengers in December 2015 and a questionnaire survey carried out at four stations (Karkardooma, Dwarka mor, Lajpat Nagar and Vaishali) to capture the last mile mobility patterns of commuters in march 2019.

2.6 Inference

The review provided insights on the gap between the theoretical and scientific establishment of standards for transit catchment areas and the TOD influence areas. Existing studies show that the size of the influence area varies among different cities; it also varies with different access modes. Evidently, a single influence zone size is not suitable for all cases. In developed countries, the TOD influence area has been primarily formulated based on walking as the main access mode. Even though cycling is also a predominant access mode, it has been deemed insignificant in the planning practice. Because there is no consensus among researchers on whether the half-mile radius is the appropriate distance for catchment areas, such a criterion should be carefully examined in the planning of TODs in Indian cities. It holds for most of cities in India whose walking mobility patterns vary compared with those of developed countries. Accordingly, it is proposed that the local characteristics of cities be carefully studied in relation to the influence zone of the TODs. Moreover, it is not advisable for cities in India to consider only the walk-based TODs. This is because last-mile travel patterns are multimodal. Therefore, these various modes need to be taken into consideration in the design of TOD. To reach a conclusion on how the influence area of TOD can be defined is difficult because the last-mile connectivity of cities, various mobility modes used, trip purpose, travel distances, time taken to reach the transit station and the type of transit itself have to be analyzed in detail. It is necessary to examine the adequate size of the influence area in Indian cities by considering the characteristics of each city.

CHAPTER 3 - DATA COLLECTION

3.1 Study area and surveys conducted

New Delhi, the capital city of India, has been chosen as the case study as it is one of the first cities in India to come up with a TOD plan, and it has already been integrated into the city planning process. Additionally, the city is served by a metro rail system with a well-established network and good patronage.

New Delhi has been served by its rapid transit system, the DMR, since 2002; it was built in phases. Currently, its network is 317 km long, with 231 stations. The DMR connects New Delhi to the cities of Bahadurgarh, Faridabad, Ghaziabad, Gurgaon and Noida in the National Capital Region (NCR). It is operated and managed by the DMRC. New Delhi is one of the first cities to have adopted TOD in India. For the Master Plan of Delhi (MPD), the Delhi Development Authority (DDA) categorized the city's TOD influence areas into three zones: intense, standard and transition. The intense zone is the most compact, with 300 m around all metro stations, and 800 m around regional interchange stations. The standard zone is 800 m around all metro stations. The transition zone is 2000 m around all metro and regional interchange stations, taking 10 min of cycling into account. In these zones, a mixed land use has been suggested which allows flexibility in the mix of various possible uses, except for polluting and potentially hazardous uses [32]. The MPD-2021 [33] specifies a belt with a width of approximately 500 m on both sides of the Mass Rapid Transit System (MRTS) corridor. These influence areas are planned to promote NMT infrastructure, mixed land use, and to improve first and last mile connectivity to encourage transit usage. These standards need to be verified according to the city's characteristics considering last mile connectivity travel patterns.

3.2 Data collected

Primary and secondary data regarding last mile connectivity was used for conducting analysis for this research.

3.2.1 Secondary data collection

Existing data regarding last mile connectivity patterns of DMR network commuters was obtained from DMRC. This data is from an extensive survey carried out by DMRC in December 2015 for the purpose of carrying out a fare elasticity study. In addition to the fare related questions regarding the main trip and personal information like age, education, income, vehicle ownership, etc., the survey also collected information regarding the modes used for access and egress, last mile distances, time taken and the associated costs. This data was obtained in February 2018 after obtaining necessary permissions from DMRC.

The DMRC survey was carried out across 131 metro stations covered by DMR at the time of the survey. Figure 4 shows the Delhi Metro route network (Phase I and II) existing at the time of our studied data. After excluding records for incomplete responses, a total of 1348 individual samples were obtained, with 927 records for access and 858 for egress (A cross-table representing various access and egress modes has been given in Appendix 1). There existed a correlation between the access and egress modes; however, it was not considered in this study and it was a limitation of the study. These responses were then segregated across different last mile modes, namely, walking, informal modes, bus and private modes. The sample size of each station was not adequate enough to carry out analysis on a specific station. The average sample size across all stations was about 8, less than 20 in most stations. Therefore, a generic analysis was conducted across all stations rather than conduct specific station-based analysis.

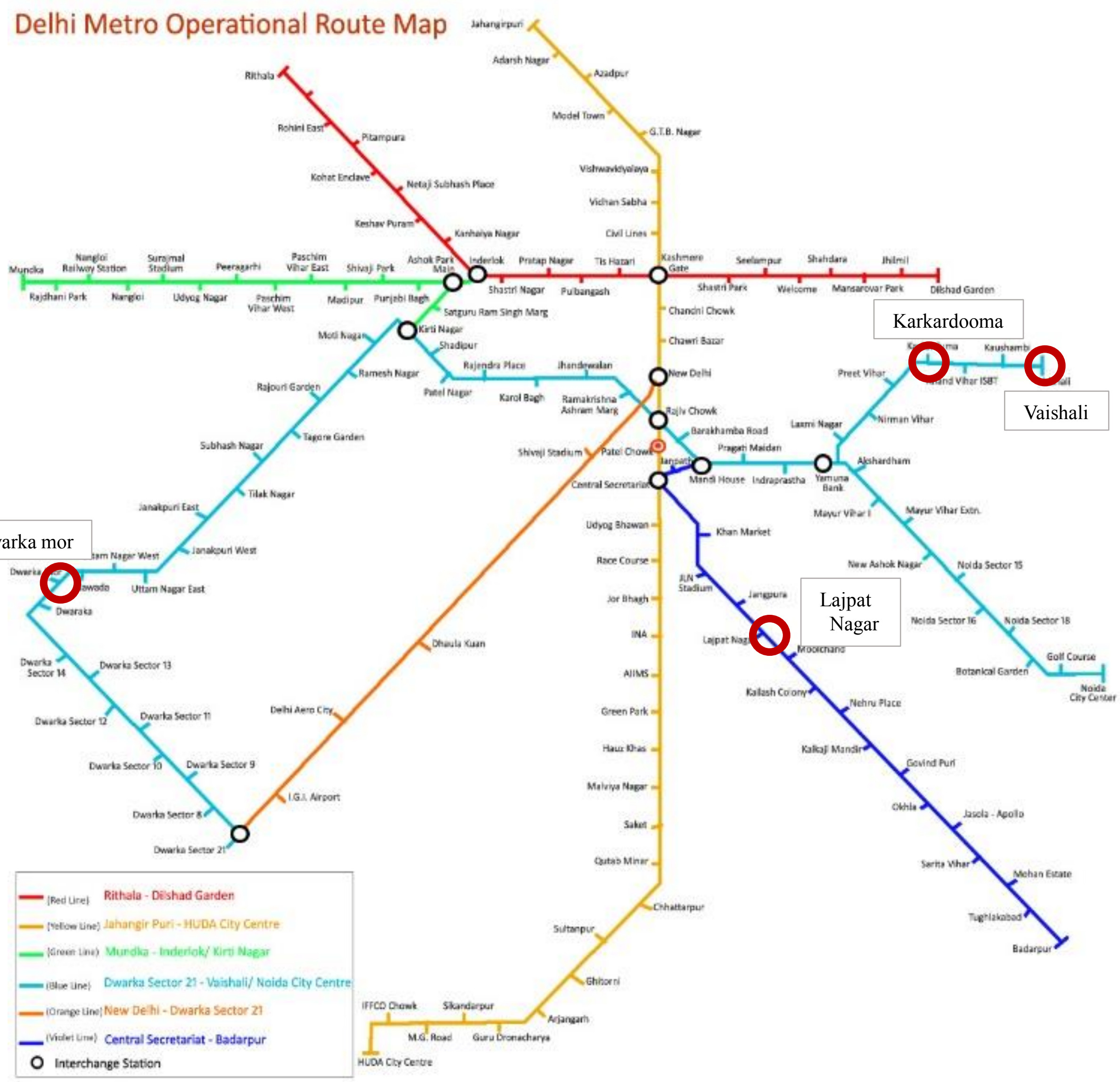
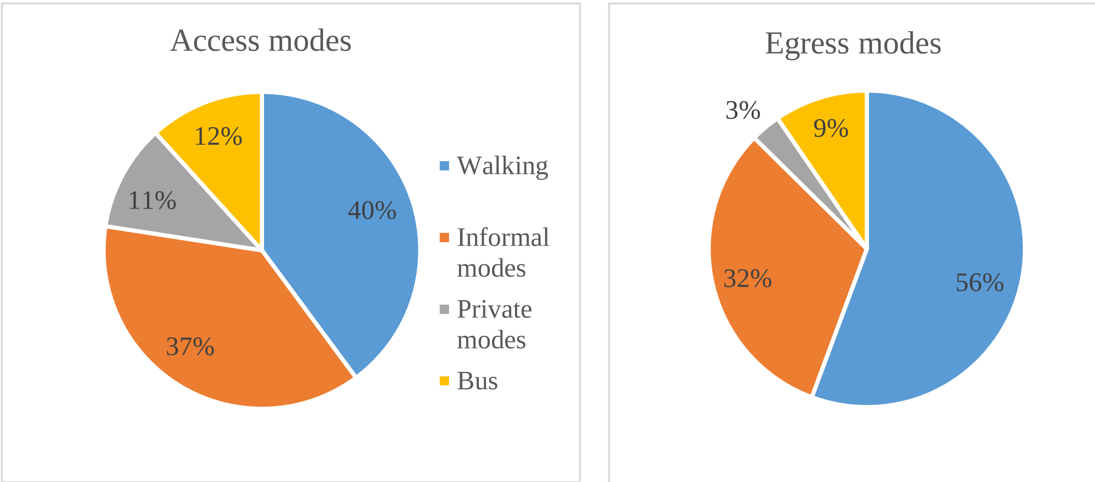


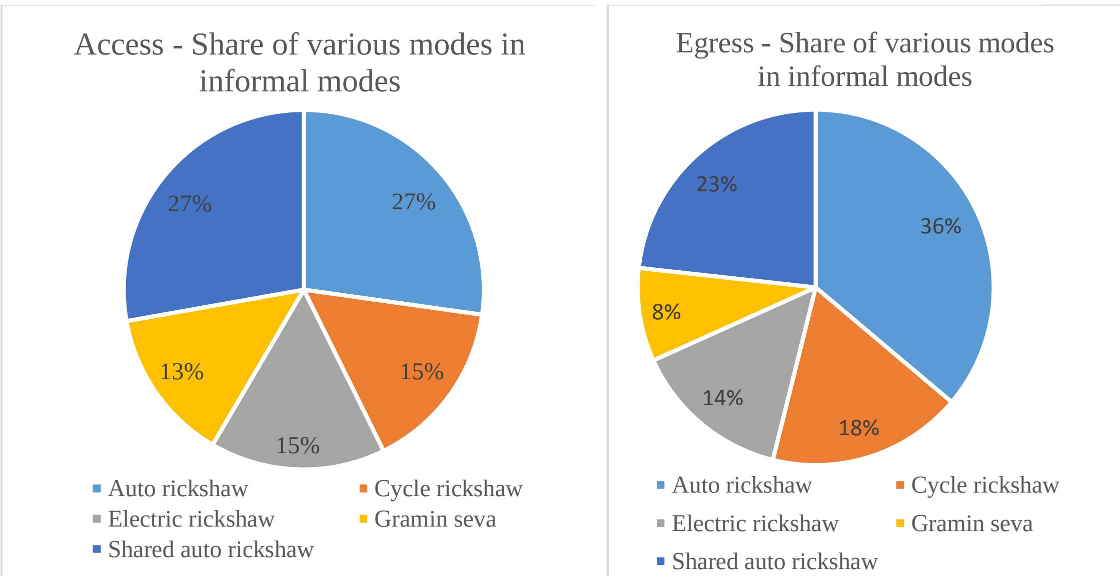
Figure 4 DMR network map (as on 2015).

Figure 5 displays the shares of various modes for last mile trips. Walking and informal transit are the most commonly used for both access and egress, followed by buses and private transport. Informal transit includes (shared) auto, cycle and electric rickshaws, in addition to a shared minivan service known as gramin-seva. private modes include cars and two-wheelers. These different modes were considered under the label informal modes. The share of each informal mode is given in Figure 6. The private modes cars and two wheelers has been grouped together, and shown in Figure 7 is the share of these two modes among private modes. It can be seen that two wheelers made a have a prominent share, which is true for Indian cities. The share of walking for egress is much greater than for access. The use of private vehicles for egress is much lower compared to access. Bicycles were not a preferred mode for access and egress.



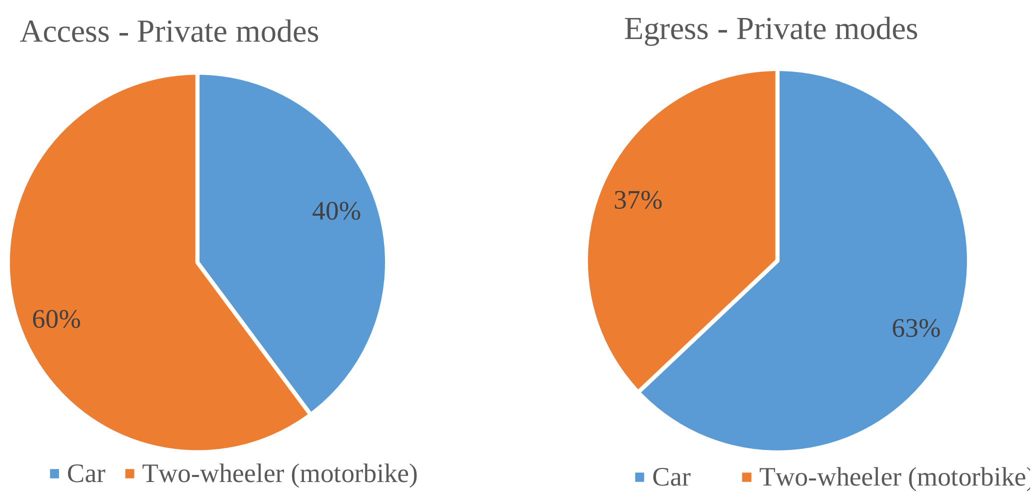
(a) (b)

Figure 5 (a) Shares of access modes; (b) shares of egress modes



(a) (b)

Figure 6 Different types of informal modes used for (a) access and (b) egress



(a) (b)

Figure 7 Share of cars and two-wheelers in private modes for (a) access and (b) egress

3.2.2 Primary data collection

Like mentioned in the previous section, the data obtained from DMRC was not adequate to carry out station specific analysis and therefore a generic analysis was carried out for the DMR network across all stations. However, it was essential to understand how the last mile distance patterns varied across different types of stations. In this light, a survey was planned and executed for specific stations. The sample questionnaire is given in Appendix 2. The survey contained questions concerning access and egress travel patterns of DMR passengers, such as trip purposes, travel modes, travel distances and time. Passengers' attributes, such as gender, age and income, were also included. These details have been provided in Appendix 3. The preferred mode for covering the last mile distance and the various alternatives available to the commuters was also collected. Additional information on the willingness to travel and the motives behind choosing a particular mode was also collected. This information was not available in the survey carried out by DMRC.

The survey for primary data collection was carried out at four specific stations, namely, Karkardooma, Dwarka mor, Lajpat Nagar and Vaishali of the DMR network.

Lajpat Nagar station area is a mixed land use, mixed income, high dense area located in New Delhi and falls on the interchange of Violet line and Pink line. One of the major markets in the city lies in close proximity to the station and the area is of great commercial and residential importance. This station will be referred to as the central city station as it lies in the main city area. Vaishali is an end station on the Red Line, in the suburbs with high dense and mixed income housing and falls outside New Delhi, but belongs to the National Capital Region (NCR) of Delhi. Mixed land use is predominant around the station area. This station will be referred to as the outer city station as it lies outside the administrative borders of New Delhi. Dwarka mor station and Karkardooma station have been selected to be developed on TOD basis by the city authorities. Delhi Development Authority (DDA) has selected Dwarka to be developed into a smart sub-city in the South-West of New Delhi with commercial, residential and entertainment facilities according to TOD norms. The area is sought after for residential purposes. This station will be referred to as the sub-city station. Similarly, Karkardooma is part of DDA's TOD projects and has been planned to develop over 30 hectares with residential and commercial centers. Karkardooma is also an interchange station and a place of commercial importance in East Delhi and this station will be referred to as a regional center station.

The purpose of this survey was to collect data pertaining to last mile connectivity of commuters at these stations and to estimate the distances travelled by commuters to access these stations. In the survey carried out by DMRC, rounding and heaping issues were observed and the data was subjected to a multiple imputation process to remove the bias/ errors. In order to increase the accuracy of distance data reported by the respondents in this survey, it was initially planned that the last mile distances be collected by asking the respondents to plot the origin/destination points on a map. However, it had to be dropped as the respondents were reluctant to give this information, which they deemed to be sensitive and personal during the pilot survey. Therefore, multiple imputation was again employed for this database also. During the surveys, while collecting information on the various alternatives for last mile mobility, it was observed that the respondents gave answers according to their established travel patterns. For example, several respondents were not aware about the options of using buses (routes, bus stops, timings) and several respondents did not list the auto rickshaw as an alternative, as the cost of this mode is relatively higher than the shared informal modes, and they could not afford its fare. Therefore, getting a true description of all the alternatives available to a respondent was not possible. Another issue faced while carrying out the surveys was the low participation of female commuters. They were not comfortable with the interaction with the surveyors, probably because the surveyors were males and they did not want to talk to strangers. The survey was conducted at the platform when commuters were waiting for the train. Commuters getting off the train were always in a hurry to exit the station and was it was difficult to capture them for the survey. A total of 1061 respondents were interviewed during the survey across the four stations (Dwarka mor- 250, Karkardooma – 267, Lajpat Nagar – 286, Vaishali – 258). Responses for access and egress were combined as the sample size was small for station. Analysis of last mile modes indicated that walking is the most preferred mode, followed by informal modes. Only one case of a bicycle user was obtained across all stations. Like in the previous study, the different types of informal modes were grouped together under a single category informal mode. The share of various modes among informal modes is given in Figure 8. The mode share for last mile connectivity is shown in Figure 9. Description of key data from survey 2 is given in Appendix 4.

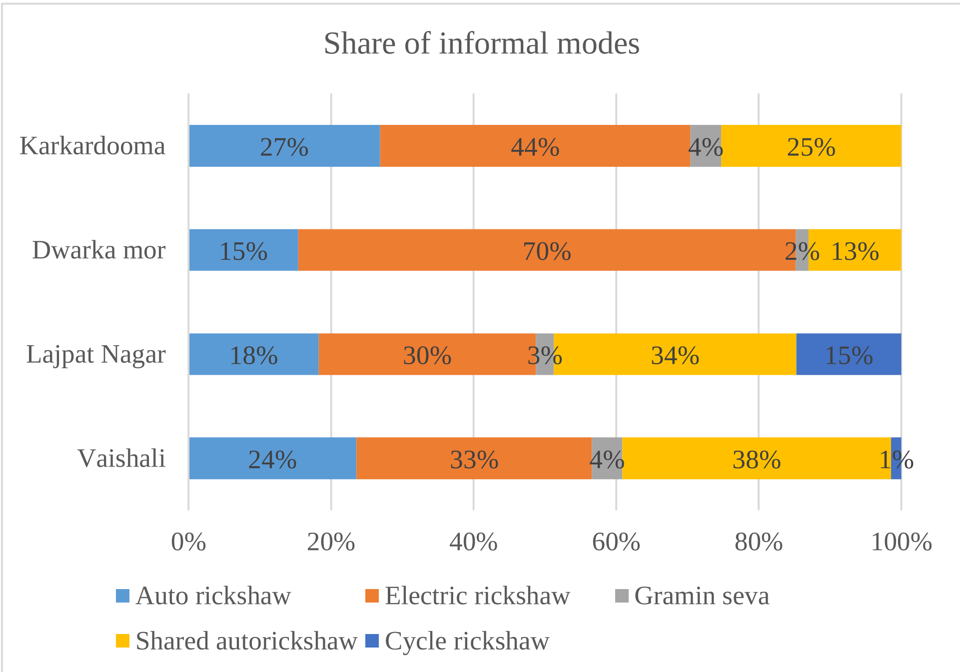


Figure 8 Share of various modes among informal modes

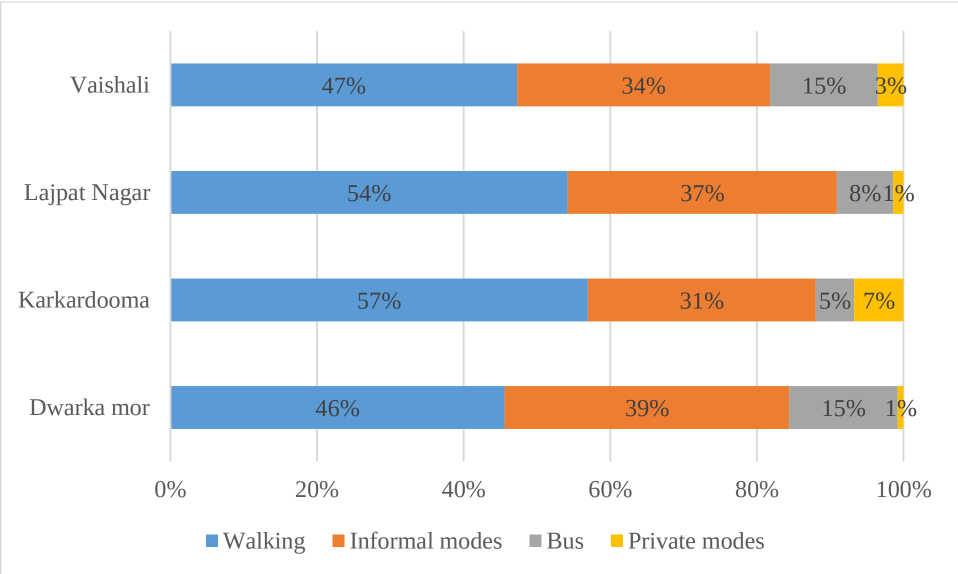


Figure 9 Share of last mile modes across stations.

3.3 Rounding problem of reported distance data

The data collected from the DMRC survey (survey 1) and the station specific survey (survey 2) had considerable rounding and heaping for the reported data. Figure 6 shows the relative frequency distribution and cumulative distribution of access distances by walking obtained from survey 1. It can be seen that these distances have been heaped at particular points, multiples of 100, 500 and 1000 m. This confirms that the reported distance contains rounding effects. In addition, more observations are reported for shorter (less than 1000 m) versus longer distances. The observations become coarser and clustered around multiples of 500 or 1000 m for longer distances. This implies that the respondents rounded most distances, and the coarseness level of the reported distance increases with the traveling distance. Figure 10 also demonstrates big jumps at multiples of 500 and 1000 m. This behavior was also observed in survey 2, across all the four stations. Distribution of reported distances travelled on informal modes by commuters of Karkardooma station is shown in Figure 11. The histogram of reported distances for various modes for access and egress from survey 1 and for various modes for different stations from survey 2 is given in Appendix 5 and Appendix 6 respectively.

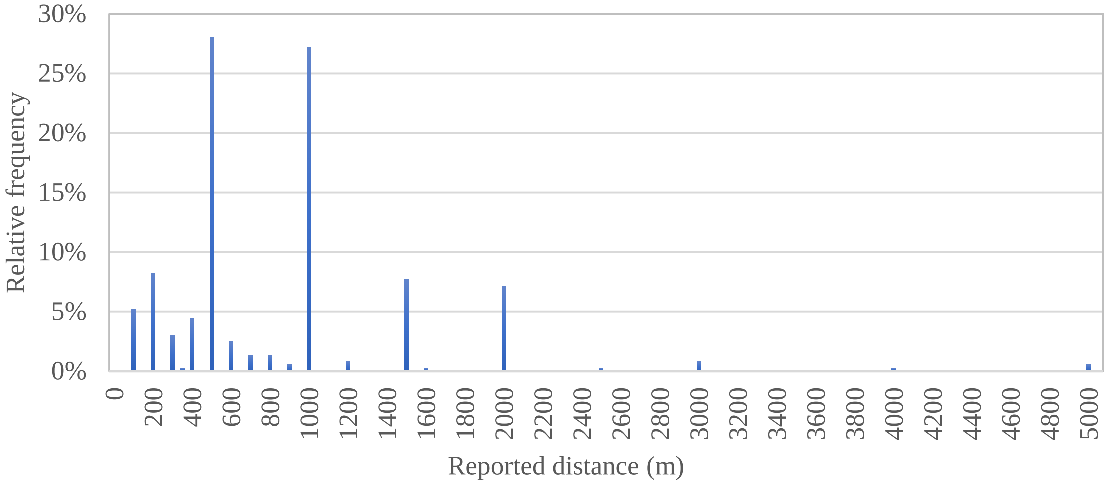


Figure 10 Distribution of reported distances for access by walking.

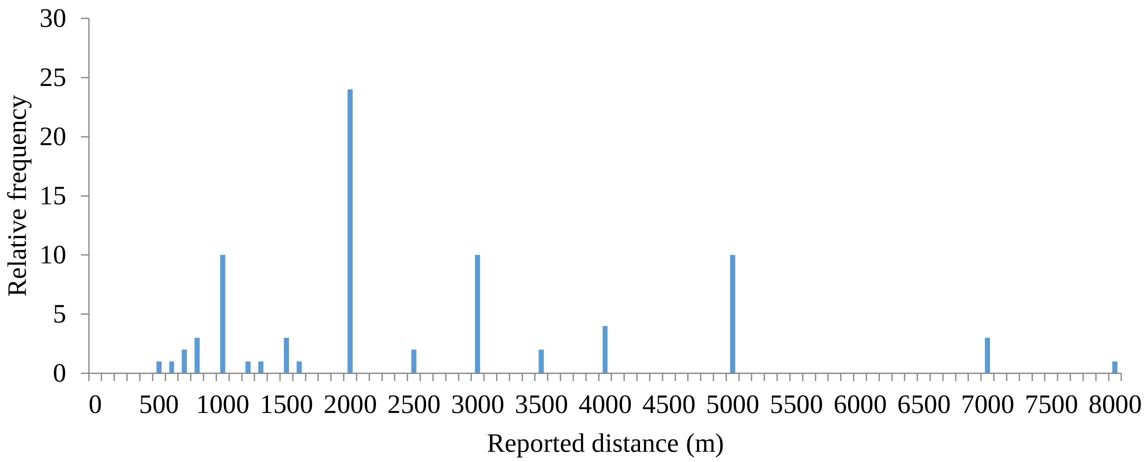


Figure 11 Distribution of reported distances for informal distances to Karkardooma.

Table 5 and Table 6 presents sample distributions of reported distance in terms of rounding for survey 1 and survey 2 respectively. The outlined cells indicate the categories with the significant number of rounding. This shows that almost all reported distances are rounded as multiples of 100, 500, 1000 and 5000 m, and in some cases even rounded to 10000 m. It was observed that data rounding appeared at higher numbers (500, 1000, 5000, 10000 m) for private transport and buses, whereas rounding at 100, 500 and 1000 m seems to be popular for walking. This implies that longer distance may raise higher level of coarseness caused by the rounding. Meanwhile, distances traveled by informal modes are rounded at 100, 500, 1000 and 5000 m. Bicycling was removed from this study for both the analysis due to small sample size.

Table 5 Rounding of reported distances for various modes for survey 1*

	Cases	Walking	Informal	Private	Bus	Bicycle
Access distances	Multiples of 5000 m excluding multiples of 10,000 m	2	45	19	31	2
	Multiples of 1000 m excluding multiples of 5000 m	129	240	67	69	11
	Multiples of 500 m excluding multiples of 1000 m	131	51	11	7	0
	Multiples of 100 m excluding multiples of 500 m	101	7	0	0	1
	Not multiples of 100 m	1	0	2	0	0
	Total cases	364	343	99	107	14
Egress distances	Multiples of 5000 m excluding multiples of 10,000 m	1	28	8	21	1
	Multiples of 1000 m excluding multiples of 5000 m	137	198	15	54	6
	Multiples of 500 m excluding multiples of 1000 m	183	38	3	5	1
	Multiples of 100 m excluding multiples of 500 m	147	5	0	1	1
	Not multiples of 100 m	4	0	0	0	0
	Total cases	472	269	26	81	9

* The outlined cells indicate the categories with significant number of rounding.

Table 6 Rounding of reported distances for various modes for different stations (survey 2)*

Station	Cases	Walking	Informal	Bus & private modes
Dwarka mor	Multiples of 5000 m excluding multiples of 10,000 m	0	14	13
	Multiples of 1000 m excluding multiples of 5000 m	37	106	29
	Multiples of 500 m excluding multiples of 1000 m	33	17	1
	Multiples of 100 m excluding multiples of 500 m	68	9	1
	Not multiples of 100 m	1	0	0
	Total cases	139	146	53
Karkardooma	Multiples of 5000 m excluding multiples of 10,000 m	0	14	7
	Multiples of 1000 m excluding multiples of 5000 m	47	88	23
	Multiples of 500 m excluding multiples of 1000 m	39	26	4
	Multiples of 100 m excluding multiples of 500 m	83	21	2
	Not multiples of 100 m	8	1	0
	Total cases	177	150	39
Lajpat Nagar	Multiples of 5000 m excluding multiples of 10,000 m	0	16	10
	Multiples of 1000 m excluding multiples of 5000 m	42	92	17
	Multiples of 500 m excluding multiples of 1000 m	46	28	3
	Multiples of 100 m excluding multiples of 500 m	74	6	1
	Not multiples of 100 m	2	0	0
	Total cases	164	142	33
Vaishali	Multiples of 5000 m excluding multiples of 10,000 m	0	25	14
	Multiples of 1000 m excluding multiples of 5000 m	43	93	35
	Multiples of 500 m excluding multiples of 1000 m	25	16	2
	Multiples of 100 m excluding multiples of 500 m	63	7	0
	Not multiples of 100 m	2	0	0
	Total cases	133	149	60

* The coloured cells indicate the categories with significant number of rounding.

The rounded reported distances may cause errors in the final goal to estimate distances people are willing to travel for access via each mode. In order to account for the rounding errors of reported distance, imputation methodology was applied to correct the reported distance as described in the coming chapter. In order to account for the rounding errors of reported distance, two steps were taken: Firstly, a heaping model was constructed to account for the rounding errors of the reported distance data, which formulates a model to predict the coarseness of reported distances. Secondly, MI was carried out to draw actual distances according to the given distribution of the heaping model.

CHAPTER 4 - EXAMINATION OF TOD INFLUENCE ZONES FOR NEW DELHI

4.1 Introduction

The studies regarding last mile connectivity and access to transit only focused on the transit access distance by walking and cycling, although various forms of travel are used for last mile connectivity, including informal modes (such as auto rickshaws, cycle rickshaws, electric rickshaws, gramin-seva, etc.), buses and private modes such as cars and two wheelers). Informal transit is one of the most popular modes, especially for the middle class in Indian cities. Informal transit has been defined as “public transport services that are provided differently as compared to the typical government-provided bus- and rail-based transport in cities” (Kumar et al.,2016). They perform a critical role in urban mobility by helping to reduce the demand-supply gap of public transit. Guillen et al. (2013) (highlighted the importance of informal modes in developing countries and found that commuters tend to use these modes even for a short distance. Besides, buses and private modes are also popular access modes to transit stations in Indian cities. This multimodal accessibility is highly different from developed countries, which have simpler transport modes. Furthermore, Indian cities’ high density and income disparities require a myriad of access travel modes.

This study focuses on the multimodal accessibility of transit users in India to examine the appropriate influence area of TOD using a survey data carried out in New Delhi, India. The data set was obtained from a questionnaire survey administered by Delhi Metro Railway (DMR) Corporation (DMRC) to DMR passengers in December 2015.The sample size of respondents from individual stations was not enough to carry out analysis separately specific stations. Therefore, the data was used to carry out a general analysis for the city of New Delhi. The data was rounded and had heaping issues as reported in the previous section. Rounded reported distance may cause errors in estimating the distances people are willing to travel for access via each mode. In order to account for the rounding errors of reported distance, three steps were taken to calculate the influence area of transit stations for each access mode. First, a heaping model was created to account for the rounding errors of the data set, which formulates a model to predict the coarseness of reported distances. Second, MI was conducted to draw actual distances according to the given distribution of the heaping model. Thirdly, distance decay and ROC analysis was carried out on the imputed data set to estimate the possible range of access and egress distances for each mode.

4.2 Data correction

4.2.1. A Heaping Model to Account for Rounding Errors

The heaping model to account for rounding errors consists of two functions: a data model function to formulate the distribution of the heaping data and a coarseness function for the rounding behavior. As shown in Figure 6, the reported distance data shows approximately log-normal distribution that is similar to the distribution of vehicle kilometers in Yamamoto et al. (2018). In addition, the coarseness level may increase with longer distance traveled as shown in Table 1. This feature of the data is also similar to the data studied by Yamamoto et al. (2018). Therefore, their heaping model was applied in this analysis.

The heaping model is built upon Yamamoto et al. (2018). It takes the form of a discrete mixture of an ordered probit model. The model of reported distance is given as:

$$\ln(y_i^*) = \beta x_i + \varepsilon_i, \tag{1}$$

where y_i^* is the actual distance of individual i, y_i is the reported distance, β is a parameter vector, x_i is a vector of explanatory variables, and ε_i is a random variable that follows a normal distribution. x_i was treated differently for different modes. Based on the cases of rounding shown in Table 5, it was assumed walking distances to be rounded to multiples of 100, 500 and 1000 m. Distances traveled by informal modes was assumed to be rounded to multiples of 100, 500, 1000 and 5000 m and distances traveled by private transport and bus to be rounded to multiples of 500, 1000 and 5000 m. This means that y_i^* lies in the range $[y_i - 50, y_i + 50]$ if the reported distance is rounded to multiples of 100 m, in the range $[y_i - 250,\ y_i + 250]$ if multiples of 500 m, in the range $[y_i - 500,\ y_i + 500]$ if multiples of 1000 m, and in the range $[y_i - 2500,\ y_i + 2500]$ if multiples of 5000 m.

The levels of coarseness are latent variables and cannot be observed. Therefore, it is not possible to determine whether a distance was rounded to the nearest 100, 500, 1000 or 5000 m. For example, a reported distance of 3000 m could be rounded to multiples of 100, 500 or 1000 m. According to Yamamoto et al. (2018), the coarseness of the reported value can be modeled as a latent variable. Since the coarseness level changes with the length of distance, it can be defined as a function of the actual distance. In addition, respondents' socio-economic characteristics may also affect the coarseness of their report. Therefore, the coarseness function is defined as

$$z_i^* = \alpha \ln(y_i^*) + \gamma X_i + \zeta_i\ , \tag{2}$$

where, z_i^* stands for the coarseness of the report, α and γ are parameters, and ζ_i is a normally distributed random variable.

The coarseness of the reported data can be discretized as Equation (3) where θ_1 is the threshold, if there are three multiple cases according to walking, private transport and bus.

$$\begin{aligned} z_i &= 1 \quad \text{if } z_i^* < 0 \\ &= 2 \quad \text{if } 0 \le z_i^* < \theta_1 \\ &= 3 \quad \text{if } \theta_1 \le z_i^*. \end{aligned} \tag{3}$$

On the other hand, it can be extended to Equation (4) if there are four multiple cases, as shown in the informal mode, considering two threshold values θ_1 and θ_2.

$$\begin{aligned} z_i &= 1 \quad \text{if } z_i^* < 0 \\ &= 2 \quad \text{if } 0 \le z_i^* < \theta_1 \\ &= 3 \quad \text{if } \theta_1 \le z_i^* < \theta_2 \\ &= 4 \quad \text{if } \theta 2 \le z_i^*. \end{aligned} \tag{4}$$

Given the coarseness, the reported distance can be represented by the ordered response model with known thresholds. For example, in the case of walking, the reported distance is heaped as multiples of 100 m if $z_i = 1$, multiples of 500 m if $z_i = 2$, and multiples of 1000 m if $z_i = 3$. One of the thresholds is normalized at 0 to identify an intercept term in the latent coarseness process.

Since the coarseness z_i^* depends on ln(y_i^*), it is assumed to be distributed as a bivariate normal with mean

$$E\begin{pmatrix}\ln y_i^*\\ z_i^*\end{pmatrix} = \begin{pmatrix}\beta xi\\ \alpha\beta xi+\gamma xi\end{pmatrix}, \tag{5}$$

and covariance matrix V is given by:

$$V\begin{pmatrix}\ln y_i^*\\ z_i^*\end{pmatrix} = \begin{pmatrix}\sigma_\varepsilon^2 & \alpha\sigma_\varepsilon^2\\ \alpha\sigma_\varepsilon^2 & \sigma_\zeta^2+\alpha^2\sigma_\varepsilon^2\end{pmatrix}, \tag{6}$$

where σ_ε^2 and σ_ζ^2 are variances of ε_i and ζ_i, respectively. In order to identify α, $\sigma_\zeta^2+\alpha^2\sigma_\varepsilon^2$ is normalized to 1 to fix the scale.

A region S(y_i) of possible values for (y_i^*, z_i^*) can be defined, which all map to y_i. It is defined in the case of the informal mode whereby the region $L_i = [y_i - 50, y_i + 50) \times (-\infty, 0)$ corresponds to heaped multiples of 100 m, $M_i = [y_i - 250, y_i + 250) \times [0, \theta_1)$ corresponds to heaped multiples of 500 m, $N_i = [y_i - 500, y_i + 500) \times [\theta_1, \theta_2)$ corresponds to heaped multiples of 1000 m, and $H_i = [y_i - 2500, y_i + 2500) \times [\theta_2, \infty)$ corresponds to heaped multiples of 5000 m, as shown in Equation (7). The same rule applies to walking, private transport, and buses.

$$\begin{aligned}
S(y_i) &= L_i && \text{if } y_i \bmod 100 == 0\text{, and } y_i \bmod 500 \neq 0\\
&= L_i \cup M_i && \text{if } y_i \bmod 500 == 0\text{, and } y_i \bmod 1000 \neq 0\\
&= L_i \cup M_i \cup N_i && \text{if } y_i \bmod 1000 == 0\text{, and } y_i \bmod 5000 \neq 0\\
&= L_i \cup M_i \cup N_i \cup H && \text{if } y_i \bmod 5000 == 0.
\end{aligned} \tag{7}$$

The log-likelihood function for the parameters is given as Equation (8) and estimated by the maximum likelihood (ML) method.

$$LL = \sum_{i=1}^{n} \ln \int_{S(y_i)} f(ln\ \ y_i^*, z_i^*) dy_i^* dz_i^* \ , \tag{8}$$

where $f(\ln\ \ y_i^*, z_i^*)$ is the bivariate normal of E and V.

Table 7 displays the explanatory variables used in the model. The rounding level of reported distance may differ among the respondents. In order to account for differences between them, individual and household characteristics (such as gender, age, household income, individual income and vehicle ownership) was studied as explanatory variables based on the data set. The heterogeneity of the passengers was addressed in the model by including these socio-economic variables in the reported distance function as well as in the coarseness function. The vectors x_i in Equation (1) and X_i in Equation (2) include socio economic explanatory variables mentioned in Table 7. Further, the error terms in these functions take into account the unobserved heterogeneity and unpredictability of travel behavior of passengers.

Table 7 Explanatory variables used for the heaping model.

Variable	Definition	Percentage of Value 1 for Access				Percentage of Value 1 for Egress		
		Walking	Informal	Private	Bus	Walking	Informal	Bus
Gender	Dummy: 1 if respondent is male; 0 if otherwise	0.74	0.69	0.80	0.70	0.75	0.67	0.69
Under 30 years old	Dummy: 1 if respondent is younger than 30; 0 if otherwise	0.67	0.72	0.48	0.73	0.66	0.69	0.69
Low household income	Dummy: 1 if monthly household income is less than 30,000 INR; 0 if otherwise	0.29	0.32	0.15	0.29	0.27	0.32	0.23
Low individual income	Dummy: 1 if monthly individual income is less than 30,000 INR; 0 if otherwise	0.74	0.79	0.53	0.76	0.71	0.78	0.81
Vehicle ownership	Dummy: 1 if there is a vehicle in the home; 0 if otherwise	0.75	0.74	0.93	0.81	0.76	0.74	0.96

This bivariate ordered response probit model was estimated using GAUSS (Aptech, 1997) a matrix-programming software that provides routines for MI estimation. Table 8 presents the estimation results. Private transport was excluded from the analysis of egress due to the small sample size. Only significant variables are left for each mode. In the coarseness function, the estimated values of log-distance coefficient α are positive in all modes with large t-statistics. This verifies that the coarseness level increases with travel distance. The estimate for gender showed a negative value for access by walking, but a positive value for informal access. This implies that men give less coarseness than women in the case of walking, but more coarseness for informal travel. The reason for this difference requires further research. The estimate of low individual income showed a positive value in the case of buses for egress, but was not significant for other cases. The percentage of low individual income among bus users is higher for egress compared to other modes, as shown in Table 8. This suggests that those with low individual incomes may often ride the bus, and that higher frequency of use may lead to more coarseness since users become accustomed to the distance. In the distance function, the estimates of gender and young age are positive and significant in the case of walking and informal transit. This indicates that men or young people travel longer than others in those cases. The estimates for low household income also show positive values in the case of informal and private transport, implying that individuals with low household incomes travel more than others. This is reasonable for private transport since two-wheelers, a popular form of travel among low-income Indians, is included in the private mode. The estimates of vehicle ownership show negative values for walking in terms of both access and egress, suggesting that vehicle owners are less willing to walk. These estimation outcomes reasonably explain the rounding of reported distances, and are expected to properly account for the rounding errors in the analysis of the data set.

Table 8 Estimation results of the heaping model.

Variables	Access				Egress		
	Walking	**Informal**	**Bus**	**Private**	**Walking**	**Informal**	**Bus**
	Estimates (t-stat.)	**Estimates (t-stat.)**	**Estimates (t-stat.)**	**Estimates (t-stat.)**	**Estimates (t-stat.)**	**Estimates (t-stat.)**	**Estimates (t-stat.)**
Coarseness function							
Log-distance (α)	1.081 (15.670)	0.969 (8.505)	0.982 (5.365)	1.101 (9.784)	1.149 (19.241)	1.061 (11.106)	0.809 (5.773)
Constant (γ)	−6.346 (−13.133)	−5.908 (−6.207)	−7.098 (−4.614)	−8.379 (−8.514)	−6.836 (−16.425)	−6.400 (−7.383)	−6.128 (−4.875)
Gender (male)	−0.311 (−1.949)	0.346 (1.963)	-	-	-	-	-
Low individual income (less than Rs. 30000)	-	-	-	-	-	-	0.838 (2.278)
Threshold (θ_1)	1.564 (8.871)	1.499 (8.268)	2.301 (7.463)	2.119 (7.998)	1.712 (9.266)	1.336 (6.434)	2.460 (7.588)
Threshold (θ_2)	-	3.629 (14.441)	-	-	-	3.620 (13.298)	-
Distance function							
Constant (β)	6.301 (46.412)	7.677 (107.859)	8.450 (102.551)	8.126 (85.327)	6.164 (57.366)	7.816 (182.213)	8.370 (72.098)
Gender (male)	0.306 (3.150)	-	-	-	0.214 (2.683)	-	-
Young age (between 18 and 30 years old)	0.262 (3.096)	0.178 (2.267)	-	-	0.212 (3.047)	-	-
Low household income (less than Rs. 30000)	-	0.173 (2.110)	-	0.635 (2.803)	-	-	-
Vehicle ownership (household with no car/ 2 wheeler)	−0.319 (−3.141)	-	-	-	−0.226 (−2.794)	-	-
Std. deviation (σ_e)	0.736 (24.923)	0.647 (25.284)	0.827 (13.063)	0.828 (12.005)	0.694 (27.797)	0.682 (22.318)	0.949 (10.462)
Sample size	364	343	107	99	472	269	81
Mean log-likelihood	−2.124	−2.435	−2.822	−2.722	−2.173	−2.398	−2.968

4.2.2. Multiple imputation to obtain probable values of reported distances

With the random heaping model described in the previous section, the interval into which the true distance y_i^* falls was determined. Given the reported values and estimated parameters of the heaping model, MI was used to draw the missing values of the true distance based on the work of Heitjan and Rubin (1990) and Drechsler and Kiesl (2016). Heitjan and Rubin (1990) carried out a Monte Carlo experiment to test the effectiveness of their model and the experiment showed that the model was statistically and numerically consistent to retrieve biased data from the rounded data. Later, Drechsler and Kiesl (2016) also performed a repeated simulation process by repeating the whole process of sampling, imputing and analyzing data to verify that the imputation method provides unbiased point estimates. According to their verification, it was assumed that the imputation method can draw unbiased imputed values, and does not execute experiment on the evaluation of this methodology. The procedure of the imputation task is described as following.

Given the estimated parameters of the heaping model, $\varphi = (\beta, \gamma, \theta, \alpha, \sigma_\varepsilon)$ and the fixed observed data (y_i, x_i), the $(\ln(y_i^*), z_i^*)$ for individuals $i = (1, \dots, n)$ follows bivariate normal distributions. The value of y_i confines $(\ln(y_i^*), z_i^*)$ to the plausible region defined by Equations (3), (4) and (7) for each mode. The imputation task was implemented using a simple rejection sampling approach:

1. Draw candidate values for $\left(\ln(y_i^*)^{imp}, z_i^*\right)$ from a truncated bivariate normal distribution with mean vector (5) and covariance matrix (6) using the estimated parameters φ, where the truncation points are provided by the maximum possible degree of rounding given the reported distance y_i (e.g., for a reported distance value of 500 m with possible degrees of rounding of 100, 500 and 1000 m), $\ln(y_i^*)$ is bounded by ln(250) and ln(750), and z_i^* has to be $(-\infty, \theta)$.
2. Accept the drawn values if they are consistent with the observed rounded distance (i.e., rounding the drawn value y_i^* according to the drawn rounding indicator z_i^* gives the observed distance y_i), and impute $\exp\left(\ln(y_i^*)^{imp}\right)$ as the exact distant value.
3. Otherwise, draw again.

Repeating this procedure m times, gives m imputed data points that reflect the uncertainty of imputation. In this study, the procedure was repeated 1000 times to approximate the true values of distance for each mode. For example, Figures 12 and 13 display the original and imputed data of the informal mode, respectively. Before imputation, all reported distance data were concentrated at multiples of 100, 500, 1000 and 5000 m. This reported distance data also presents relatively high frequencies at 1000, 2000 and 3000 m. After imputation, the rounding effect is accounted for, and imputed distances are distributed around the original report values. Meanwhile, the imputed data properly reflect the relative frequency characteristics of the original data. The histogram of imputed distances for various modes for access and egress in given in Appendix 7.

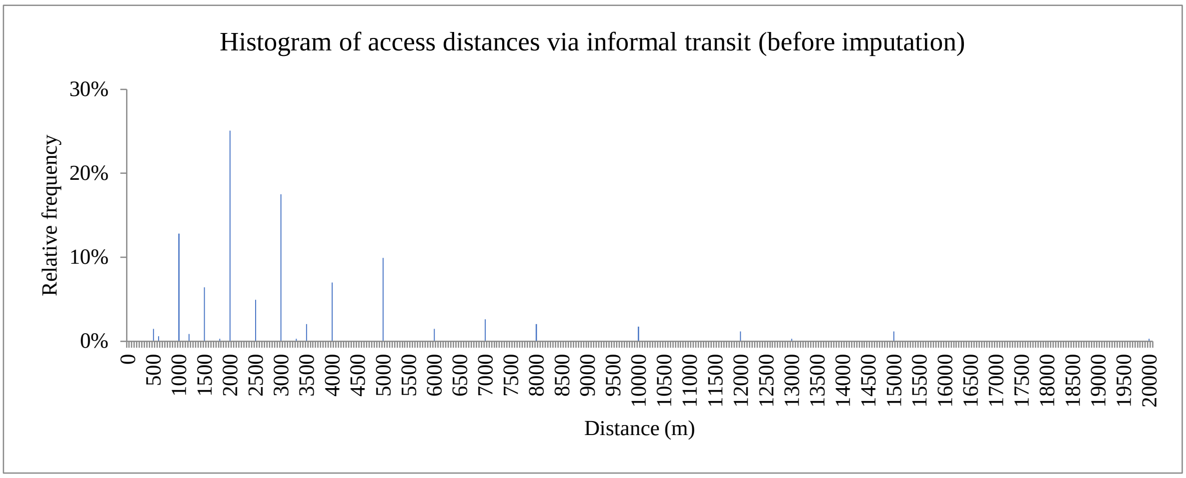


Figure 12 Histogram of access distances via informal transit (before imputation).

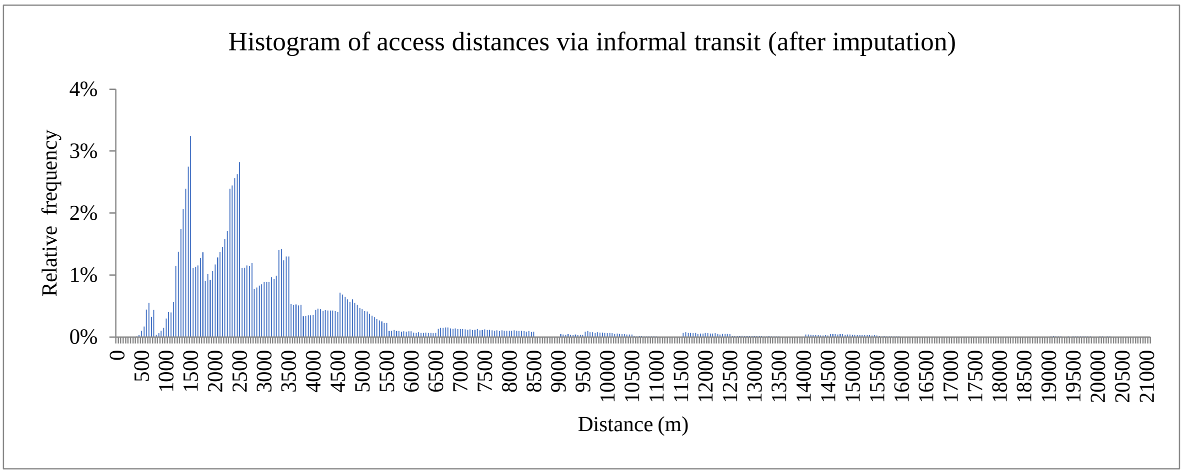


Figure 13 Histogram of access distances via informal transit (after imputation).

4.3 Estimating influence areas of each mode

4.3.1. Distance decay analysis

Distance decay analysis has received more attention in field of investigating distances travelled to access transit stations (Zhao et al., 2003; Kimpel et al., 2007; Larsen et al., 2010; Halas et al., 2014). The exponential distance decay function to forecast transit walking accessibility was put forward by Zhao et al. (2003). As shown in Figure 14, after data imputation, it is clear that the coverage of people who walk a given distance (or more) decreases in an exponential shape. Thus, the exponential form of the decay function (Given by equation 9) was used to study travel distances of each mode.

$$y = \exp(-\alpha d), \tag{9}$$

where y is the percentage of passengers traveling a particular distance d (or more), and α is the exponential decay constant to be estimated. According to this decay function, the mean distance can be calculated as $1/\alpha$, and the median value of the distance can be calculated as the 50th percentile of the exponential decay, $\ln(2)/\alpha$.

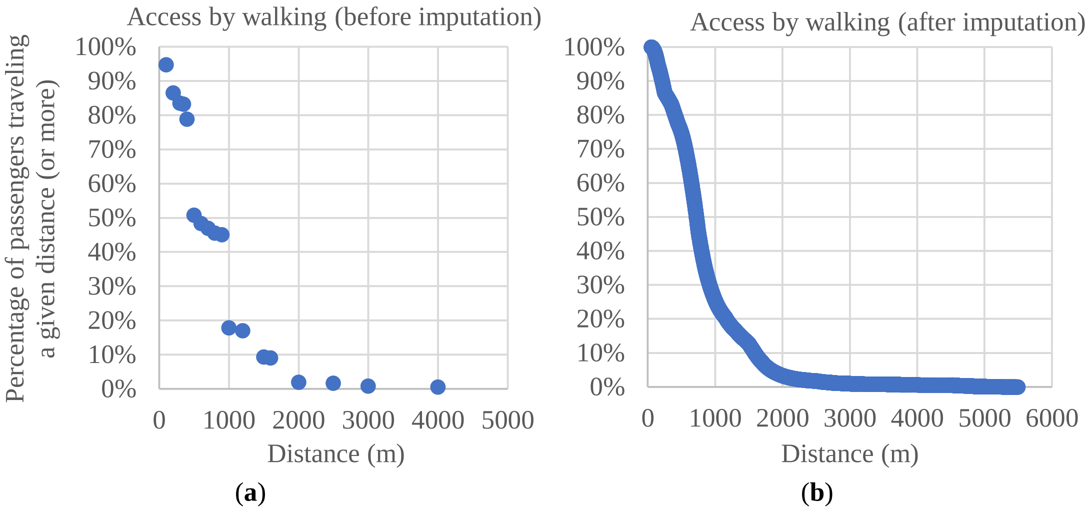


Figure 14 (**a**) Distribution of distances for access by walking before imputation; (**b**) distribution of distances for access by walking after imputation.

Distance decay analysis was conducted using the original data set before and after implementing MI. Table 9 summarizes the estimation results of the data set before and after MI for access, while Table 10 covers egress. Since the sample sizes are enlarged after imputation, the modified t-statistic values were used for imputed datasets giving identical sample sizes to before and after MI. The estimation outcomes of the imputed data show a higher model fit in all modes than data before imputation. In addition, the original data without imputation failed to yield estimations in the case of buses and private transport for access. Moreover, the exponential decay constant α is highly significant across all modes after MI. The estimation results of buses and private transport for access have very close values, implying that they have the same distance decay curve. The exponential decay constant α for walking is significantly higher than that of other modes, showing a rapid fall of coverage percentile with the increase in walking distance.

Table 9 Estimation results of decay functions for access.

	Walking		Informal		Bus		Private	
	Before MI	**After MI**	**Before MI**	**After MI**	**Before MI**	**After MI**	**Before MI**	**After MI**
Coefficient α (t-stat)	0.00119 (25.14)	0.00135 (34.68)	0.00030 (46.95)	0.00034 (44.03)	7.70×10^{-6} (0.87)	0.00016 (35.03)	8.42×10^{-6} (0.91)	0.00016 (36.79)
R^2	0.974	0.986	0.991	0.989	0.040	0.985	0.040	0.984
Adjusted R^2	0.915	0.967	0.941	0.983	−0.015	0.982	−0.010	0.982
Sample size	18	18	21	21	19	19	21	21

Table 10 Estimation results of decay functions for egress.

	Walking		Informal		Bus	
	Before MI	**After MI**	**Before MI**	**After MI**	**Before MI**	**After MI**
Coefficient α	0.00136	0.00164	0.00033	0.00038	0.00011	0.00013
(t-stat)	(23.45)	(35.72)	(41.77)	(27.99)	(27.56)	(25.94)
R^2	0.973	0.988	0.991	0.978	0.969	0.964
Adjusted R^2	0.907	0.965	0.928	0.972	0.928	0.962
Sample size	16	16	17	17	25	25

Figures 15 and 16 show the decay curves estimated from the reported data for access by walking before and after MI respectively. The distribution of imputed data shows a gentle decline at short distances, a shaper decline at a certain distance, and a gradual tail which is consistent with the studies of (El-Geneidy et al., 2014; Halas et al., 2014). However, the distribution of original data cannot catch this feature because of the rounding error. The exponential decay function used in this study cannot reflect the gentle decline character of the coverage at short distances properly, while it shows a good fit at long distances. A further improvement in the decay function is required for future study.

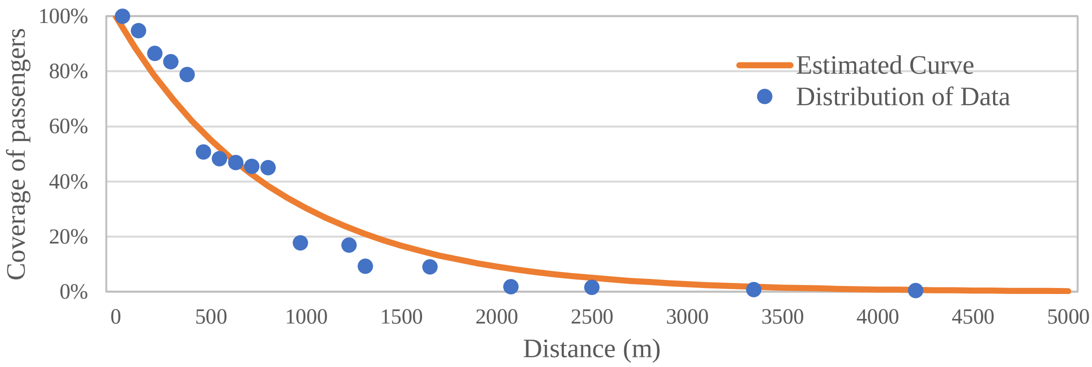


Figure 15 Distance decay curve for access by walking before MI.

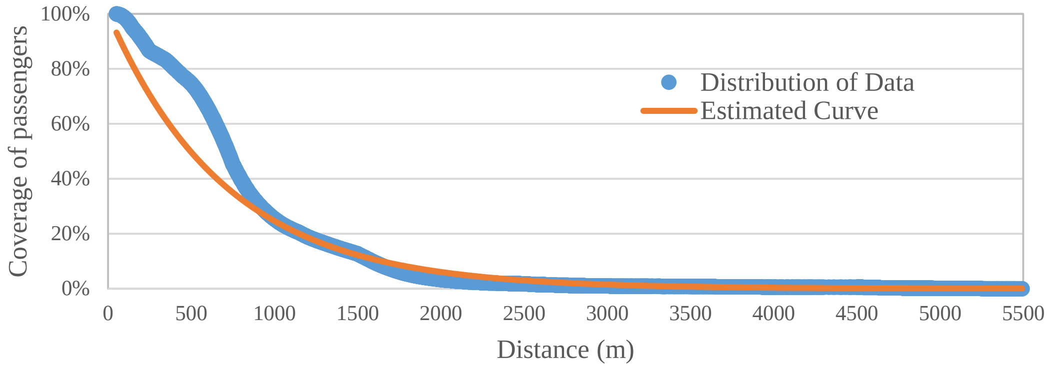


Figure 16 Distance decay curve for access by walking after MI.

Figures 17 and 18 present the decay curves estimated from the imputed data for access and egress, respectively. At the same coverage of passengers, the travel distance increases in the order of walking, informal transit, buses and private transport.

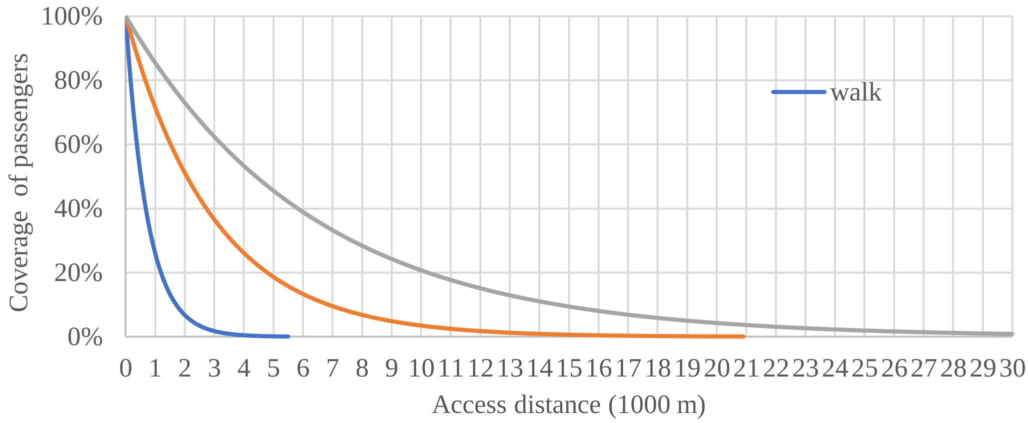


Figure 17 Distance decay curves for all modes of access.

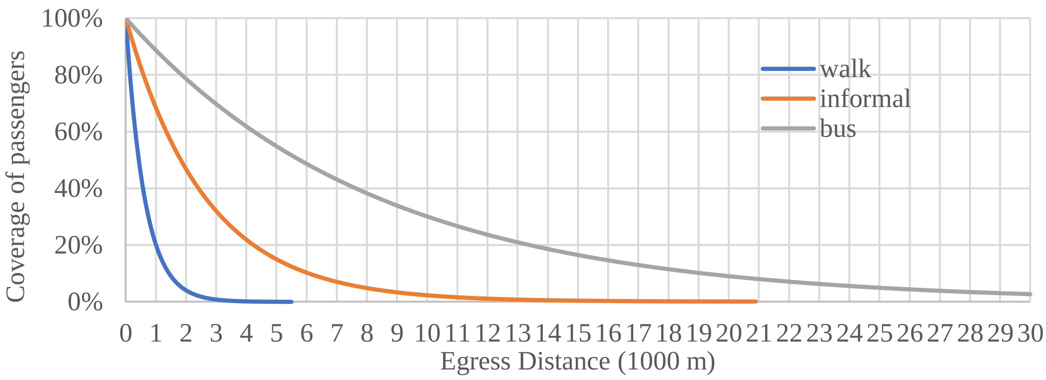


Figure 18 Distance decay curves for all modes of egress.

Tables 11 and 12 summarize travel distances estimated directly from the dataset

set as well as from decay functions. The results of before and after MI are also compared. In many cases, the raw data before MI only gives the same distances for different coverage percentiles while the imputed data can catch distance differences among various coverage percentiles. The decay analysis on the raw data can overcome this problem to a certain extent but not for all cases. For example, in the decay analysis of buses and private transport for access, we could not get any useful regression result. On the other hand, the MI can cover the heaping problem properly giving different travel distance values to each coverage percentile through all modes. Furthermore, the decay analysis on the imputed data can detect the different decay tendencies of travel distances in various modes.

Distances estimated from the imputed dataset were rounded to multiples of 100 m in order to give a reference for TOD policies. The distant curves of private transport and buses are consistent with each other since their exponential decay constants are of the same value.

Comparing access and egress, access distance is slightly longer than egress in the case of walking and informal, while shorter in the case of bus. The mean distance increases in the order of walking, informal transit, private transport and buses. It was concluded that faster modes are attributed to longer distances. The estimation result of decay function with the imputed data shows that the mean values of distance for access are 700 m for walking, 2900 m for informal transit, 6300 m for buses and private transport. India's national TOD policy specifies 500–800 m as the extent of an influence area for walking. According to the decay curves, this distance only covers 50%–65% of transit passengers who walk to stations.

The 85th percentile value has been calculated to define catchment areas around transit stations for walking and cycling (Zhao et al., 2003; El-Genediy et al., 2014; Hochmair, 2015). Therefore, the 70th–90th coverage percentile was considered for each mode in order to evaluate the appropriate influence areas. As shown in Table 11, the 85th percentile distances for access are 1400 m for walking, 5600 m for informal transit, 11,900 m for private transport and buses, estimated from the decay functions with imputed data. Results for egress are given in Table 12. Informal transit has a shorter distance than private transport and buses, since some informal modes (such as cycle rickshaws) cannot cover distances as long as motorized modes.

Table 11 Summary of travel distances for access (m).

	Walk				Informal				Bus				Private			
	From Dataset		From Decay Function		From Dataset		From Decay Function		From Dataset		From Decay Function		From Dataset		From Decay Function	
	Before MI	After MI	Before MI	After MI	Before MI	After MI	Before MI	After MI	Before MI	After MI	Before MI	After MI	Before MI	After MI	Before MI	After MI
Minimum	100	50	-	-	500	269	-	-	500	253	-	-	500	253	-	-
Maximum	5000	5497	-	-	20,000	20,982	-	-	35,000	37,488	-	-	40,000	42,477	-	-
Mean	800	800	800	700	3300	3300	3300	2900	6600	6600	-	6200	5500	5700	-	6300
Median	600	700	600	500	2500	2500	2300	2000	4000	4400	-	4300	3000	3500	-	4300
70th percentile	1000	900	1000	900	3000	3400	4000	3500	7000	7200	-	7500	5000	5200	-	7500
75th percentile	1000	1000	1200	1000	4000	3900	4600	4100	8000	8100	-	8700	6000	6100	-	8700
80th percentile	1000	1200	1300	1200	5000	4400	5400	4700	10,000	9800	-	10,100	8000	8100	-	10,100
85th percentile	1500	1400	1600	1400	5000	4900	6300	5600	12,000	11,900	-	11,900	12,000	11,700	-	11,900
90th percentile	1500	1600	2000	1700	6000	6000	7700	6800	15,000	13,200	-	14,400	15,000	13,400	-	14,400

Table 12 Summary of travel distances for egress (m).

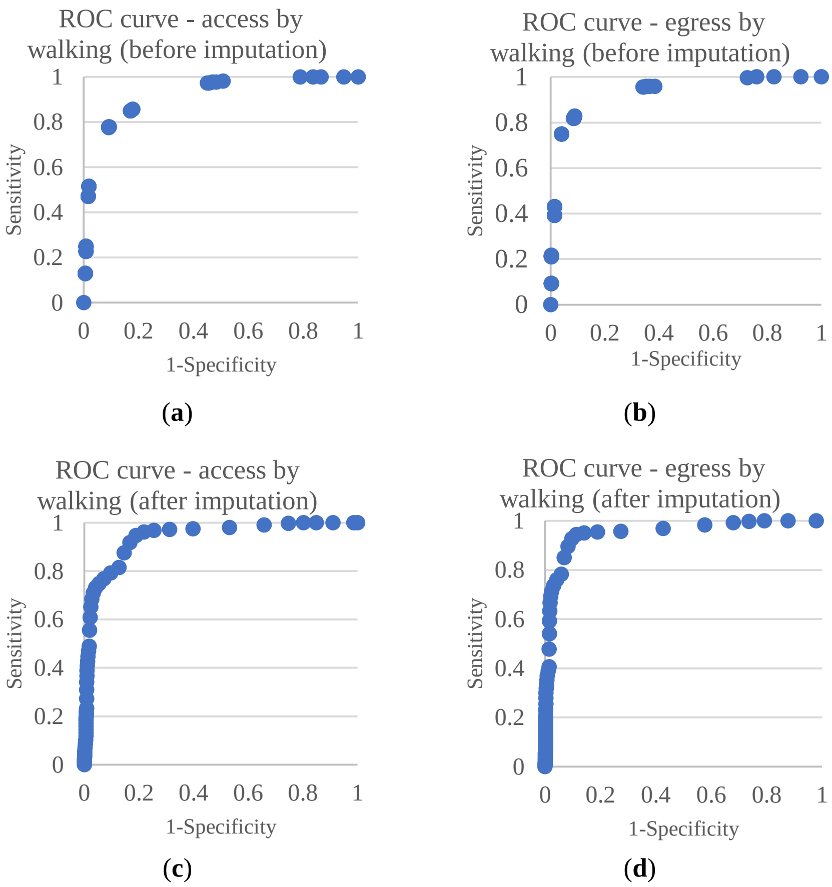
	Walk				Informal				Bus			
	From Dataset		From Decay Function		From Dataset		From Decay Function		From Dataset		From Decay Function	
	Before MI	After MI	Before MI	After MI	Before MI	After MI	Before MI	After MI	Before MI	After MI	Before MI	After MI
Minimum	50	26	-	-	400	274	-	-	500	255	-	-
Maximum	5000	5483	-	-	15,000	16,000	-	-	35,000	37,498	-	-
Mean	700	700	700	600	3200	3200	3000	2600	7100	7000	9100	7700
Median	500	700	500	400	2000	2400	2100	1800	3500	3500	6300	5300
70th percentile	1000	800	900	700	3200	3500	3600	3200	7000	6700	11,000	9300
75th percentile	1000	800	1000	800	4000	4000	4200	3600	7000	7400	12,600	10,700
80th percentile	1000	900	1200	1000	4000	4400	4900	4200	10,000	8800	14,600	12,400
85th percentile	1000	1000	1400	1200	5000	4800	5800	5000	12,000	12,400	17,200	14,600
90th percentile	1000	1200	1700	1400	6000	6200	7000	6000	20,000	18,900	21,000	17,800

4.3.2. ROC Analysis

The distance decay analysis provides useful insight into the relationship between the coverage of passengers and travel distance. A criterion for estimating the influence area can be deduced from the decay curves according to the appropriate coverage of passengers in TOD planning. However, decay curves cannot give the threshold for how far people are willing to travel via each mode. In this study, ROC analysis was applied to find the threshold value of distance that passengers are actually willing to walk with imputed data.

The passive walkers are defined as passengers who use informal transit, private transport, and buses instead of walking for a given distance. Figure 19 displays the ROC curves for access and egress for walking before and after MI. The ROC curves estimated with original data have fewer numbers of data points and do not provide a smooth curve like that estimated with imputed data. Due heaping of original data, the Youden's index was the same for multiple data points, the threshold value could not be assigned to a single distance range and the maximum value was therefore considered to be the threshold.

Table 13 contains the estimation results. In terms of distinguishing between active and passive participants, it was found that found Youden's index criteria to be 0.757 and 0.834 for access and egress distances after MI, respectively. The AUC values are close to 1 showing the effectiveness of those results. The threshold distance is around 1200 m for both access and egress. This means that people are willing to walk no more than 1200 m, and most passengers change to another form of travel when the access and egress distances are longer than 1200 m. This distance is close to the 80th coverage distance for access and between 80th and 85th coverage distance for egress, as shown in the decay analysis. The threshold distance calculated using original data for access is around 1700 m and it matched to the 90th coverage distance of the decay analysis. For egress, the threshold value is the same for distance data before and after MI.



(a) (b) (c) (d)

Figure 19 (a) Receiver operating characteristic (ROC) curve for access by walking before imputation; (b) ROC curve for egress by walking before imputation; (c) ROC curve for access by walking after imputation; (d) ROC curve for egress by walking after imputation.

Table 13 Estimation results of ROC for walking.

ROC Analysis	**Access**		**Egress**	
	Before MI	**After MI**	**Before MI**	**After MI**
Maximum Youden index	−0.688	−0.757	−0.739	−0.831
Threshold (m)	1700	1200	1100	1100
AUC	0.918	0.942	0.932	0.933
Observations N	51	56	51	55

4.4 Conclusions

In this chapter, passengers' multimodal accessibility and last mile distances to DMR stations was used to examine the appropriate influence area for TOD planning in New Delhi. According to the 2015 survey administered to Delhi metro passengers by the

DMRC, walking, informal transit, buses and private transport are considered effective access and egress modes in New Delhi. The reported distance obtained from such passenger surveys causes considerable rounding and heaping problems, which leads to bias in the estimation of the distance. Therefore, a random heaping model was applied to account for the rounding problem and MI to impute the missing data, before employing distance decay and ROC analysis to determine the distances travelled by each mode to estimate influence area of each mode.

The estimated distance by decay analysis showed different values for different modes. Travel distance increases in the order of walking, informal transit, buses and private transport. Buses and private transport showed the same decay curve, implying that they cover the same distance from transit stations. In addition, travel distance varies with the coverage percentile of passengers.

The result shows that the current TOD strategies, while it specifies 500 m for the influence area, can only cover 50% of the current transit passengers who walk to stations (i.e., 20% of total transit passengers since only 40% of transit passengers walk to stations), and cover very few of the passengers who travel by other modes. This means that almost 80% of current transit passengers would be excluded from the TOD target area. In other words, it would be required to provide about four times the amount of high-density land for a 500 m circle around a transit station in order to cover all transit passengers. This would be unreasonable because Indian cities already have very high-density land use, especially around transit stations. Therefore, as it is not feasible to delineate a single influence area, it is proposed that a multiple range of influence areas for TOD planning in Indian cities, considering their multimodal accessibility and high-density populations. In addition, the goal of coverage percentage should be carefully specified, taking into account urban population density, population distribution and land use characteristics.

The informal modes are the most preferred mode after walking for the last mile connectivity in New Delhi as shown in the survey data. The distance decay analysis results show that the catchment areas of transit stations with regard to this access mode will be largely extended compared to walking. By including the informal modes, the TOD influence area can be extended to benefit larger areas of the city with sustainable and inclusive development. Furthermore, ROC analysis was used to check the threshold distance for walking. The threshold value was 1200 m for access and 1110 m for egress, which is consistent with the results of the 80th percentiles of decay analysis. This implies that most passengers are willing to walk longer distances to access transit stations than what is mentioned in the current TOD guidelines for India and the standards adopted by MPD-2021 for New Delhi.

The study approach can be applied in other developing countries especially where there is multimodal last mile connectivity. Many cities in south east Asian countries also have the presence of informal transport modes as well as buses and private vehicles (cars and two-wheelers). These cities can use the empirical findings and the methodology of this study to understand the last mile distances travelled by various modes to transit stations when they explore the concepts of TOD in urban planning.

However, there are some limitations here. Only distance was considered because reliable time data was not available, although time is an important factor in the last mile connectivity. Moreover, this study gives a generic analysis across all stations only considering access and egress distances among different modes. For future work, the effect of land use, built environment and route conditions on the catchment area of TOD can be done focusing on any specific transit station area.

CHAPTER 5 - EXAMINATION OF TOD INFLUENCE ZONES FOR SPECIFIC METRO STATIONS

5.1 Introduction

It has been described that influence areas for transit vary depending on the type of access mode, type of main mode, trip purpose and type of area as shown in Table 3. Walk as the access mode has been popularly studied by a multitude of researchers and the distances that are used quite often range between approximately 400 to 800 m (Calthrope, 1993,1994; Cervero et al., 1994; Bernick & Cervero, 1997; Cervero, 1997; Untermann, 1984; Dittamar & Ohland, 2004; Community Design + Architecture, 2001; Guerra et al., 2012; Flamm & Rivasplata, 2014). Walk is undoubtedly the most popolar access mode across the world. Bicycles are also popular in many cities in the developed worlds as access modes, with many transit agencies allowing bicycles to be taken aboard. For cyclists the access distances have been found to have a large range (1.96 to 4.8 km) varying from study to study and city to city (FTA, 2011; Flamm & Rivasplata, 2014; Lee et al., 2016). Considering the various other types of modes (such as the multitude of informal modes, private modes and buses) used for last mile connectivity in developing countries, particularly in India, Chapter 4 focused on estimation of last mile distances based on multimodal accessibility for metro stations in New Delhi.

The estimated distance decay function from the imputed distance data gave the mean values of distance for access to be 700 m for walking, 2900 m for informal transit, 6300 m for buses and private transport and the 85th percentile distances for access were estimated to be 1400 m for walking, 5600 m for informal transit, 11,900 m for private transport and buses. Moreover, the threshold distance for access walking distances was found to be 1200 m. These results are far from India's national TOD policy, which specifies 500–800 m as the extent of an influence area for walking, which only covers 50%–65% of the current transit passengers who walk to stations according to the estimated decay curves.

The study brought to light how different the last mile connectivity in Indian cities are from cities in the cities of the developed world, with the case study of New Delhi and impact it can have on spatial extent of TOD influence areas. This multimodal accessibility, if not accounted may lead to exclusion of almost 80% of the transit users. Or raise a requirement to increase the density of developments around transit about four times the amount of high density in what are already high dense developed urban areas. A brownfield development in such conditions would not be cost effective in developing countries and also possibly displacing many low-income households who would not be able to afford to live in the new developments.

This chapter focuses on estimating the influence areas for various last mile modes for various station types. Four stations were chosen from the DMR network, Karkardooma – a city station, interchange and urban regional center station, Dwarka mor – sub-city residential area station, Lajpat Nagar – interchange and market station in a central city environment and Vaishali – an outer city station. The reasons behind choosing these stations are given in Chapter 3. The main objective of the paper is to compare the last mile distances for these four stations and to test whether they are in tune with the distances estimated for New Delhi.

5.2 Study area

The survey was carried out for four DMR stations in New Delhi. Lajpat Nagar station area is a mixed land use, mixed income, high dense area located in New Delhi and falls on the interchange of Violet line and Pink line. One of the major markets in the city lies in close proximity to the station and the area is of great commercial and residential importance. Vaishali is an end station on the Red Line, in the suburbs with high dense and mixed income housing and falls outside New Delhi, but belongs to the National Capital Region (NCR) of Delhi. Mixed land use is predominant around the station area. Dwarka mor station and Karkardooma station have been selected to be developed on TOD basis by the city authorities. Delhi Development Authority (DDA) has selected Dwarka to be developed into a smart sub-city in the South-West of New Delhi with commercial, residential and entertainment facilities according to TOD norms. The area is sought after for residential purposes. Similarly, Karkardooma is part of DDA's TOD projects and has been planned to develop over 30 hectares with residential and commercial centers. Karkardooma is also an interchange station and a place of commercial importance in East Delhi. The locations of these station are given in Figure 20. The details of the station area description are given in Table 14. Aerial shots of the station and its surrounding area is shown in Figure 21. The densely developed areas around the station area can be noted clearly.

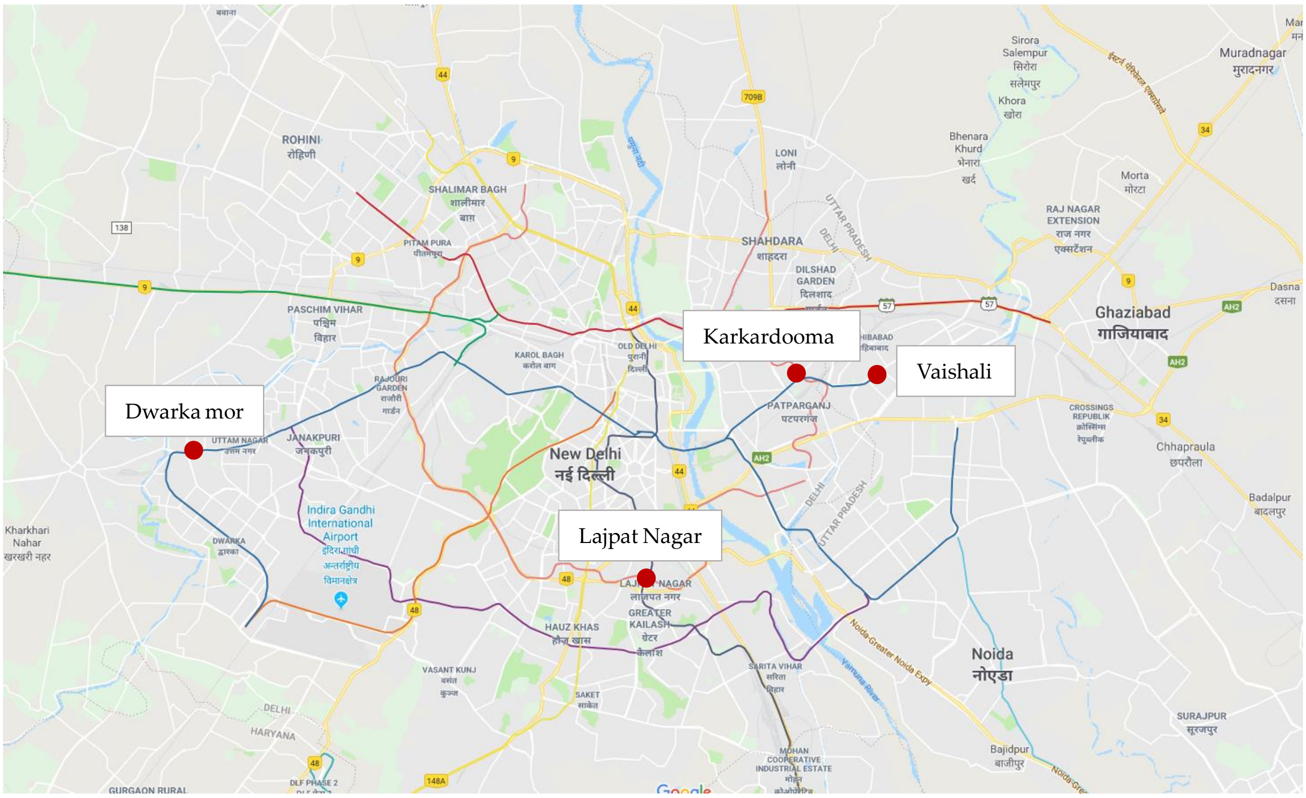
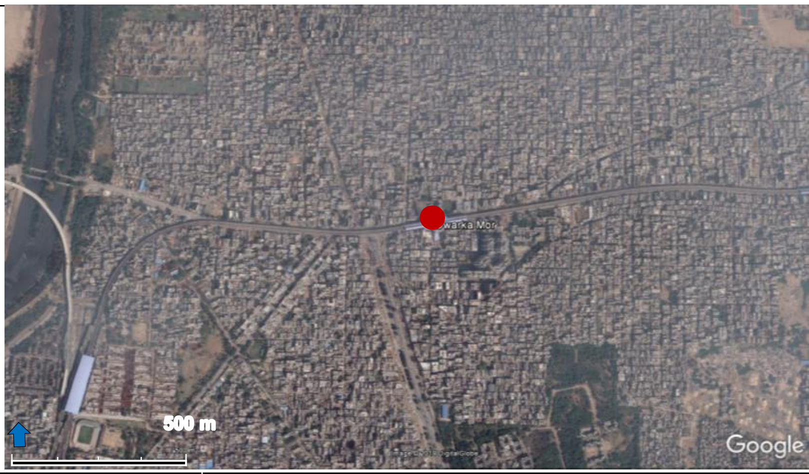


Figure 20 Location of the survey locations in New Delhi

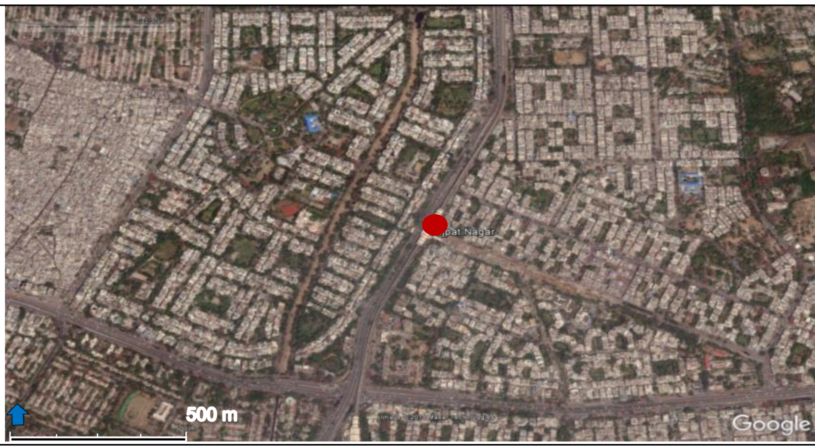
Table 14 Station area description

	Karkardooma (urban regional center)	**Dwarka mor** (sub-city)	**Lajpat Nagar** (central area)	**Vaishali** (outer city)
Type of station	Elevated	Elevated	Elevated and underground	Elevated
	Interchange	Mid station	Interchange	End station
Land use around the station	Mixed (residential, commercial)	Mixed (residential, commercial, institutional)	Mixed (residential, commercial, medical)	Mixed (residential, commercial)
Location of station	Within city of New Delhi	Within city of New Delhi	Within city of New Delhi	Outside New Delhi city limits
Areas served	Urban area	Urban areas - Sub city	Urban areas	Urban and sub urban areas
TOD development plan	Selected for TOD development	Selected for TOD development, smart city project	-	-

(a)



(b)



(c)

(d)

Figure 21 Aerial shots of station areas showing surrounding built up area: (a) Karkardooma, (b) Dwarka mor, (c) Lajpat Nagar and (d) Vaishali

5.3 Data correction – accounting for rounding and heaping errors through Multiple Imputation

The cases of rounding in the reported distance data for the four stations are given in Table 6. Therefore, it was necessary to create a heaping model to account for the heaping issues and carry out MI for this dataset, in order to obtain unbiased results. It was shown in Chapter 4, that the imputed data gave better results during the distance decay and ROC analysis as compared to raw data. The imputation process adopted for the reported distance data is given below. Henceforth, the imputed dataset was used to carry out analysis. In this case, the bus and private modes were combined together as a single group. In Study 1, the heaping model, bus and private modes, showed different estimates for the heaping model (distance function and coarseness function). However, the estimates for distance decay in Study 1 was the same and therefore the distance estimates were the same. Moreover, the sample size was very small in case of bus and private modes to consider these modes separately, hence they were combined

5.2.1. A Heaping Model to Account for Rounding Errors

Yamamoto et al., (2018) encountered the issue of rounding in the reported vehicle kilometers travelled in their study, and a heaping model was used to account for the rounding and heaping errors. The model takes the form of a discrete mixture of an ordered probit model. Ann et al., (2019) used the same heaping model to account for rounding and heaping issues in last mile distances, which followed a log normal distribution. Higher coarseness was observed at larger distances in both studies. The present study draws from the two preceding studies (Yamamoto et al., 2018; Ann et al., 2019). The first part of the model uses a distance function to articulate the distribution of the heaping data, as defined in Equation 1:

$$\ln(y_i^*) = \beta x_i + \varepsilon_i, \tag{1}$$

where y_i^* is the actual distance of individual i, and y_i is the reported distance. β is a parameter vector, x_i is a vector of explanatory variables, and ε_i is a random variable that follows a normal distribution with a mean of 0 and variance of σ_ε^2. Three modes were considered: walking, informal modes, and bus and private modes, and for each mode, x_i was treated differently. Based on the cases of rounding presented in Table 1, different categories of rounding were considered. The walking distances were most likely to be rounded to multiples of 100, 500, and 1000 m all the four stations. The distances travelled by informal transport were assumed to be rounded to multiples of 500, 1000, and 5000 m for the Lajpat Nagar and Vaishali stations. However, for Karkardooma and Dwarka Mor, the rounding was considered to occur at multiples of 100, 500, 1000, and 5000 m. As mentioned earlier, bus and private modes were treated as a single category owing to the small sample size, and the corresponding rounding was considered at multiples of 500, 1000, and 5000 m. Considering these rounding ranges, the actual distance y_i^* was expected to lie in the ranges [y_i − 50, y_i + 50], [y_i − 250, y_i + 250], [y_i − 500, y_i + 500], and [y_i − 2500, y_i + 2500], respectively, if the reported distance was rounded to multiples of 100, 500, 1000, and 5000 m.

The latent variable, which indicates the coarseness of the reported distance, is a function of the actual distance, and the coarseness function can be defined as in Equation 2.

$$z_i^* = \alpha \ln(y_i^*) + \gamma X_i + \zeta_i \quad , \tag{2}$$

where, z_i^* denotes the unobserved tendency of the coarseness of the reported data, α and γ are parameters, and ζ_i is a normally distributed random variable with a mean of 0 and variance of σ_ζ^2. X_i is the socioeconomic parameter.

The coarseness of the reported data, z_i, can be discretized as given in Equation (4), considering only θ_1 if three cases of rounding are present, and considering two threshold values θ_1 and θ_2 if four cases are present.

$$\begin{aligned} z_i &= 1 \quad \text{if } z_i^* < 0 \\ &= 2 \quad \text{if } 0 \le z_i^* < \theta_1 \\ &= 3 \quad \text{if } \theta_1 \le z_i^* < \theta_2 \\ &= 4 \quad \text{if } \theta_2 \le z_i^*. \end{aligned} \tag{4}$$

In the ordered response model, the reported distances can be assigned to specific rounding categories based on the known coarseness levels. Specifically, if z_i = 1, the distance is assumed to be rounded to the nearest 100 m. Similarly, if z_i = 2, 3, 4, the reported distance is assumed to be rounded to the nearest multiple of 500, 1000, and 5000 m, respectively. $(\ln y_i^*, z_i^*)$ is assumed to be distributed as a bivariate normal with mean and covariance as given in Equations 5 and 6, respectively.

$$E\begin{pmatrix}\ln y_i^* \\ z_i^*\end{pmatrix} = \begin{pmatrix}\beta x_i \\ \alpha\beta x_i + \gamma X_i\end{pmatrix}, \tag{5}$$

$$V\begin{pmatrix}\ln y_i^* \\ z_i^*\end{pmatrix} = \begin{pmatrix}\sigma_\varepsilon^2 & \alpha\sigma_\varepsilon^2 \\ \alpha\sigma_\varepsilon^2 & \sigma_\zeta^2 + \alpha^2\sigma_\varepsilon^2\end{pmatrix}. \tag{6}$$

A region S(y_i) of possible values for $(y_i^*,\ z_i^*)$ can be defined, which all map to y_i. For the case of walking, the regions $L_i = [(y_i - 50, y_i + 50) \ \times (-\infty, 0)]$, $M_i = [(y_i - 250, y_i + 250) \ \times (0, \theta_1)]$, and $N_i = [(y_i - 500, y_i + 500) \ \times (\theta_1, \theta_2)]$ respectively correspond to multiples of 100, 500, and 1000 m. In the case of informal transport modes for Dwarka mor and Karkardooma, for which four cases of rounding are considered, a fourth region $H_i = \ [(y_i - 2500, y_i + 2500) \ \times (\theta_2, \infty)]$ corresponds to multiples of 1000 m. For bus and private transport, the regions M_i, N_i and H_i are effective. The region of possible values is defined as follows:

$$\begin{aligned} S(y_i) &= L_i && \text{if } y_i \bmod 100 == 0, \text{ and } y_i \bmod 500 \neq 0 \\ &= L_i \cup M_i && \text{if } y_i \bmod 500 == 0, \text{ and } y_i \bmod 1000 \neq 0 \\ &= L_i \cup M_i \cup N_i && \text{if } y_i \bmod 1000 == 0, \text{ and } y_i \bmod 5000 \neq 0 \\ &= L_i \cup M_i \cup N_i \cup H_i && \text{if } y_i \bmod 5000 == 0. \end{aligned} \tag{7}$$

The log-likelihood function for the parameters is estimated by maximum likelihood (ML) method; the log likelihood function is given by Equation 8.

$$LL = \sum_{i=1}^{n} \ln \int_{S(y_i)} f(ln\ \ y_i^*, z_i^*) dy_i^* dz_i^* \ , \tag{8}$$

where $f(\ln\ \ y_i^*, z_i^*)$ is the bivariate normal of E and V.

The estimation results of the bivariate ordered response probit model are presented in Table 15. The estimates have high statistical significance.

Variables like age, gender, income, vehicle ownership, etc. were found to be not significant in explaining the reported distance or the coarseness. The log-distance coefficient α, was positive for all modes across the four stations, signifying the increase in coarsened with travel distance. Comparing across stations, α, was least for Vaishali station for all modes. It signifies that commuters from had the least tendency to round travel distances. The estimate for α for bus and private modes for Dwarka Mor was comparable to Karkardooma. It may be said that for these two stations, last mile distances travelled on bus had lesser coarseness levels with distance than other modes and other stations. The coarseness function constant, γ, also comparatively lower for Vaishali, imply lower rounding for last mile distances reported in Vaishali. Considering the distance function, β signifies the distances travelled for each mode. The estimates of β were highest for Vaishali followed by Dwarka Mor, i.e. stations far away from the city center had longer last mile distances for all modes compared to stations nearer to the city center.

Table 15 Estimation results of the heaping model

Variables	Karkardooma			Dwarka mor			Lajpat Nagar			Vaishali		
	Walking	Informal modes	Bus and private modes	Walking	Informal modes	Bus and private modes	Walking	Informal modes	Bus and private modes	Walking	Informal modes	Bus and private modes
	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)	Estimates (t-stat)
Coarseness equation-constant	-7.025 (-10.983)	-6.549 (-8.518)	-9.362 (-4.676)	-7.389 (-6.967)	-7.927 (-5.134)	-5.683 (-1.218)	-6.927 (-6.890)	-9.280 (-5.13)	-9.374 (-1.983)	-6.665 (-7.062)	-7.470 (-8.358)	-4.025 (-0.817)
Distance equation-constant	6.348 (101.924)	7.421 (113.128)	8.088 (59.612)	6.398 (85.493)	7.796 (169.138)	8.589 (107.720)	6.306 (99.623)	7.670 (149.097)	8.301 (74.968)	6.411 (83.323)	8.136 (116.466)	8.779 (118.871)
Threshold (θ2)	0.779 (3.738)	0.848 (4.978)	1.628 (3.981)	0.900 (3.216)	1.013 (4.052)	2.339 (4.400	1.403 (3.414)	1.464 (5.603)	1.518 (3.048)	0.549 (2.739)	1.569 (6.75)	2.173 (5.135)
Threshold (θ1)	-	2.519 (9.651)	-	-	3.246 (7.986)	-	-	-	-	-	-	-
Std. deviation (σe)	0.766 (14.693)	0.766 (17.263)	0.742 (6.44)	0.727 (14.084)	0.516 (11.764)	0.506 (7.112)	0.723 (13.082)	0.572 (11.987)	0.536 (5.676)	0.750 (13.056)	0.804 (11.858)	0.540 (9.55)
Log-distance (α)	1.059 (11.688)	1.002 (9.962)	1.225 (5.035)	1.103 (6.994)	1.205 (5.899)	0.867 (1.607)	1.072 (7.147)	1.210 (5.425)	1.225 (2.149)	0.997 (7.437)	0.973 (9.116)	0.626 (1.158)
Number of cases	175	150	39	139	146	52	164	141	33	133	142	60
Mean log-likelihood	-2.478	-2.641	-2.476	-2.526	-2.311	-2.358	-2.347	-2.141	-2.326	-2.519	-2.706	-2.721

5.2.2. Multiple imputation to obtain probable values of reported distances

The distance intervals of the true distance y_i^* was determined with the random heaping model described in the previous section. The true distance can be drawn out using the reported distance values and the estimated parameters of the heaping model given in Table 14. The MI has been based on the work of Heitjan and Rubin (1990) and Drechsler and Kiesl (2016). The imputation task is based on a simple rejection sampling approach, using the estimated parameters of the heaping model, $\varphi = (\beta, \gamma, \theta, \alpha, \sigma_\varepsilon)$ and the fixed observed data (y_i, x_i), the $(\ln(y_i^*), z_i^*)$ for individuals $i = (1, \ldots, n)$ and based on the condition, y_i confines $(\ln(y_i^*), z_i^*)$ to the plausible region defined by Equations (4), and (8) for each mode.

The candidate values are drawn m times (here m=1000 times) from a truncated bivariate normal distribution and tested for boundary conditions to get imputed data with m points. Figure 22 and Figure 23 display the relative distribution of the distance data before and after imputation. It can be seen from these graphs that the through the MI process the shape of the distribution is maintained and the heaping of the data is removed. The histogram of imputed distances for the various modes considered for each station is given in Appendix 8.

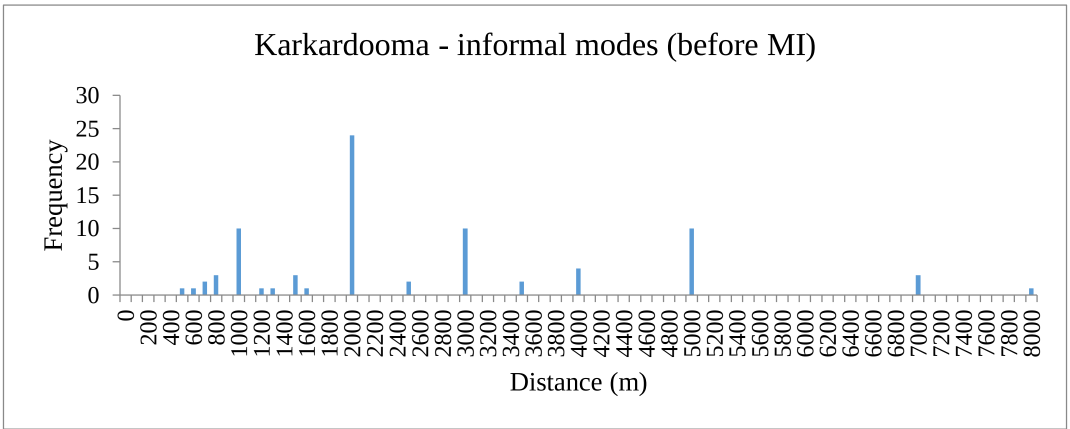


Figure 22 Histogram of distances travelled on informal modes for Karkardooma station (before imputation)

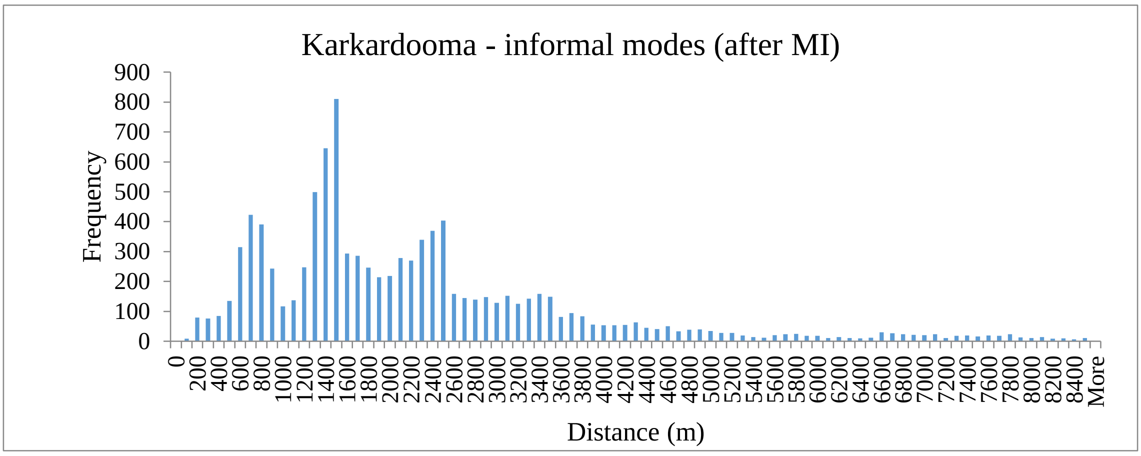


Figure 23 Histogram of distances travelled on informal modes for Karkardooma station (after imputation)

5.4 Estimating influence areas of each mode

5.4.1. Distance decay analysis

The exponential form of distance decay was proposed by Zhao et al., (2003), Larsen et al., (2010), El-Geneidy et al., (2014) and Hochmair (2015), and to forecast the travel demand. Compared to buffer analysis, the exponential form of distance decay provides a better understanding of the transit catchment areas, by assuming varying demand with distance. This method was adopted by Ann et al., (2019) to estimate the influence areas for metro stations in New Delhi, and the following equation was used

$$y = \exp(-\alpha d), \qquad (9)$$

where y is the percentage of passengers traveling longer than a particular distance d, and α is the exponential decay constant to be estimated.

This function has a limitation that it cannot reflect the curve shape change with the distance. In our studies, the coverage curve declines gently in short distances implying that people do not mind the distance increase in short trips. However, it decreases rapidly in a certain range of distances which means that the distance increase causes a strong impact on one's perception. Finally, the curve decreases slowly with a long tail for long trips as shown in Figure 24. This tendency was observed for all stations studied.

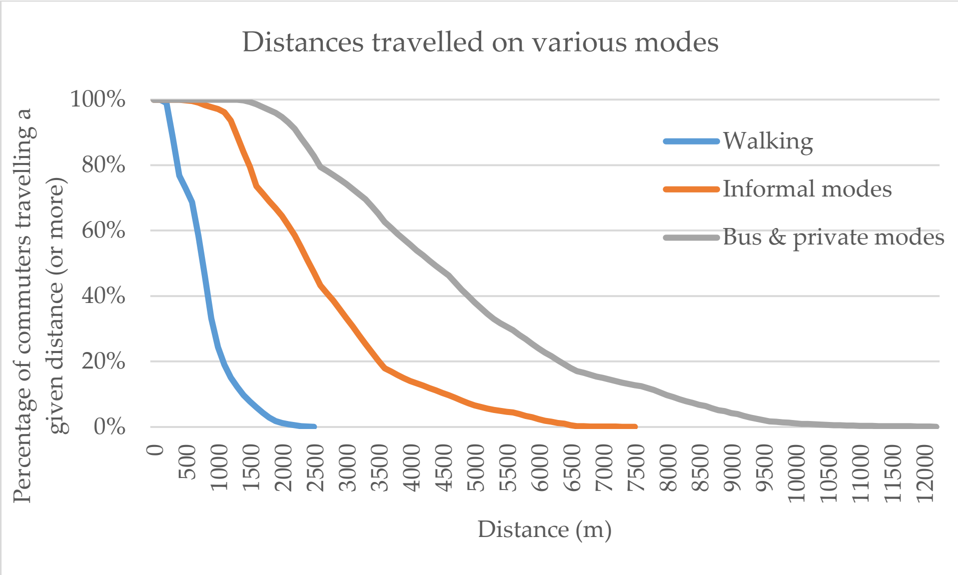


Figure 24 Distribution of distances (after imputation) travelled for Lajpat Nagar on various modes (walking, informal modes and bus & private modes).

Halas et al. (2014) suggested a compound power exponential form of the distance decay with two parameters to investigate the daily travel to work flows. The equation of this function can be written as

$$f(d) = \exp\left(-\alpha d^{\beta}\right), \tag{10}$$

where d is the distance from the center, and α and β are positive parameters. The function follows a bell-shaped curve reflecting shape changes with the distance. The curve is concave in the beginning and then changes to a convex shape. The parameter α indicates the variation in the interaction with distance, i.e., the extent of interaction, and β explains the perception of commuters at various distances, determining the shape of the curve. Therefore, this function is expected to reflect our data properly.

In this study, both of Equations 8 and 9 were used to estimate the distance decay curves for the different stations with different modes. The estimates of the two decay functions for each station are presented in Table 16. The high t-statistic values for the parameter estimates signify satisfactory outcomes for the estimation. The correlation coefficient was close to one for all the categories in the compound power exponential function, indicating the closeness of the observed and estimated data. In the compound function, when the value of β is close to one, the function adopts the simpler exponential form. All the estimation results of β are higher than 1 to indicate the limitation of the simple exponential function. In addition, the estimated β values are different for the four stations and for the various modes. Therefore, this function makes it possible to catch differences in the effects of station locations and access modes to the transit passengers.

Table 16 Estimation results of distance decay functions

Modes	Estimate of parameters	Karakardooma (urban regional center)		Dwarka Mor (subcity)		Lajpat Nagar (central city)		Vaishali (outer city)	
		Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
Walking	α (t-stat)	1.1491 (56.75)	1.3838 (133.18)	1.0820 (37.94)	1.3836 (107.43)	1.1786 (43.34)	1.5242 (69.21)	1.081(43.33)	1.3019 (111.51)
	β (t-stat)	-	1.4991 (110.47)	-	1.9062 (82.41)	-	1.7681 (55.54)	-	1.648 (84.45)
	Corelation coefficient	0.996	0.998	0.988	0.999	0.988	0.997	0.990	0.999
	Residual standard error	0.019	0.005	0.024	0.005	0.024	0.009	0.017	0.005
	Sample size	139	139	175	175	164	164	133	133
Informal modes	α (t-stat)	0.3863 (41.40)	0.2322 (61.35)	0.2816 (28.23)	0.0659 (40.08)	0.3098 (30.04)	0.1052 (41.82)	0.1936 (49.57)	0.1126 (24.60)
	β (t-stat)	-	1.7449 (84.11)	-	2.4243 (104.74)	-	2.2017 (88.53)	-	1.424 (48.51)
	Correlation coefficient	0.988	0.998	0.990	0.998	0.989	0.998	0.988	0.990
	Residual standard error	0.012	0.003	0.022	0.003	0.019	0.003	0.007	0.004
	Sample size	146	146	150	150	141	141	142	142
Bus and private modes	α (t-stat)	0.1958 (41.40)	0.0641 (61.35)	0.1152 (28.23)	0.0279 (40.08)	0.172 (30.04)	0.0269 (41.82)	0.1117 (49.57)	0.0159 (24.60)
	β (t-stat)	-	1.7713 (84.11)	-	1.7479 (104.74)	-	2.2388 (88.53)	-	2.018 (48.51)
	Correlation coefficient	0.991	0.997	0.996	0.993	0.995	0.998	0.988	0.988
	Residual standard error	0.007	0.002	0.007	0.003	0.008	0.001	0.010	0.004
	Sample size	52	52	39	39	33	33	60	60

Comparing goodness of fit of Model 1 and Model 2, correlation coefficient is close to 1 for both the models and residual standard error is also very small (close to zero). However, Model 2 gives a better fit with respect to the shape of distribution of the imputed data, than compared to Model 1. As an example, the distance decay curves estimated for Lajpat Nagar station considering walking as the mode are shown in Figure 25. The compound power exponential curve closely follows the distribution of the imputed data, whereas the exponential curve takes a simple form that does not reflect the observed data. This phenomenon was witnessed across the three modes for the four stations (the graphs are given in Appendix 9).

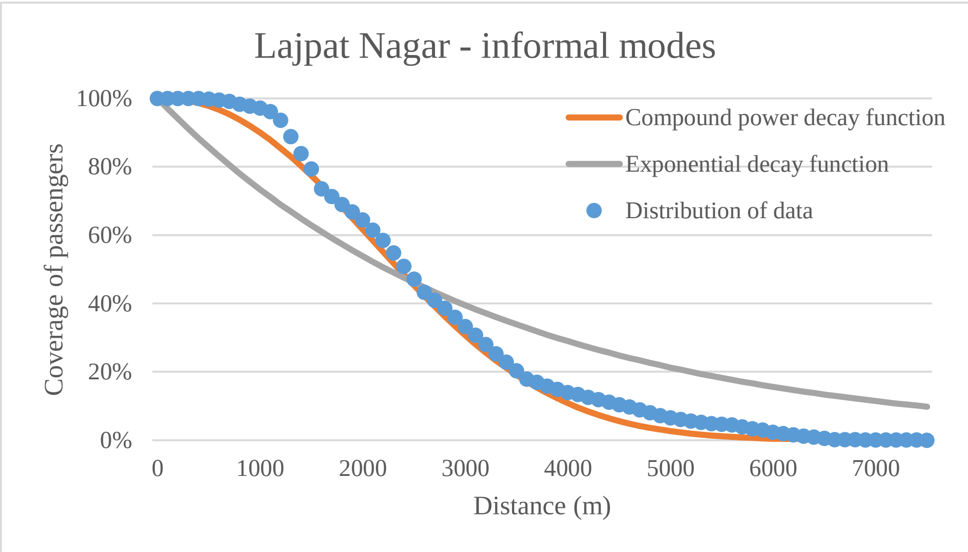
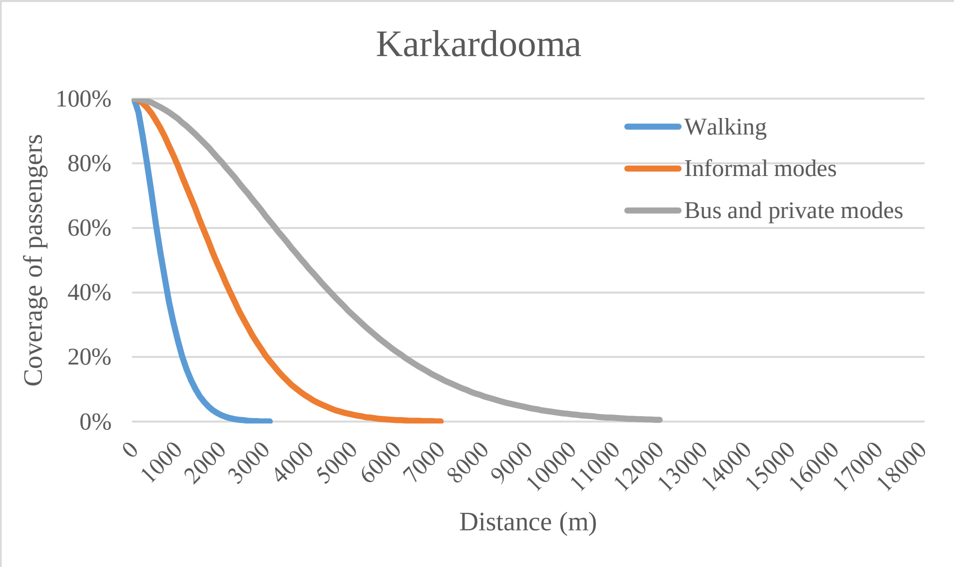
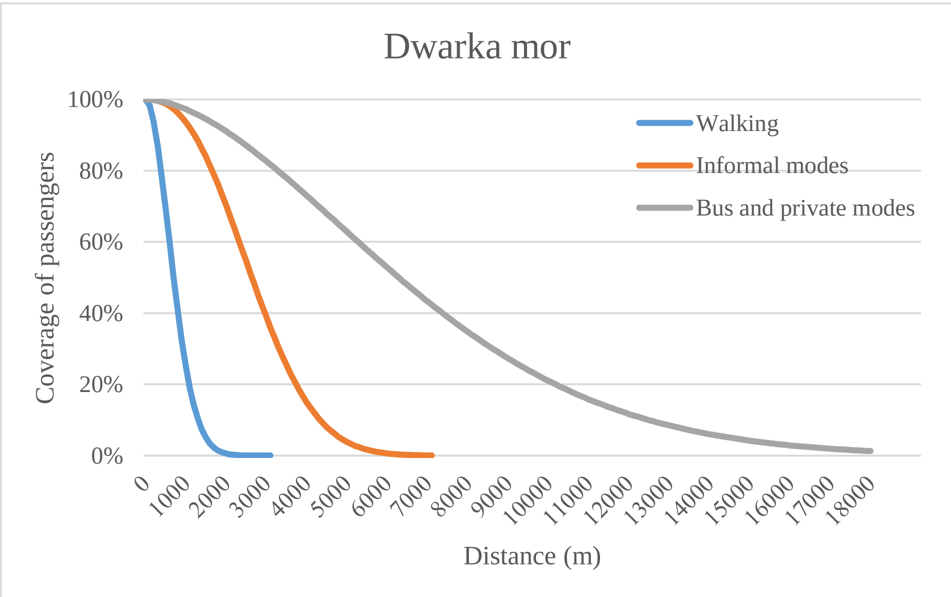


Figure 25 Distance decay curves for Lajpat Nagar station by informal modes

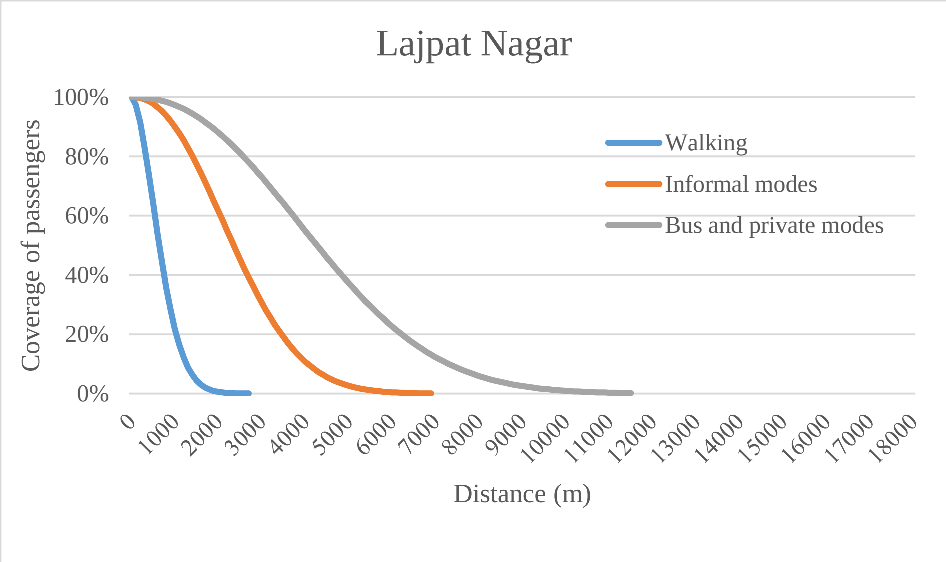
Figure 26 shows the decay curves with different modes for each station. For walking, all stations show similar results. The stations nearer to the city centre, Karkardooma & Lajpat Nagar, show similar decay curves for all these modes. For informal modes, Vaishali shows gradual decay and longer distance than other stations, almost twice of other stations. Being an end station, outside the city limits, it can be assumed that commuters rely on informal modes to access the metro station from long distances; informal modes hence play a more prominent role around this station. In case of bus and private modes, Dwarka mor and Vaishali show gradual decay and depict longer distance than the other two stations, highlighting the preference of these modes for long distances.



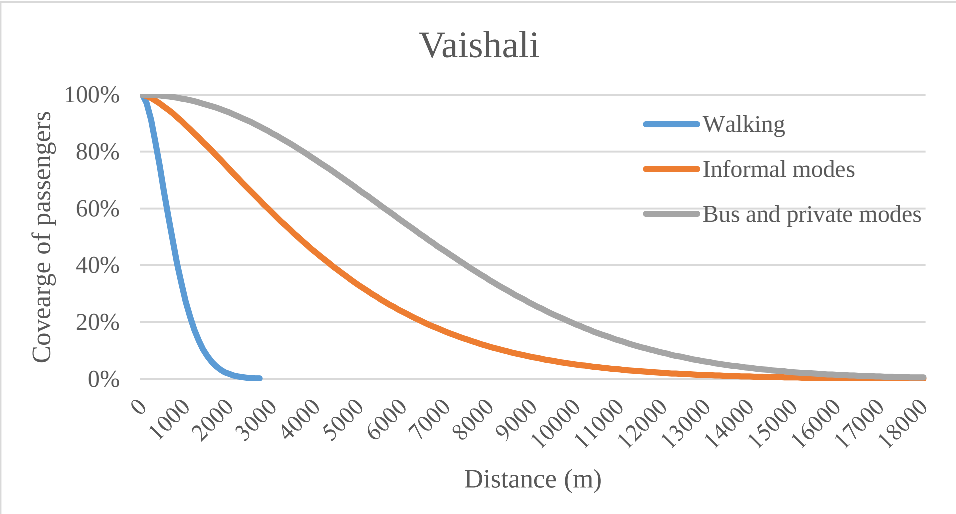
(a)



(b)



(c)



(d)

Figure 26 Distance decay curves (compound power exponential form) for all modes for (a) Karkardooma (b) Dwarka mor (c) Lajpat Nagar and (d) Vaishali

The compound power exponential decay function was used to estimate the influence areas based on different percentiles. The mean, median, and percentile distances were estimated accordingly. Tables 17, 18, and 19 summarize the estimated travel distances pertaining to walking, informal modes, and bus and private modes, respectively. The distances were rounded to the nearest 100 m to facilitate the provision of references for the TOD planning. The statistical summary of the imputed data was compared with the estimates obtained using the distance decay function. The mean and median estimated from the distance function yielded slightly larger distances than those corresponding to the estimates from the statistical summary.

The mean, median, and percentile walking distances were comparable for all the stations. The decay function estimation provided a mean walking distance of 800 m for Karkardooma, Lajpat Nagar and Dwarka mor and 900 m for Vaishali. The 85th percentile distance, used to define the catchment areas for transit stations, was 1200, 1200, 1100 and 1300 m for Karkardooma, Dwarka mor, Lajpat Nagar, and Vaishali, respectively. Compared to these distances, the influence area (500–800 m) specified in the National TOD policy is extremely conservative.

The mean distances travelled by informal modes exhibited considerable differences among the stations. Vaishali, the outer city station, exhibited the largest mean distance (4600 m) compared to that of the other stations. The mean distances for Karkardooma, Dwarka mor and Lajpat Nagar were 2300, 3100, and 2800 m, respectively. The 85th percentile distances for the three stations within the city boundaries (Karkardooma: 3300 m, Dwarka mor: 4000 m, and Lajpat Nagar: 3700 m) were considerably smaller, than for Vaishali (7300 m).

The variations in the mean and 85th percentile distances were more evident when the distances for bus and private modes were examined. In this study, for Karkardooma, Dwarka mor, Lajpat Nagar and Vaishali, the estimated mean distances were 4700, 7800, 5000, and 7800 m, respectively, and the estimated 85th percentile distances were 6800, 11200, 6700, and 10700 m, respectively. Dwarka mor (subcity station) and Vaishali (outer city station) exhibited larger mean and 85th percentile values compared to those of the other two stations situated in the core urban areas of New Delhi. These stations being far away from the station, and being one of the easiest ways to reach other parts of the city, commuters are willing to travel further on buses than other stations. In this study, for Karkardooma, Dwarka mor, Lajpat Nagar and Vaishali, the estimated 85th percentile distances were 6800, 11200, 6700, and 10700 m, respectively.

Table 17 Summary of travel distances for walking (m)

Walking - Summary of travel distances (rounded to the nearest 100 m)	Karkardooma		Dwarka mor		Lajpat Nagar		Vaishali	
	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function
Minimum	50	-	50	-	50	-	50	-
Maximum	2500	-	2500	-	2497	-	3498	-
Mean	700	800	800	800	700	800	800	900
Median	600	600	700	700	700	600	700	700
70th percentile	900	900	900	900	800	900	900	1000
75th percentile	1000	1000	1000	1000	900	900	1000	1000
80th percentile	1100	1100	1000	1100	1000	1000	1200	1100
85th percentile	1300	1200	1200	1200	1100	1100	1200	1300
90th percentile	1600	1400	1400	1300	1300	1300	1500	1400

Table 18 Summary of travel distances for informal modes (m)

Informal modes - Summary of travel distances (rounded to the nearest 100 m)	Karkardooma		Dwarka mor		Lajpat Nagar		Vaishali	
	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function
Minimum	87	-	650	-	266	-	751	-
Maximum	8499	-	7495	-	7482	-	17474	-
Mean	2200	2300	2800	3100	2600	2800	4700	4600
Median	1800	1900	2600	2600	2300	2400	3300	3600
70th percentile	2500	2600	3300	3300	3000	3000	5000	5300
75th percentile	2700	2800	3400	3500	3200	3200	5800	5800
80th percentile	3100	3000	3600	3700	3400	3500	7400	6500
85th percentile	3400	3300	4000	4000	3800	3700	8700	7300
90th percentile	4100	3700	4400	4300	4500	4100	11800	8300

Table 19 Summary of travel distances for bus and private modes (m)

Bus and private modes - Summary of travel distances (rounded to the nearest 100 m)	Karkardooma		Dwarka mor		Lajpat Nagar		Vaishali	
	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function	From dataset (after MI)	From distance decay function
Minimum	258	-	1506	-	1253	-	1006	-
Maximum	12083	-	17496	-	12371	-	17489	-
Mean	4100	4700	7000	7800	4600	5000	7100	7800
Median	4100	3800	5800	6300	4300	4300	6100	6500
70th percentile	5000	5200	8600	8600	5500	5500	8300	8500
75th percentile	5500	5700	9900	9300	5800	5800	8900	9200
80th percentile	6400	6200	11300	10200	6200	6200	10600	9900
85th percentile	7000	6800	12200	11200	6900	6700	12100	10700
90th percentile	7600	7600	13100	12500	7900	7300	12800	11800

5.4.2. ROC Analysis

Adopted from the field of medicine, ROC analysis has been finding application in the field of transportation studies. ROC curves have been used to estimate the threshold distances walked/ cycled by students to school/ university (Chillon et al.,2015, 2016; Rodríguez-López et al.,2017) This method provides a simple yet effective method to estimate threshold distances. This method provides a simple yet effective method to estimate threshold by comparing number of active users (people who walk) versus passive users (commuters who use other modes) for different distance ranges. The threshold walking distance for each station was estimated taking into account the tradeoff between true positive rate (sensitivity) and the false positive rate (1-specificity) across a series of distance ranges using ROC analysis. By this method, it is possible to take into effect the distances travelled on modes such as informal modes, bus and private modes.

For each distance range, active users were the number of commuters who walked to access transit stations and the passive users where the commuters who were using informal modes, bus and private modes to access transit. The ROC curves for each of the station is given in Figure 27.

The Youden's index has been calculated as -0.575, -0.798, -0.767 and -0.763 for Karkardooma, Dwarka mor, Lajpat Nagar and Vaishali respectively. The AUC values for the curves are close to 1, and hence the analysis is effective to obtain threshold values. The estimation results are given in Table 20. The threshold walking distance for Dwarka mor and Vaishali was 1300 m and for Karkardooma and Lajpat Nagar was 1200 m.

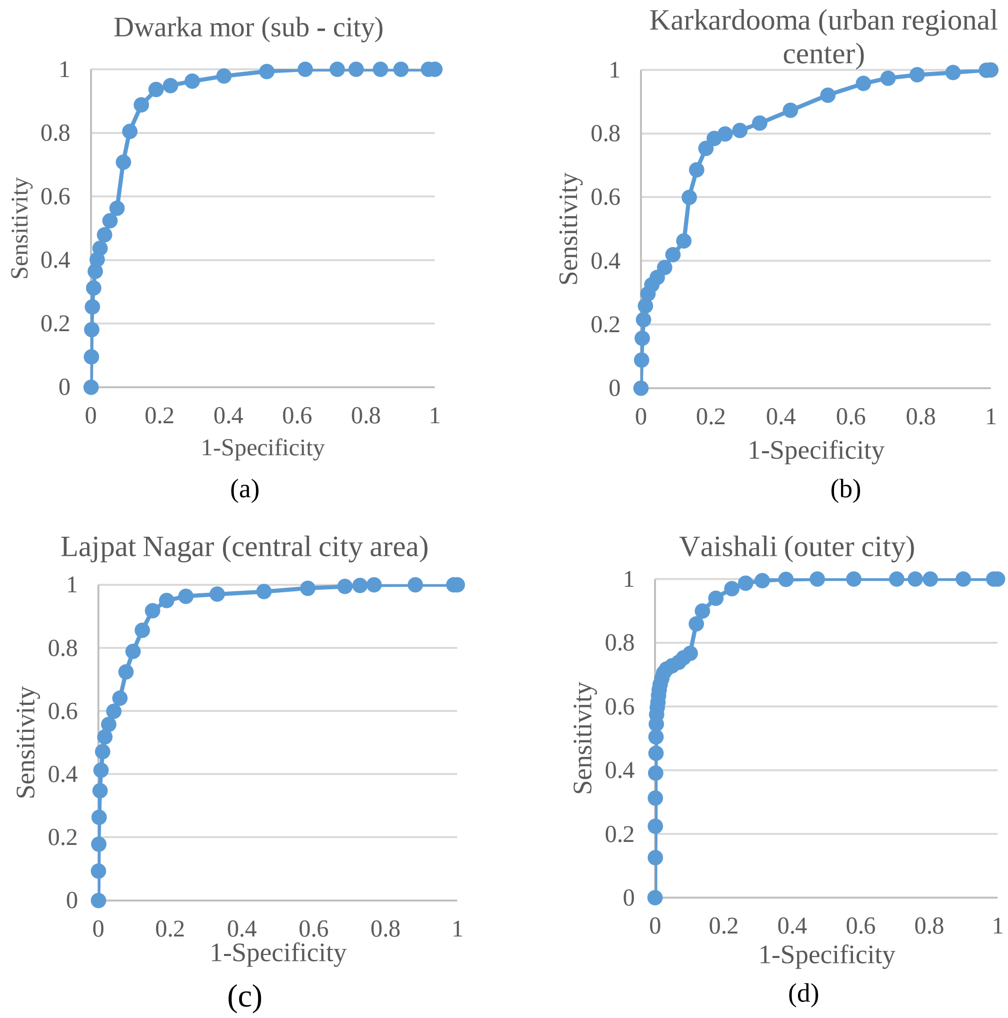


Figure 27 ROC curve for walking for (a) Dwarka mor (b) Karkardooma (c) Lajpat Nagar and (d) Vaishali

Table 20 Estimation results of ROC for walking for various station types

ROC analysis	Dwarka mor (sub city)	Karkardooma (urban regional center)	Lajpat Nagar (central city)	Vaishali (outer city)
Maximum Youden index	-0.798	-0.575	-0.767	-0.763
Threshold (m)	1300	1200	1200	1300
AUC	0.928	0.832	0.939	0.958
Observations N	26	26	26	36
Mean distance – walking (m)	754	743	698	777
Mean distance by modes other than walk(m)	3159	4891	3558	5882

The results for the threshold distances convey that commuters are willing to walk similar distances to all stations. The mean distances walked to the stations are also comparable to each other. The mean distances travelled by modes other than walk showed differences between stations. However, this did not impact the threshold distances as the maximum distances for walk was 2500 for Karkardooma, Lajpat Nagar and Dwarka mor and 3500 for Vaishali station. Distances larger than the maximum values for walking were not considered for the test and therefore the difference in travel distances n other modes did not reflect on the results. Ker and Ginn (2003) had implied that walking distances in urban areas are longer than walked to stations in sub urban areas, as demonstrated from the case of Perth. From the current study, such a conclusion cannot be drawn from the cases selected. Further research needs to be conducted with more types of stations, with more samples in each station type, to enable us to draw conclusive remarks.

5.5 Comparison of results from study 1 and study 2

The results size of influence areas estimated from distance decay analysis and ROC analysis were compared for the DMR network and for the four selected stations. The comparison for distances estimated from distance decay analysis for various modes are given in Table 21. The mean walking distance for Karkardooma, Dwarka mor and Lajpat Nagar indicate an increase of 14%, as estimated for access trips by Ann et al., (2019) for the DMR network. The outer station, Vaishali showed a 29% increase

Comparing the 85th percentile values for walking, these values were in agreement with the value of 1200 - 1400 m estimated by Ann et al. (2019), with Lajpat Nagar slightly smaller distance. The mean distances travelled on informal modes for Karkardooma, Dwarka mor and Lajpat Nagar were 2300, 3100, and 2800 m, respectively, whereas the mean distance suggested by Ann et al., (2019) for informal modes was 2900 m. For the outer city station, Vaishali, the distance was as much as 59% higher than estimated for New Delhi. The 85th percentile distance determined for informal modes in the previous study was 5600 m for informal transit. In study 2, the 85th percentile distances for the three stations within the city boundaries (Karkardooma: 3300 m, Dwarka mor: 4000 m, and Lajpat Nagar: 3700 m) were considerably smaller than estimated for DMR network, although for Vaishali, the distance was 30% higher than the distance estimated for the regions within New Delhi.

For bus and private modes, the stations well within the city, Karkardooma and Lajpat Nagar reported smaller distances than the DMR network. Vaishali and Dwarka mor reported a 26 % increase in mean distance than for DMR network. The 80th and 85th percentile estimates for Vaishali and Dwarka mor were smaller compared to estimate for DMR (access).

Table 21 Comparison of results from distance decay analysis for Study 1 and Study 2

		Study 1		Study 2			
Summary of travel distances (rounded to the nearest 100 m)		Access	Egress	Karkardooma (regional urban center)	Dwarka mor (sub-city)	Lajpat Nagar (central area)	Vaishali (outer city)
Walking	Mean	700	600	800	800	800	900
	80th percentile	1200	1000	1100	1100	1000	1100
	85th percentile	1400	1200	1200	1200	1100	1300
Informal modes	Mean	2900	2600	2300	3100	2800	4600
	80th percentile	4700	4200	3000	3700	3500	6500
	85th percentile	5600	5000	3300	4000	3700	7300
Bus and private modes	Mean	6200	7700	4700	7800	5000	7800
	80th percentile	10,100	12,400	6200	10200	6200	9900
	85th percentile	11,900	14,600	6800	11200	6700	10700

The comparison of estimated distances from the ROC analysis are given in Table 22. The threshold distances at outer stations, Dwarka mor & Vaishali were slightly longer than estimates for DMR (1100 -1200 m).

Table 22 Comparison of results from distance decay analysis for Study 1 and Study 2

	Study 1		Study 2			
ROC analysis	Access	Egress	Dwarka mor (sub city)	Karkardooma (urban regional center)	Lajpat Nagar (central city)	Vaishali (outer city)
Maximum Youden index	−0.757	−0.831	-0.798	-0.575	-0.767	-0.763
Threshold (m)	1200	1100	1300	1200	1200	1300
AUC	0.942	0.933	0.928	0.832	0.939	0.958
Observations N	56	55	26	26	26	36

5.6 Conclusions

In this study, the focus was on the last mile distances travelled to individual stations of the DMR network in New Delhi. The objective was to compare the last mile distances travelled on different modes among stations, and establish the TOD influence zones for the metro stations. The results are aimed at influencing the TOD policy in India and helping create TOD policies that are suited to the urban and transport characteristics in India.

In the primary survey carried out for the study, issues of rounding and heaping were observed, highlighting the issues in data collection for transportation studies in India, where there is already a dearth of sufficient data. The potential bias in the results of the estimation was removed by creating an imputed dataset, which was subsequently used to perform distance decay analysis and ROC analysis for determining the extent of TOD influence areas.

The bell-shaped curve of the compound power exponential form of distance decay was found to be reliable to investigate the decreasing interaction between the distance from the stations and the percentage coverage of passengers. The estimation result of the decay function provided that the extent of the TOD influence area varies with access modes as well as with the location of the station. The mean and the percentile values of the travel distances increase in the order of walking, informal modes, and bus and private modes.

For walking, the difference among stations was not significant implying the willingness to walk does not vary with the location of stations. A further study is expected to investigate whether it is true for all stations or it only comes due to the similar walking environment along the studied stations. The threshold distances estimated using the ROC analysis were in agreement with the 80th- 85th percentile distances for walking. The threshold walking distance for the four stations lies in the range of 1200-1300 m which is close to the result of the general case across all stations in New Delhi (Ann et al.,2019). These distances also indicate that the size of the influence area (500–800 m) specified in the National TOD policy and the Master Plan for Delhi 2021 is extremely conservative.

In the case of informal modes, Vaishali, which is an outer station, corresponded to nearly two times the distance for the other three stations. It means that people who live in the outside of the city usually travel longer distances on informal modes to reach stations compared those who live in the inside of the city.

This variation was also noted when comparing the last mile distances for bus and private modes. Dwarka mor (sub-city station) and Vaishali (outer city station) corresponded to larger distances compared to those of the other two stations situated in the core urban areas of New Delhi. The mean distances and the 85th percentile distances for Dwarka mor and Vaishali are nearly twice as much as those for Karkardooma and Lajpat Nagar.

It can thus be concluded that variations are present in the last mile distances among stations. Although the walking distances did not vary considerably among stations, large variations were observed when other modes were compared. The outer city station, Vaishali, exhibited longer distances for informal modes, buses, and private modes, which illustrates that to access such metro stations, commuters tend to travel longer distances on motorized modes. Therefore, when considering multimodal accessibility and multimode-based TOD, these differences in accessibility must be taken into account.

The study provides insights into the last mile patterns for four DMR stations, and the extent of influence area for each mode was calculated. The results are not the same across the selected stations; however, they are not considerably different either. Further research needs to be conducted across more station types to arrive at a conclusive remark regarding the size of influence areas for specific station types. The study also needs to be extended for different cities and for different main modes such as bus rapid transit systems, sub-urban rail systems). The research considered buffer analysis, however it non uniform demand was considered across the buffer. Spatial analysis needs to carried out to understand the actual distances travelled by commuters.

The practical implication of this research is that it provides input for TOD planning; policy recommendations can be formulated which can lead to an increased size of influence area in Indian cities. This consideration of a wider influence area can extend the benefits of TOD over a larger area. This can ensure the incorporation of current transit users into TOD planning. The consideration of various modes, especially informal modes can lead an inclusive planning practice which is much needed in India. Improved infrastructure over the actual influence area for walking and informal modes can be thus provided and this would lead to increased accessibility to public transit.

CHAPTER 6 - CONCLUSIONS

6.1 Summary

The literature review chapter, highlighted the non-consensus existing regarding the size of TOD influence areas. The commonly adapted standards have been challenged by researchers and new size of influence areas have been estimated in various studies for various cities, depending on type of access modes and type of main mode. Evidently, a single influence zone size is not suitable for all cases. Because there is no consensus among researchers on whether the half-mile radius is the appropriate distance for catchment areas, such a criterion should be carefully examined in the planning of TODs in Indian cities. In light of the TOD policy in India, it is imperative that the size of TOD influence zones be determined for Indian cities. In most Indian cities, mobility patterns vary compared with those of developed countries. The multitude of various types of last mile connectivity modes and the difference in willingness to walk between cities in developed and developing countries have to be considered before adopting standards formulated for developed countries in countries like India. Accordingly, it is proposed that the local characteristics of cities be carefully studied in relation to the influence zone of the TODs. Moreover, it is not advisable for cities in India to consider only the walk-based TODs. This is because last-mile travel patterns are multimodal. Therefore, these modes need to be taken into consideration in the design of TOD.

In addition to estimating the TOD influence zones for New Delhi, the thesis also highlights the rounding issue associated with data obtained from surveys. The study employed MI to remove the rounding and heaping bias; it was shown that the imputed data provided better results than compared to raw data when used for analysis.

The multimodal nature of last mile connectivity in New Delhi was considered and the influence area for metro stations across the city was estimated for each mode using distance decay and ROC analysis in Chapter 4. The estimated distance by decay analysis showed different values for different modes. Distance decay analysis showed that the current TOD strategies, while it specifies 500 m for the influence area, can only cover 50%

of the current transit passengers who walk to stations (i.e., 20% of total transit passengers since only 40% of transit passengers walk to stations), and cover very few of the passengers who travel by other modes. This means that almost 80% of current transit passengers would be excluded from the TOD target area. While the distance decay function was used to estimate the distances based on percentile values, ROC analysis was used to estimate the threshold walking distances. This analysis takes into account the distances travelled by modes (passive modes) other than walk and gives the threshold distances based on tradeoff between walk and the passive modes. The threshold value was 1200 m for access and 1110 m for egress, which is consistent with the results of the 80th percentiles of decay analysis. This implies that most passengers are willing to walk longer distances to access transit stations than what is mentioned in the current TOD guidelines for India and the standards adopted by MPD-2021 for New Delhi. The analysis did not however take into account the difference in size of influence areas based on station types and it need to be checked whether the generic size of influence area estimated for New Delhi would be suited for specific stations.

Chapter 5 focused on the last mile distances travelled to individual stations of the DMR network in New Delhi. This part study intended to compare the last mile distances travelled on different modes between stations and with the distances estimated by Chapter 4 (Ann et al. (2019)) for New Delhi and come up with TOD influence zones for metro stations. The survey carried out to collect last mile distances for the four stations also faced issued of heaping and rounding. Hence, multiple imputation was employed to create a imputed database to obtain unbiased results. Analysis employed an improved form of the distance decay function as the exponential form used in chapter 4 was not suited to explain the data for the various stations. A compound form of the exponential distance decay function was used to explain the decaying interaction between the distance to stations and the coverage of passengers and to estimate the percentile distances. The estimation result of decay function gives the mean walking distance as 800 m for Karkardooma and Lajpat Nagar and Dwarka mor and 900 m for Vaishali. This shows a 14% and 29% increase in the mean walking distance as estimated by Ann et.al (2019) for New Delhi. Using the 85th percentile distance, to define the catchment areas for transit stations the size of the influence area was assessed to be 1200, 1200, 1100, and 1300 m for Karkardooma, Dwarka mor, Lajpat nagar and Vaishali respectively, which is comparable to 1200 - 1400 m estimated by Ann et al. (2019). The mean distances for Karkardooma, Dwarka mor, Lajpat Nagar and Vaishali was 2300, 3100, 2800, and 4600 m respectively, whereas the Ann et al. (2019) gives a mean distance of 2900 m for informal modes. The 85th percentile distances determined for informal modes in the earlier study was 5600 m for informal transit, and in this study the 85th percentile distances for the three stations within the city boundaries (Karkardooma – 3300 m, Dwarka mor – 4000 m and Lajpat Nagar – 3700 m) was much smaller, whereas for Vaishali, the distance was 30% higher than the distance estimated for New Delhi. The mean distances for bus and private modes for Karkardooma, Dwarka mor, Lajpat Nagar and Vaishali were estimated to as 4700, 7800, 5000 and 7800 m respectively and the estimated 85th percentile distances were 6800, 11200, 6700 and 10700 m respectively. The threshold distances estimated with ROC analysis, are in tune with 85th percentile distances for walking. The threshold walking distance for Dwarka mor and Vaishali was 1300 m and for Karkardooma and Lajpat Nagar was 1200 m. Ann et al. (2019) had given the threshold distance for access and egress for metro stations New Delhi in the range of 1100 -1200 m.

The last mile distances estimated by Ann et al. (2019) give a generic estimation and can be used as a guideline for deciding extent of influence zone areas for stations well within the city limits. However, it can be concluded that there are variations in last mile distances between stations. Walking distances (mean and 85th percentile) between individual stations did not vary much between stations, however while comparing other modes large variations were observed. The outer station, Vaishali exhibited longer distances for informal modes, bus and private modes. This illustrates that in such stations, commuters tend to travel longer distances on motorized modes to access metro stations. Therefore, while considering multimodal accessibility and multimode based TODs, these differences in accessibility needs to be taken into account.

The study gives insights to the last mile patterns of DMR network and for a few DMR stations and the extent of influence area based on different last mile modes were calculated. The results are not the same across the selected stations but they are not very different. Further research needs to be conducted across more station types to arrive at a conclusive remark regarding size of influence areas for specific station types. Also, the variation in influence areas with regard to different types of informal modes should be examined separately. The study can be extended to other cities in India to understand variations if any in the influence areas for metro rail and bus rapid transit systems. The current study did not take into consideration the correlation between access and egress modes, this need to take into account in the future study. It is also advised to carry out a spatial analysis to overcome the limitations of buffer analysis for estimating size of influence areas and to determine the actual distances (as per road length) traveled by commuters. However, the current study did employ a non-uniform demand over the buffer zone by taking account distance decay function.

The results are aimed at influencing the TOD policy in India and helping create TODs that is suited to Indian urban and transport characteristics. The research provides valuable input for TOD planning, especially for policy recommendations which can increase size of influence areas. This can lead to development of TOD plans which consider a wider influence area, extending the benefits of TOD over a larger area and incorporating current transit users into TOD planning. It can lead to inclusive planning by considering various access modes, especially informal modes. The resultant improved infrastructure over the actual influence area for walking and informal modes will be a boon for transit commuters and improving the attractiveness of public transit.

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APPENDIX 1

Cross table showing relation between access and egress modes

Access modes	Egress modes					Sample size
	Walking	Informal modes	Bus	Private modes	Bicycle	
Walking	71%	21%	5%	2%	1%	364
Informal modes	55%	36%	6%	3%	0%	343
Bus	49%	20%	31%	1%	0%	107
Private modes	54%	22%	6%	16%	2%	99
Bicycle	53%	21%	5%	0%	21%	14
Sample size	473	269	81	26	12	

APPENDIX 2

Format of the questionnaire used for carrying out survey of commuters at Karkardooma, Dwarka mor, Lajpat Nagar and Vaishali stations

Survey of metro and non-metro Users

Disclaimer: The surveys are being conducted by solely for research and academic purpose. Privacy of data is ensured

Part of research conducted for academic purpose by Nagoya University

Name of surveyor: Metro station: Date:

Survey no: Time of survey:

1. Gender of commuter: Male / Female

I: Trip information

2. What is your origin and destination station? **Origin**: _________ **Destination**: _______

3. What is your ticket type: **Smart card user □** **Token user □**

4. What is the purpose of carrying out this trip:

Work related	Education	Shopping	Recreation / Leisure	Social (visiting relatives/friends)	Health related
Other:________					

5. What is the distance from your trip start point to origin metro station? _____________meters

6. What are the various mode options available to you to reach the origin metro station?

Tick the options available	**NMT**	**Time**	
□	Walk		
□	Bicycle		
	Public Transport/ Para transit/ Feeder	**Time**	**Fare**
□	Cycle rick		
□	Shared auto-rick		
□	Grameen Seva		
□	E-rick		

◻	Auto rick		
◻	Bus		
◻	Metro feeder bus		
◻	Company vehicle		
◻	If other, specify ____________________		
	Personal Transport	**Time**	**Cost**
◻	2-wheeler		
◻	Car		
	If other, specify _________________		

7. Which one do you use and which are your other two preferred alternatives?

Preferred option: ____________________

Alternative 1: ___________________ Alternative 2: ___________________

8. What is the distance from the destination metro station to your end destination? _____________meters

9. What are the various mode options available to you to reach the end destination from your destination metro station?

Tick the options available	**NMT**	**Time**	
◻	Walk		
◻	Bicycle		
	Public Transport/ Para transit/ Feeder	**Time**	**Fare**
◻	Cycle rick		
◻	Shared auto-rick		
◻	Grameen Seva		
◻	E-rick		
◻	Auto rick		
◻	Bus		
◻	Metro feeder bus		
◻	Company vehicle		
◻	If other, specify ____________________		
	Personal Transport	**Time**	**Cost**
◻	2-wheeler		
◻	Car		

If other, specify ________________		

10. Which mode do you use and which are your other two preferred alternatives?

Preferred option: ____________________

Alternative 1: ___________________ Alternative 2:___________________

II: Personal information

11. Name (*optional*): ____________________**;** Mobile no. / Email (*optional*): ________________

12. Age:

<=18 years 19-29 years 30-39 years 40-60years Above 60 years

13. What is your occupation?

Student	Working			Retired	Unemployed	Housewife	____________ Other *(specify)*
	Private service	Govt. service	Self-employed - like business, professional, freelancer, etc.				

14. What is your educational level?

High school/ higher secondary	Diploma	Bachelors (arts)	Bachelors (professional)	Masters	Above masters

15. What is your individual monthly income?

I don't earn	Less than Rs 10,000	Rs 10,000-30,000	Rs 30,000-50,000	Rs 50,000-1,00,000	More than Rs 1,00,000

16. What is your total monthly family income?

I don't earn	Less than Rs 10,000	Rs 10,000-30,000	Rs 30,000-50,000	Rs 50,000-1,00,000	More than Rs 1,00,000

17. Are you a driving license holdee? **Yes** □ **No** □

18. What is your household vehicle ownership?

No. of cars _________; No. of two-wheelers __________; No. of bicycles ________

III: User's preferences and choices

19. For what distance/ time are you willing to travel from home to metro station or work from the metro station?

WALK ______________ INFORMAL______________ BUS _____________ PRIVATE ______________

20. On a 3-point rating scale, to what extent did each of the following factors influence your decision to use a particular mode for access/ egress for this trip? (1=no influence, 2=moderate influence, 3= Strong influence)

a) Time taken

1	2	3
No influence	Moderate influence	Strong influence

b) Distance from metro

1	2	3
No influence	Moderate influence	Strong influence

c) Easy availability/ Frequency

1	2	3
No influence	Moderate influence	Strong influence

d) Cost/ fare

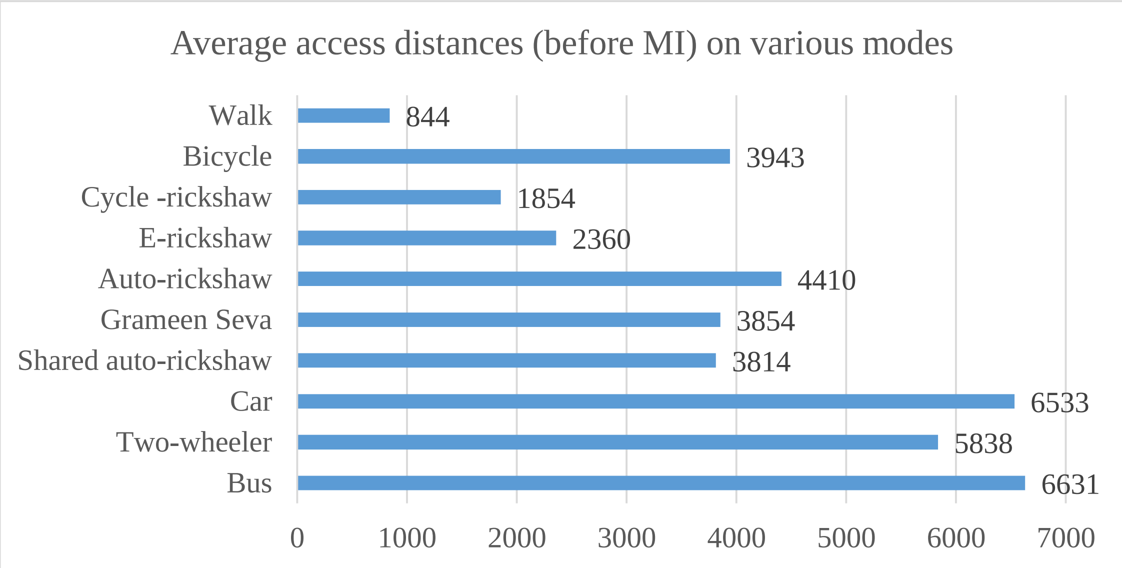
1	2	3
No influence	Moderate influence	Strong influence

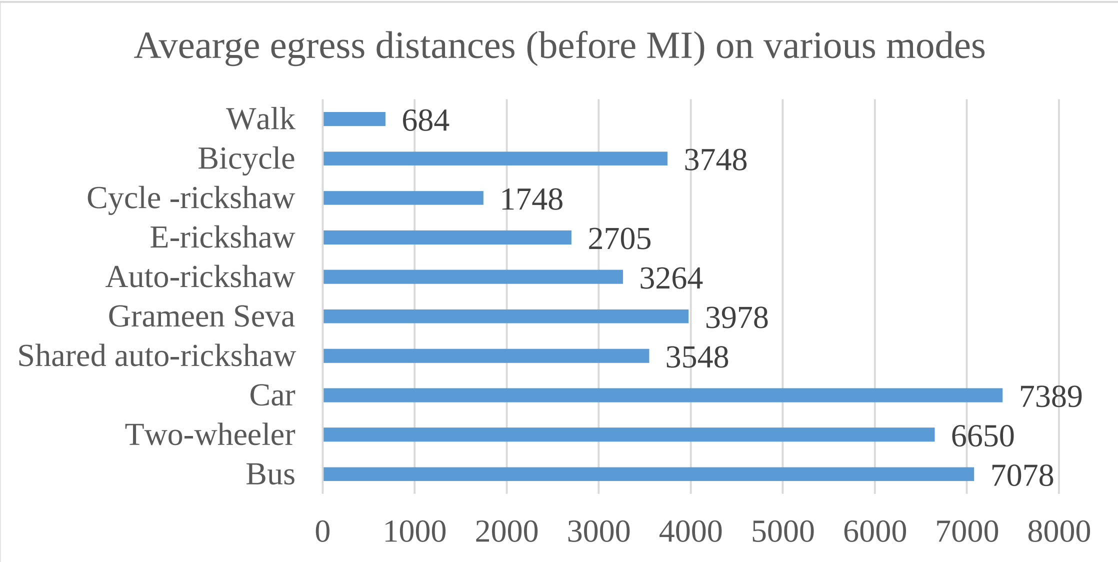
e) Safety

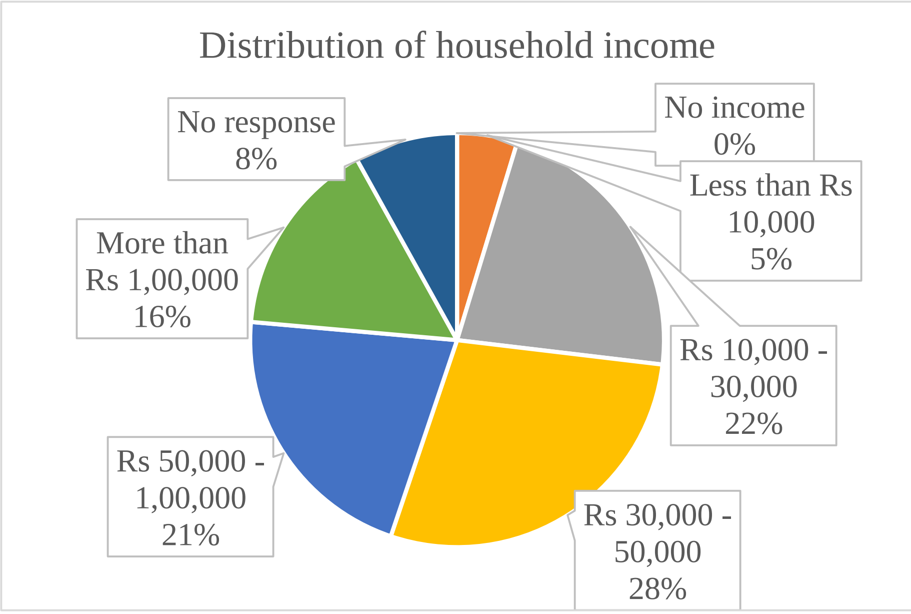
1	2	3
No influence	Moderate influence	Strong influence

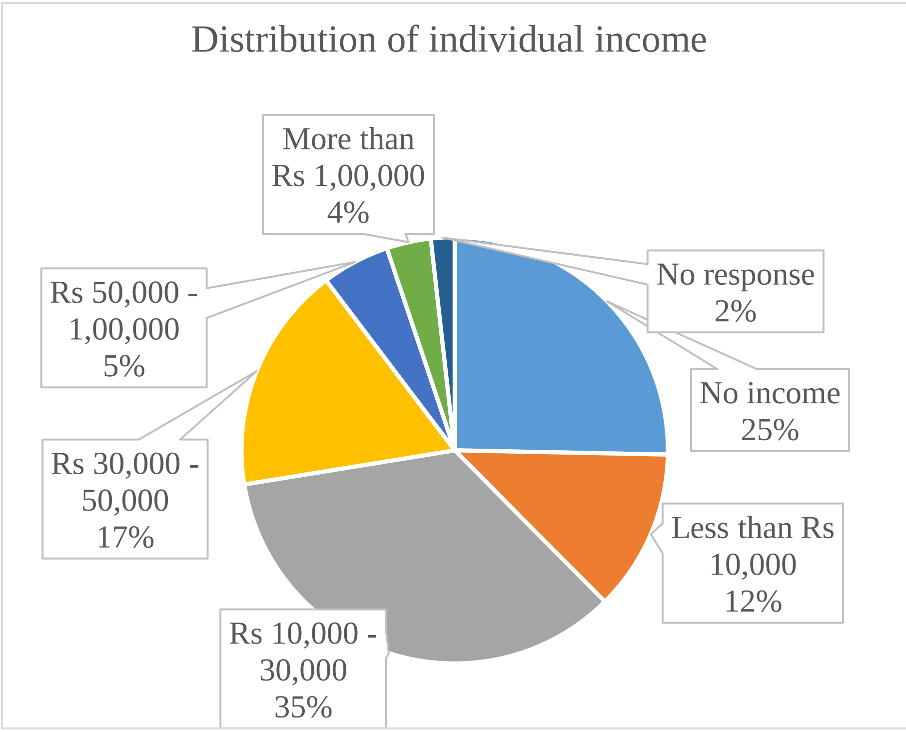
APPENDIX 3

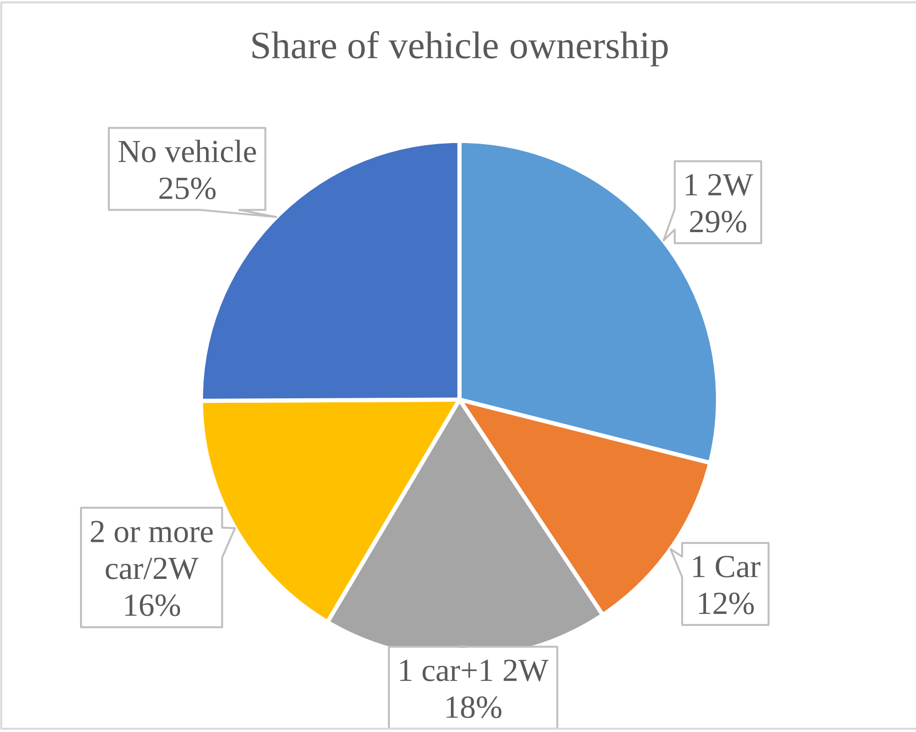
Descriptive analysis of raw data collected from DMRC for Study 1.

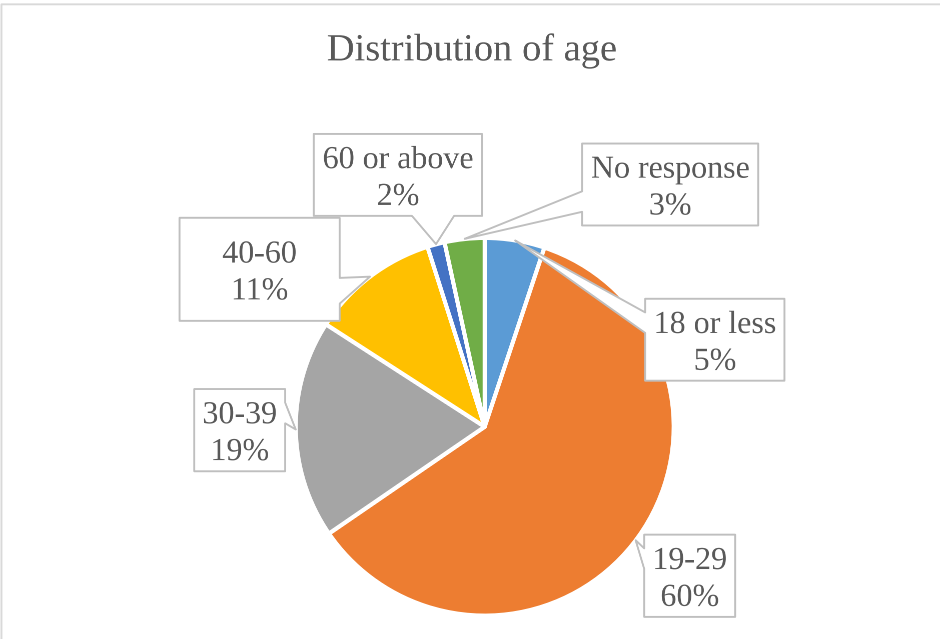


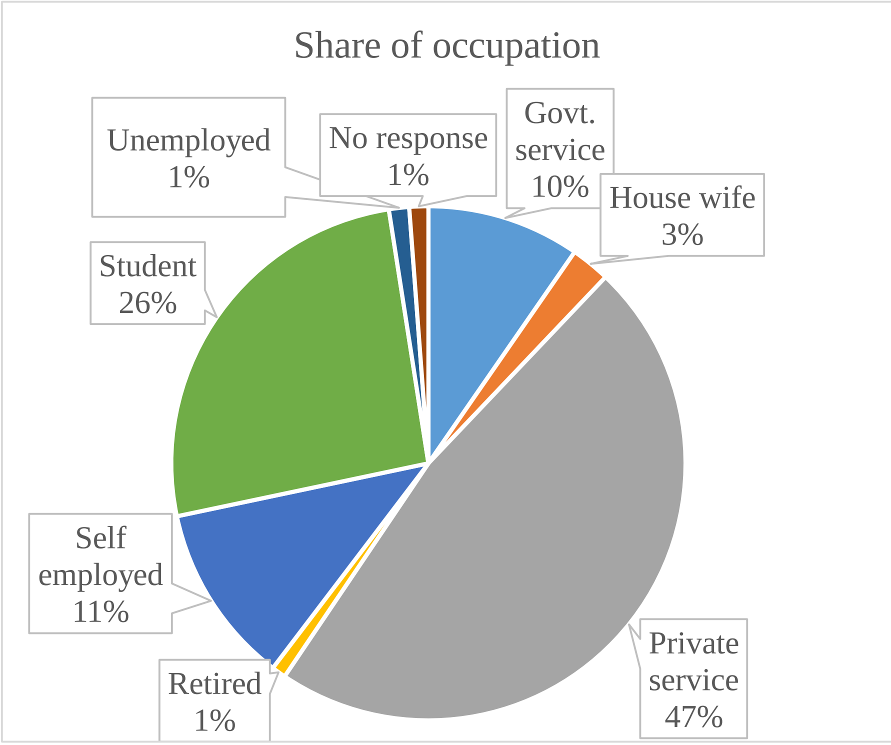


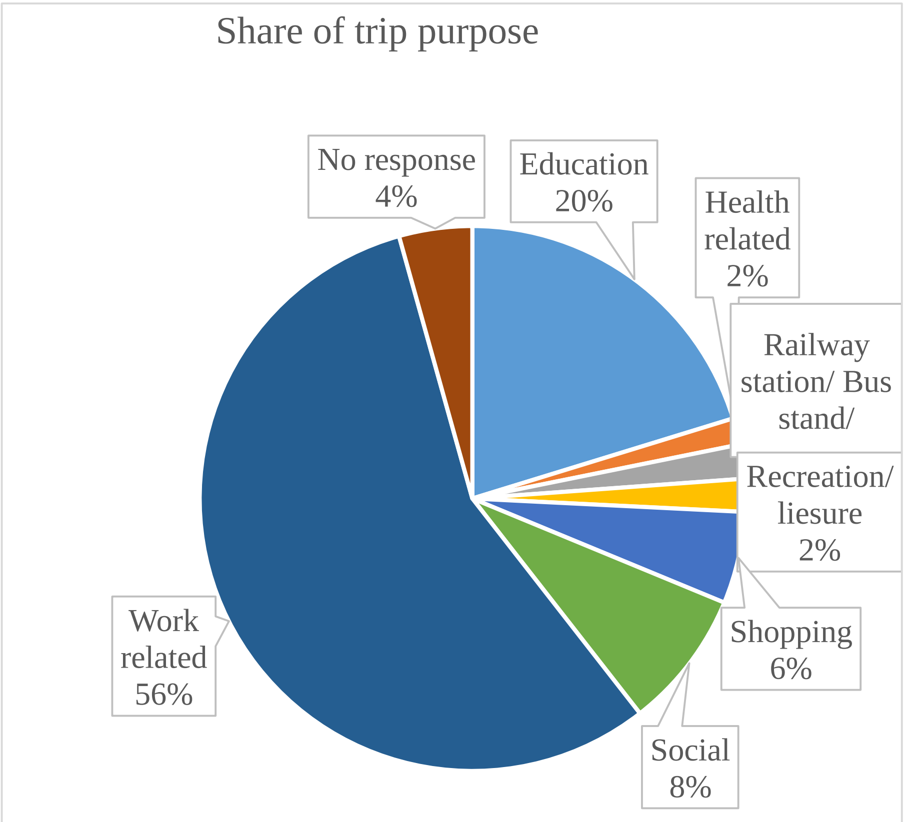

Distribution of household income
No income
0%
Less than Rs
10,000
5%
Rs 10,000 -
30,000
22%
Rs 30,000 -
50,000
28%
Rs 50,000 -
1,00,000
21%
More than
Rs 1,00,000
16%
No response
8%


Distribution of individual income
More than
Rs 1,00,000
4%
No response
2%
No income
25%
Less than Rs
10,000
12%
Rs 10,000 -
30,000
35%
Rs 30,000 -
50,000
17%
Rs 50,000 -
1,00,000
5%


Share of vehicle ownership
No vehicle 25%
1 2W 29%
1 Car 12%
1 car+1 2W 18%
2 or more car/2W 16%

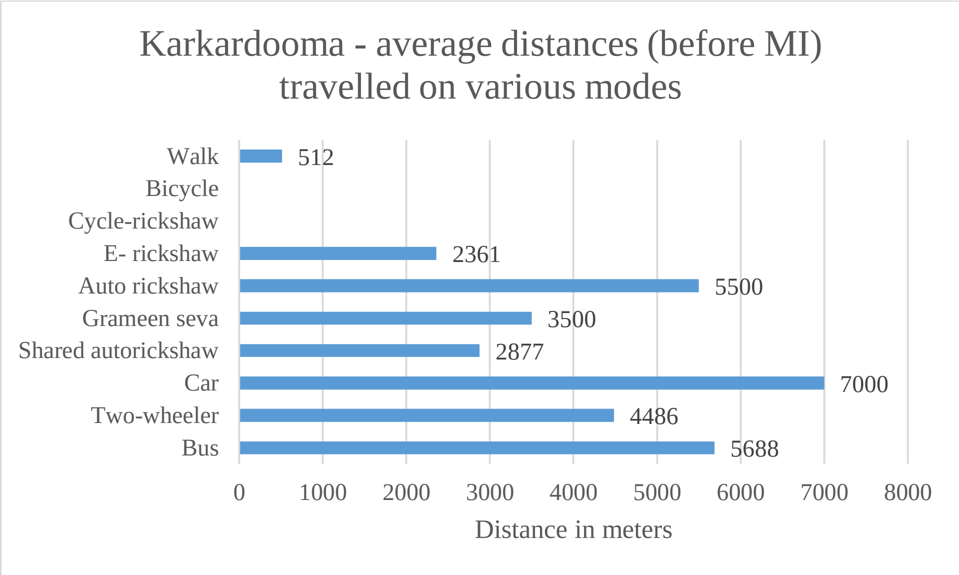

Distribution of age
60 or above 2%
No response 3%
40-60 11%
18 or less 5%
30-39 19%
19-29 60%

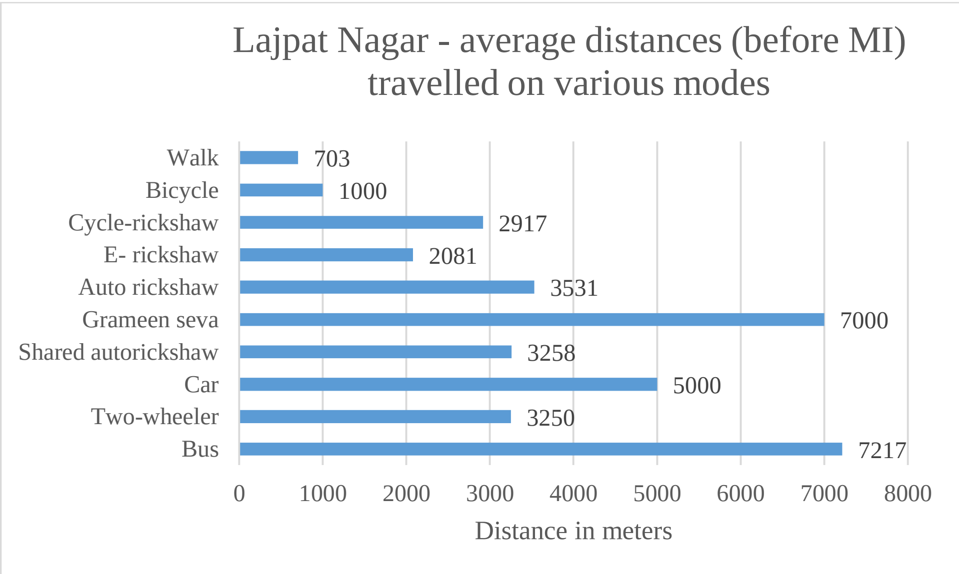

Share of occupation
Unemployed 1%
No response 1%
Govt. service 10%
House wife 3%
Student 26%
Self employed 11%
Retired 1%
Private service 47%

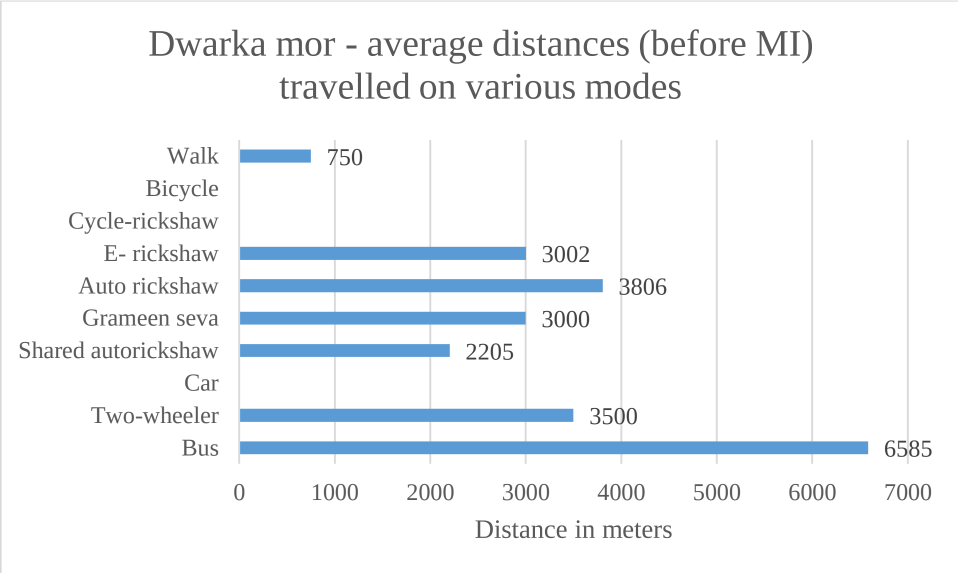

Share of trip purpose
No response 4%
Education 20%
Health related 2%
Railway station/ Bus stand/
Recreation/ liesure 2%
Shopping 6%
Social 8%
Work related 56%

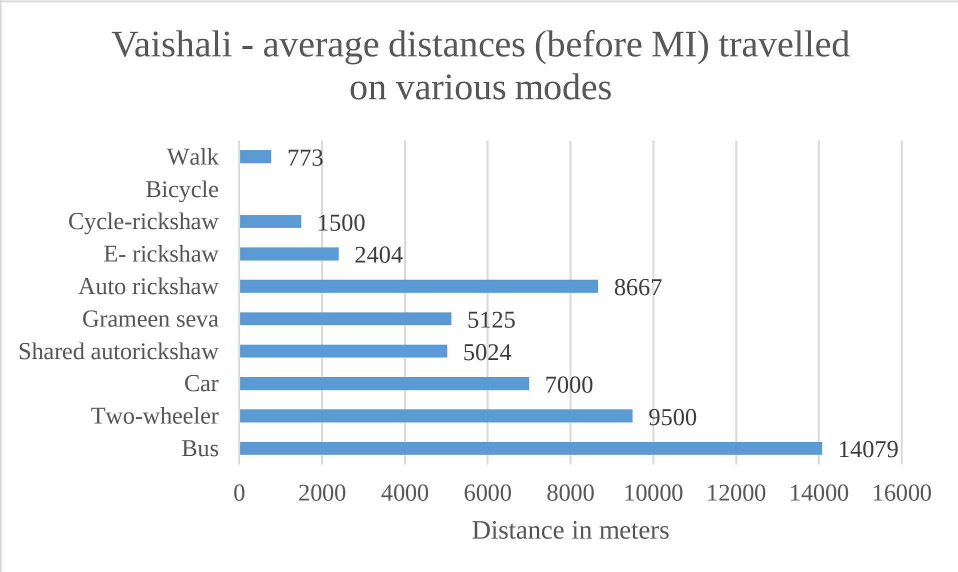
APPENDIX 4

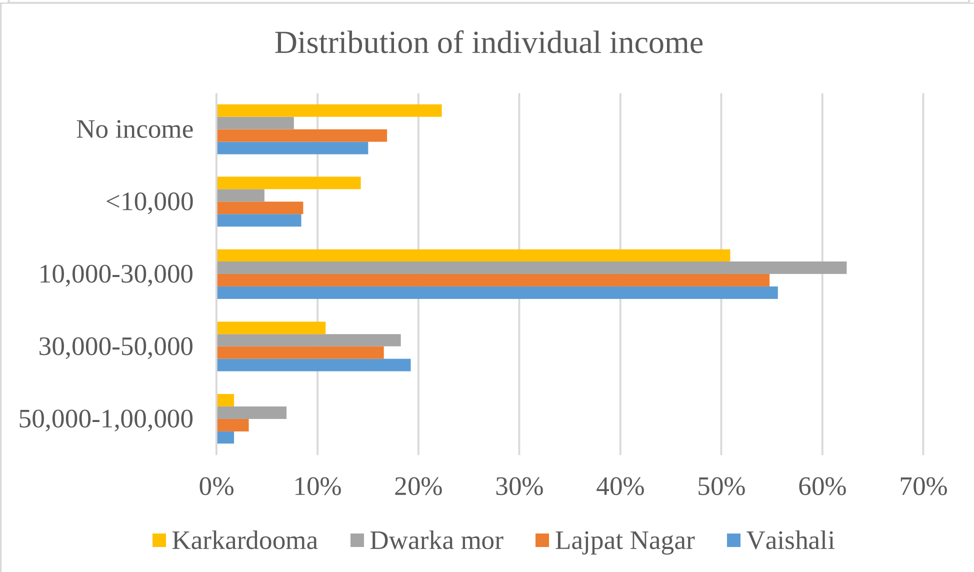
Descriptive analysis of raw data collected from various stations for Study 2

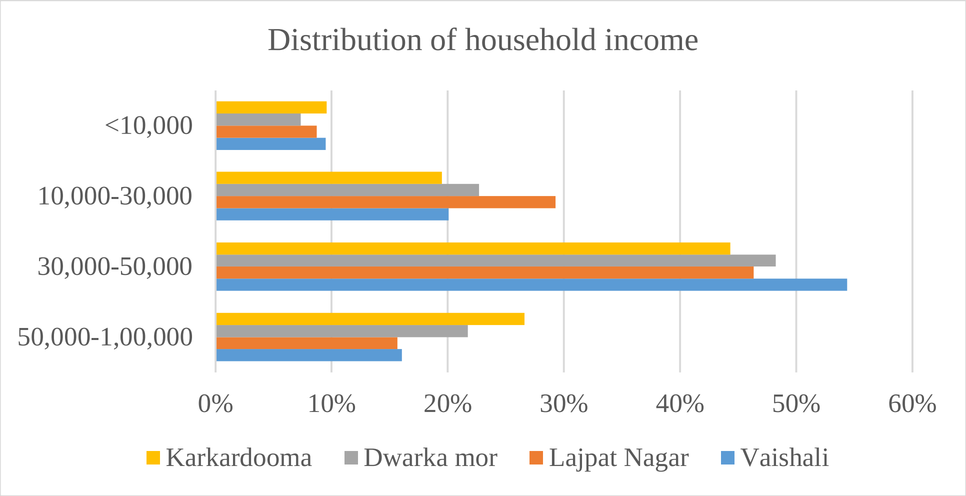


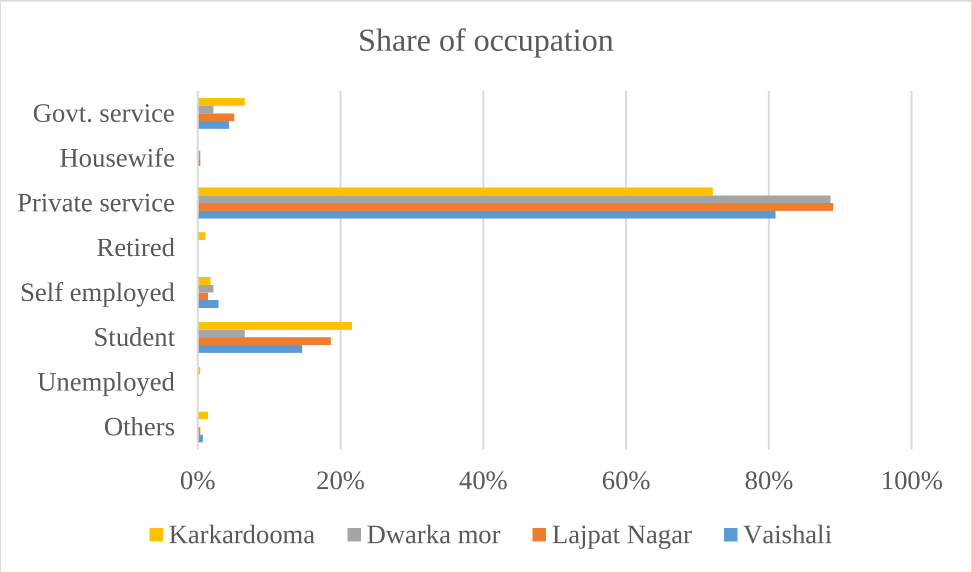


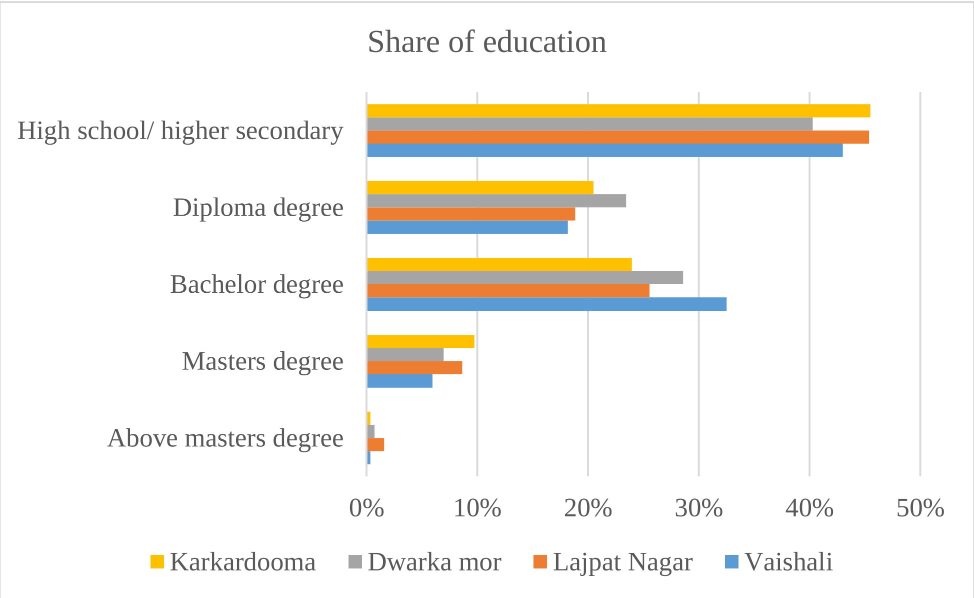

Dwarka mor - average distances (before MI) travelled on various modes
Walk
Bicycle
Cycle-rickshaw
E- rickshaw
Auto rickshaw
Grameen seva
Shared autorickshaw
Car
Two-wheeler
Bus
750
3002
3806
3000
2205
3500
6585
0
1000
2000
3000
4000
5000
6000
7000
Distance in meters

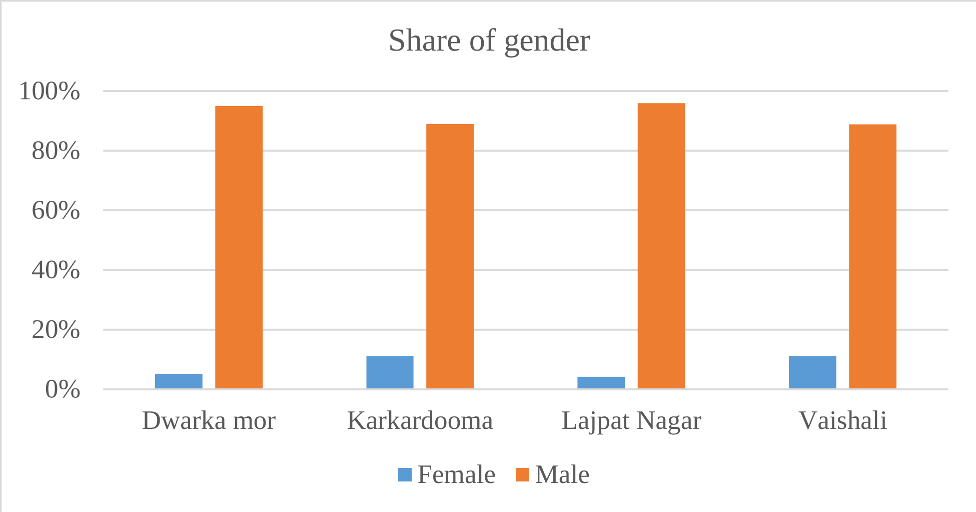

Vaishali - average distances (before MI) travelled on various modes
Walk
Bicycle
Cycle-rickshaw
E- rickshaw
Auto rickshaw
Grameen seva
Shared autorickshaw
Car
Two-wheeler
Bus
773
1500
2404
8667
5125
5024
7000
9500
14079
0
2000
4000
6000
8000
10000
12000
14000
16000
Distance in meters


Distribution of individual income
No income
<10,000
10,000-30,000
30,000-50,000
50,000-1,00,000
0%
10%
20%
30%
40%
50%
60%
70%
Karkardooma
Dwarka mor
Lajpat Nagar
Vaishali

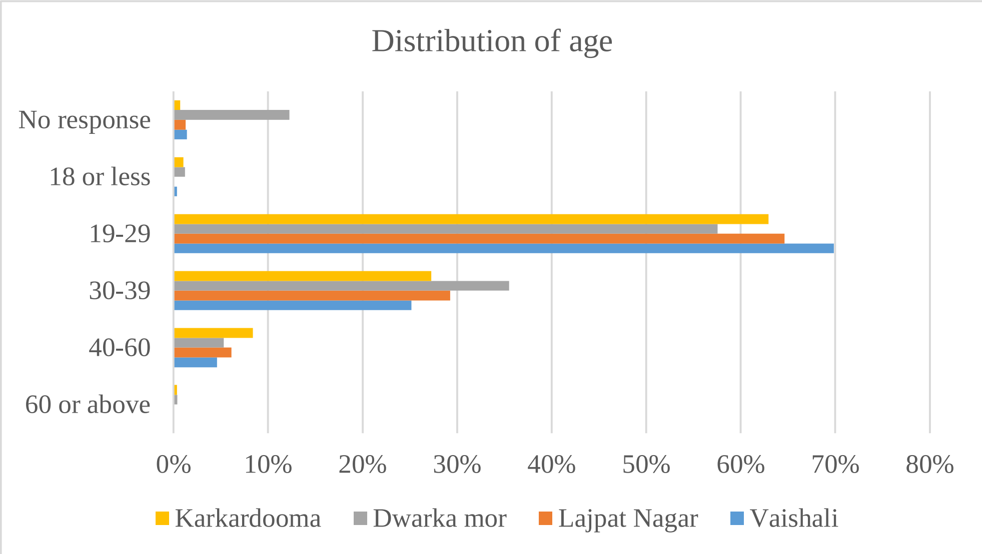

Distribution of household income
<10,000
10,000-30,000
30,000-50,000
50,000-1,00,000
0%
10%
20%
30%
40%
50%
60%
Karkardooma
Dwarka mor
Lajpat Nagar
Vaishali


Share of occupation
Govt. service
Housewife
Private service
Retired
Self employed
Student
Unemployed
Others
0%
20%
40%
60%
80%
100%
Karkardooma
Dwarka mor
Lajpat Nagar
Vaishali

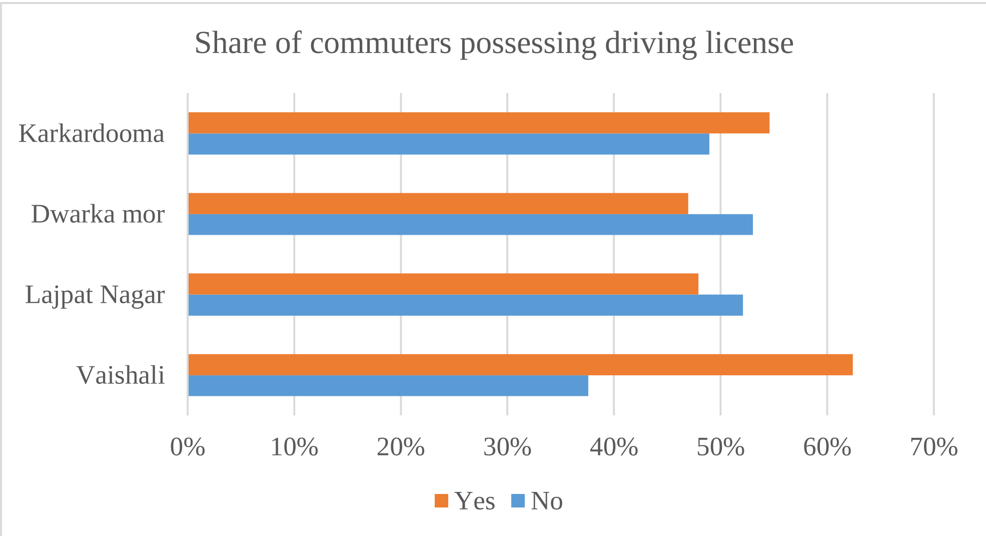

Share of education
High school/ higher secondary
Diploma degree
Bachelor degree
Masters degree
Above masters degree
0%
10%
20%
30%
40%
50%
Karkardooma
Dwarka mor
Lajpat Nagar
Vaishali



Share of gender
100%
80%
60%
40%
20%
0%
Dwarka mor
Karkardooma
Lajpat Nagar
Vaishali
Female
Male



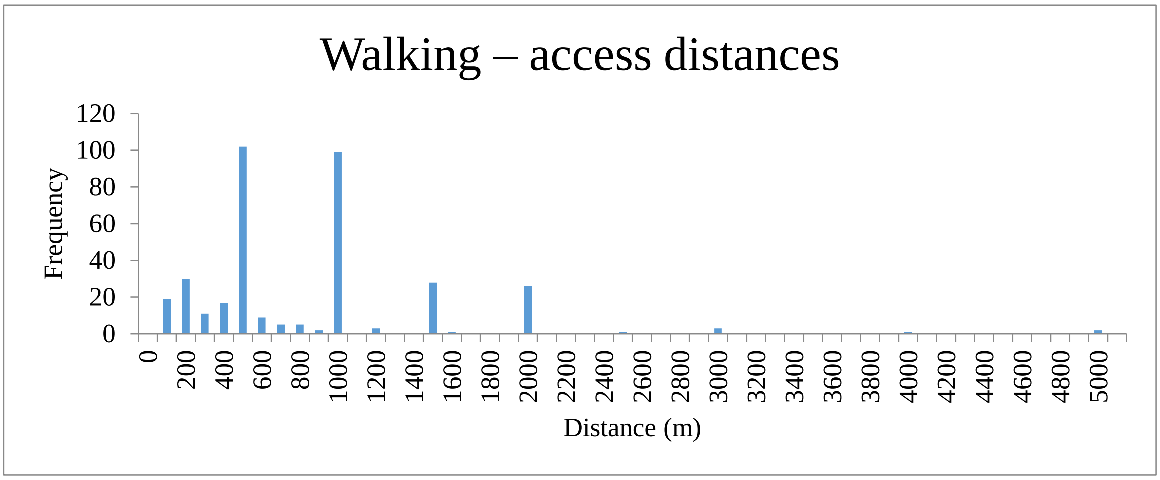
Distribution of age
No response
18 or less
19-29
30-39
40-60
60 or above
0%
10%
20%
30%
40%
50%
60%
70%
80%
Karkardooma
Dwarka mor
Lajpat Nagar
Vaishali

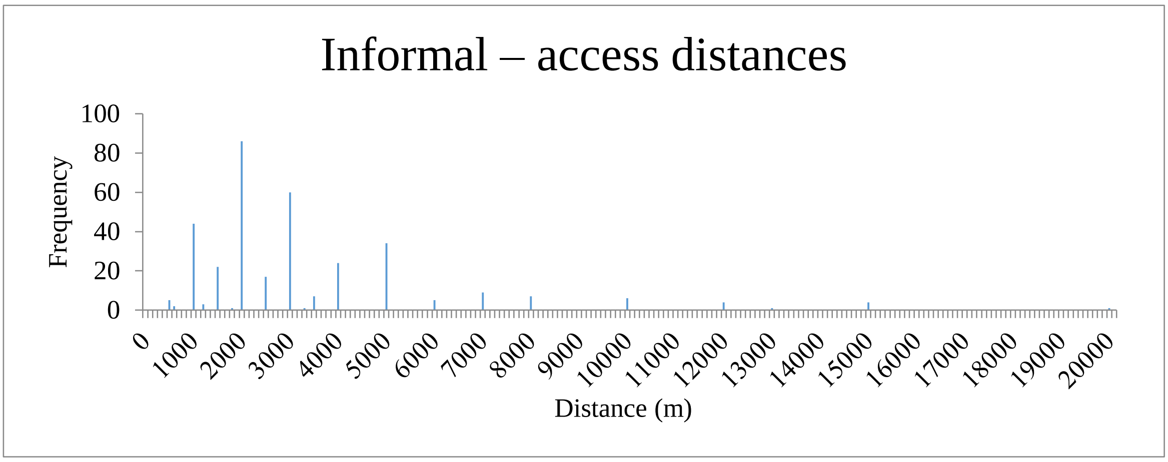


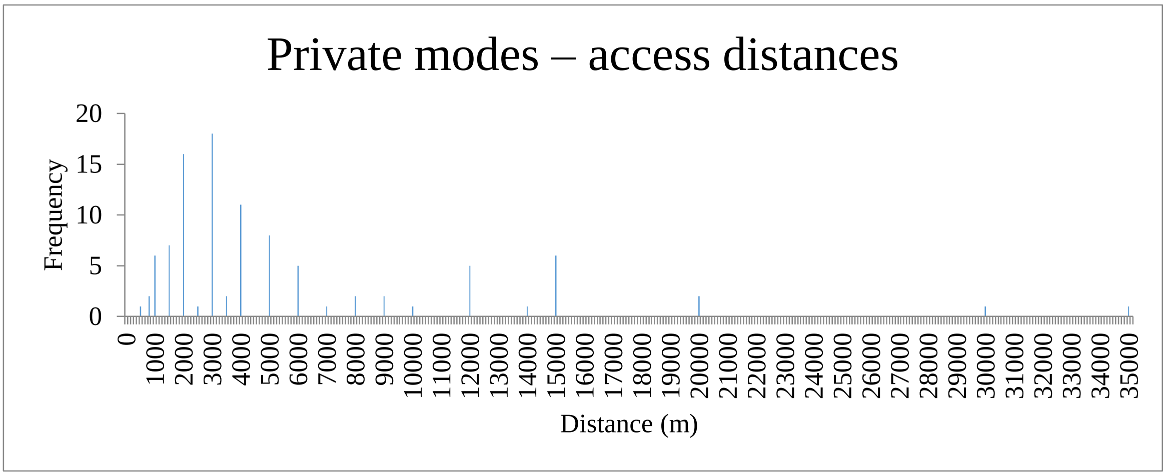
Share of commuters possessing driving license
Karkardooma
Dwarka mor
Lajpat Nagar
Vaishali
0%
10%
20%
30%
40%
50%
60%
70%
Yes
No

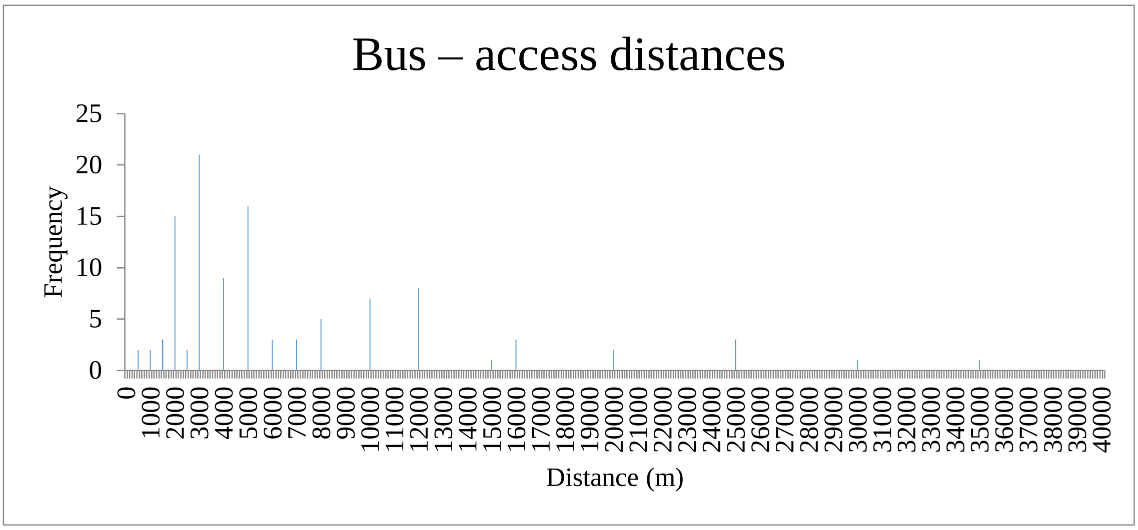
APPENDIX 5

Histogram of reported distances for different modes for access (Study 1)

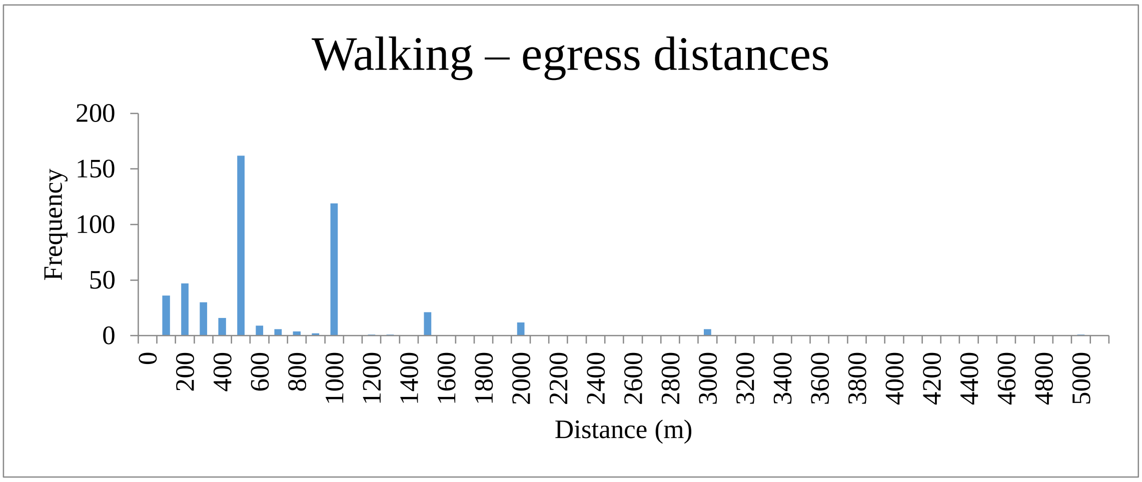


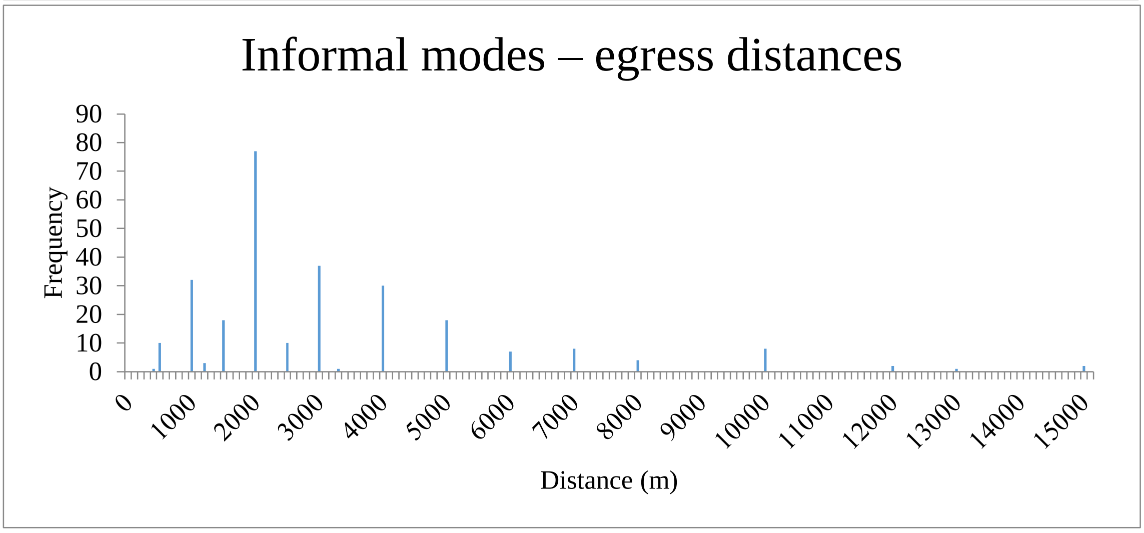


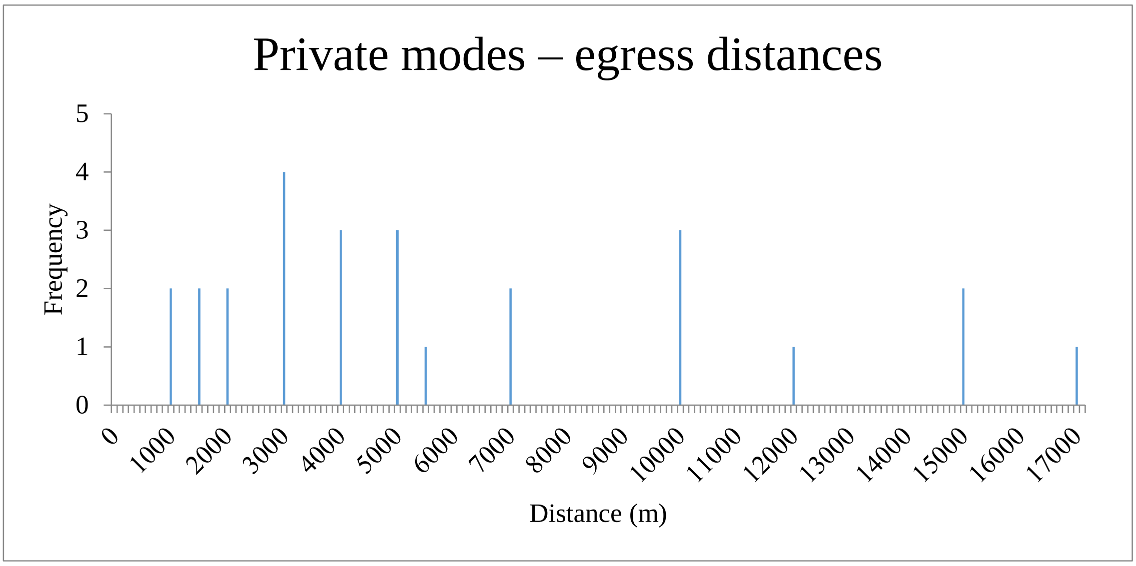


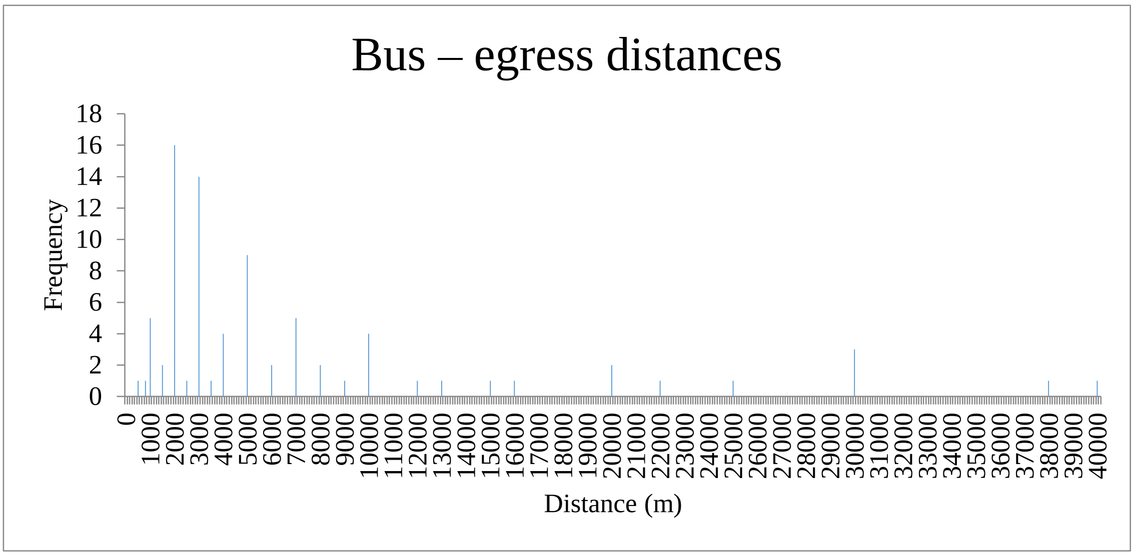


Histogram of reported distances for different modes for egress (Study 1)



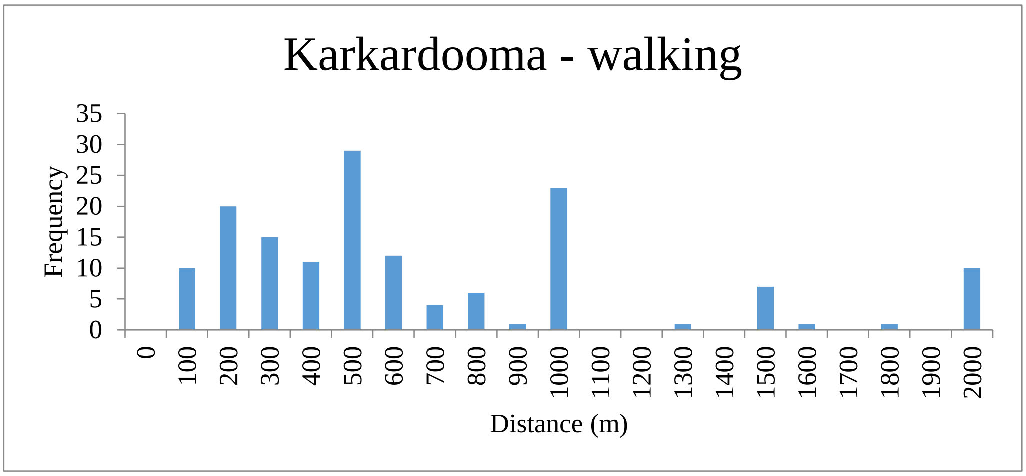


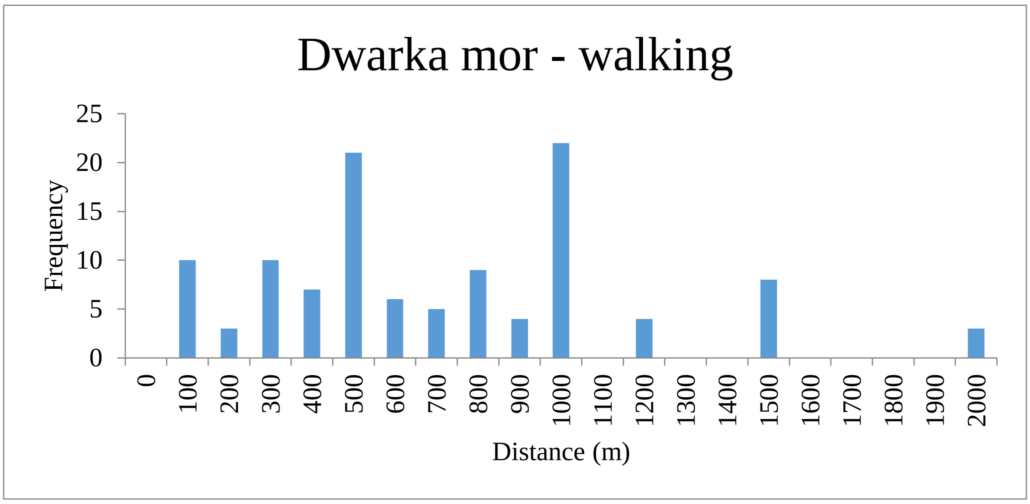

Private modes – egress distances
Frequency
0
1
2
3
4
5
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
Distance (m)

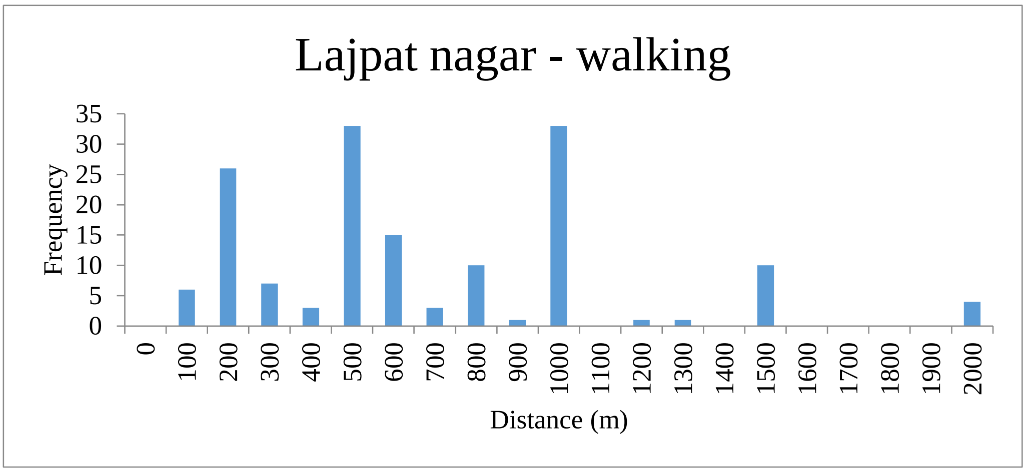

Bus – egress distances
Frequency
0
2
4
6
8
10
12
14
16
18
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
20000
21000
22000
23000
24000
25000
26000
27000
28000
29000
30000
31000
32000
33000
34000
35000
36000
37000
38000
39000
40000
Distance (m)

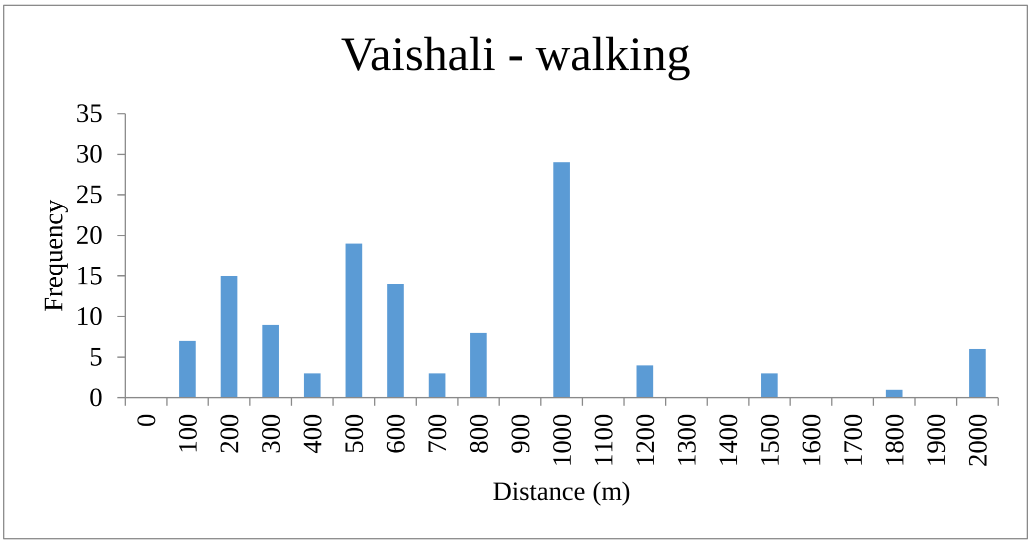
APPENDIX 6

Histogram of reported distances for different stations – walking (Study 2)

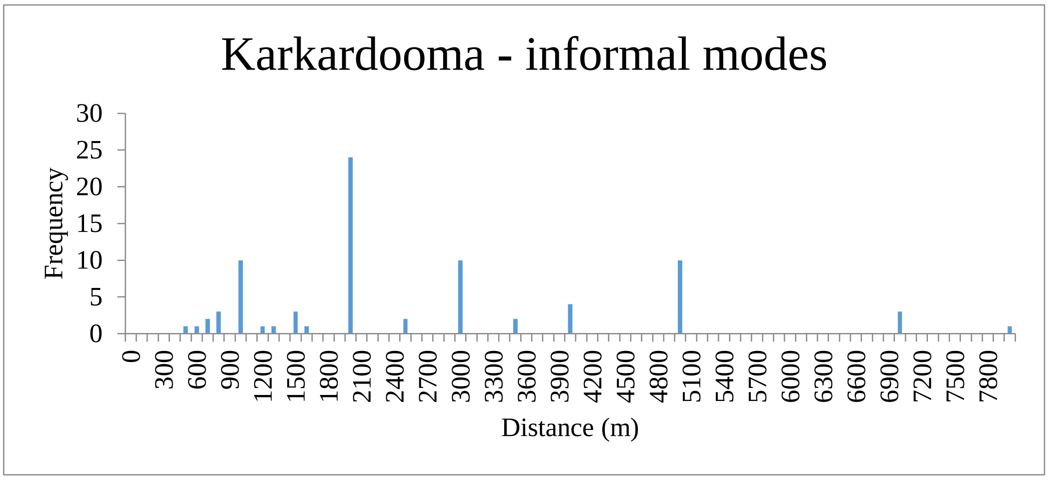


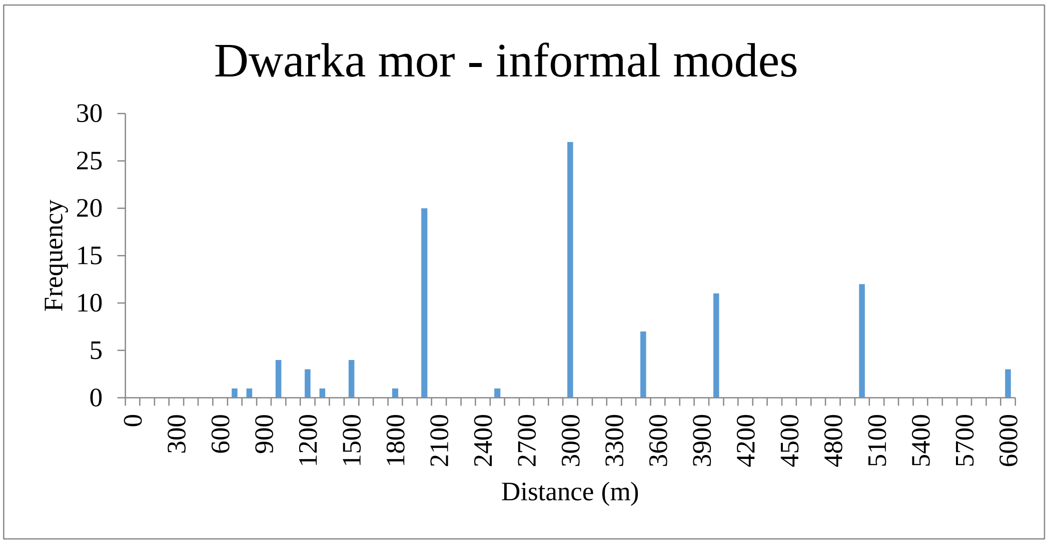


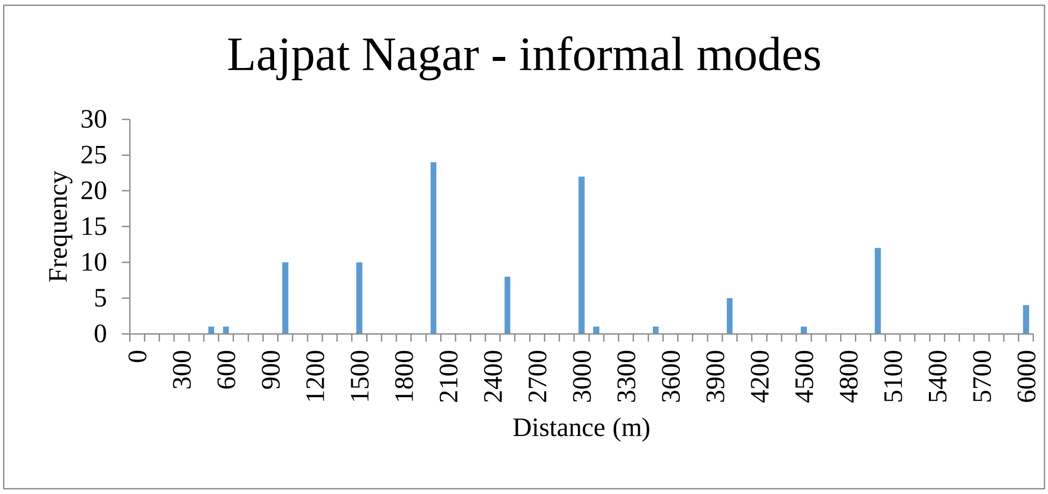


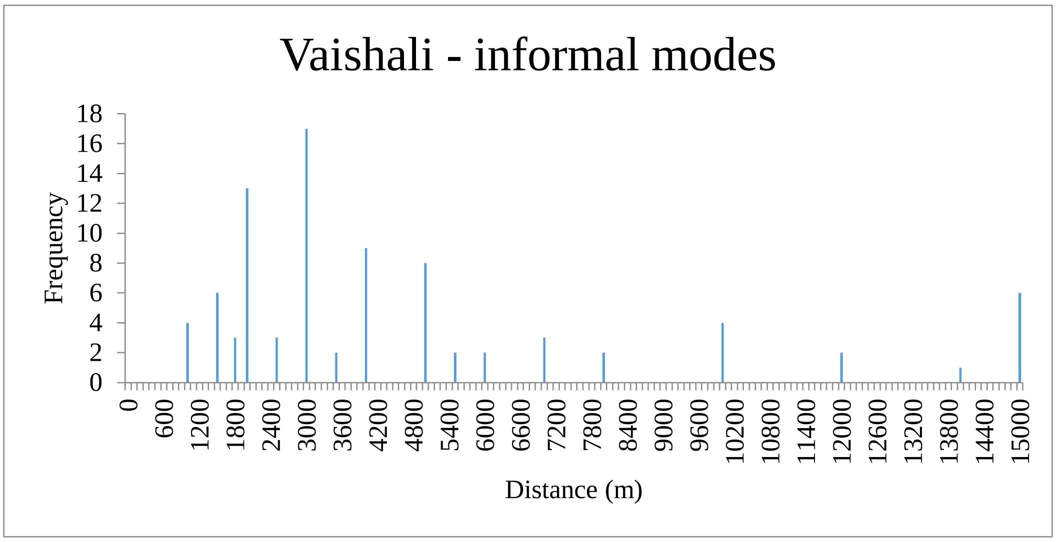


Histogram of reported distances for different stations – informal modes (Study 2)

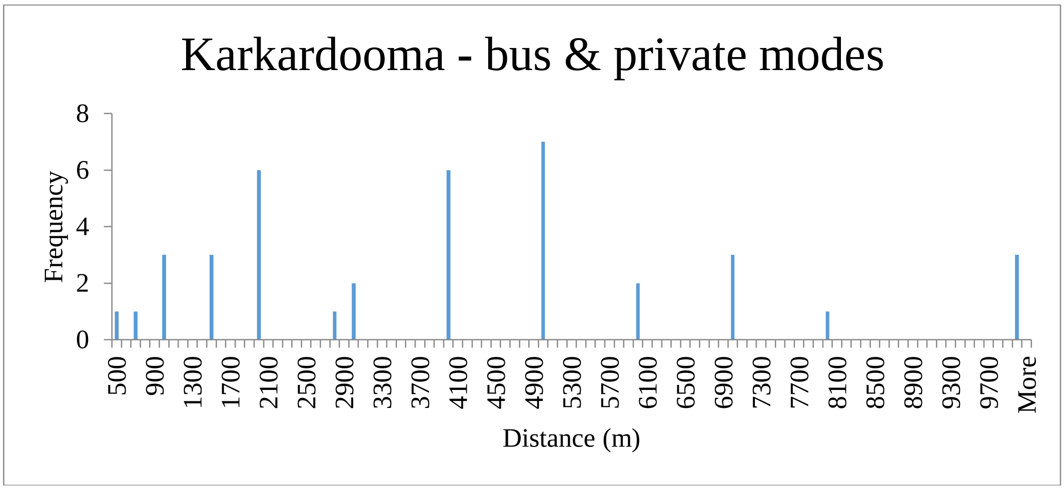


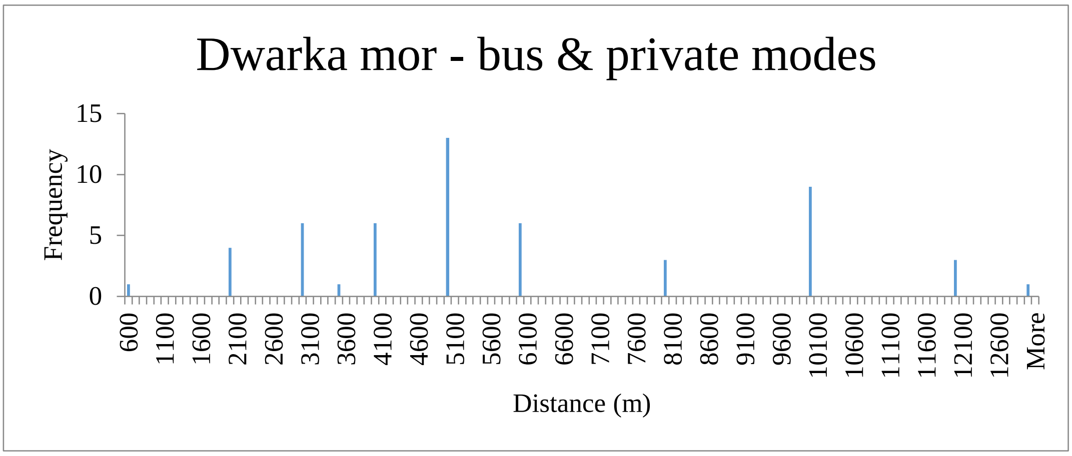


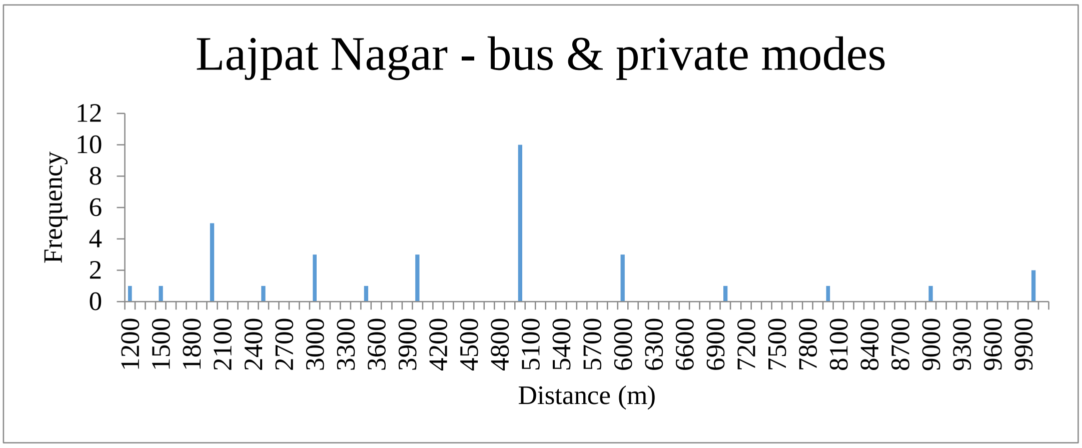


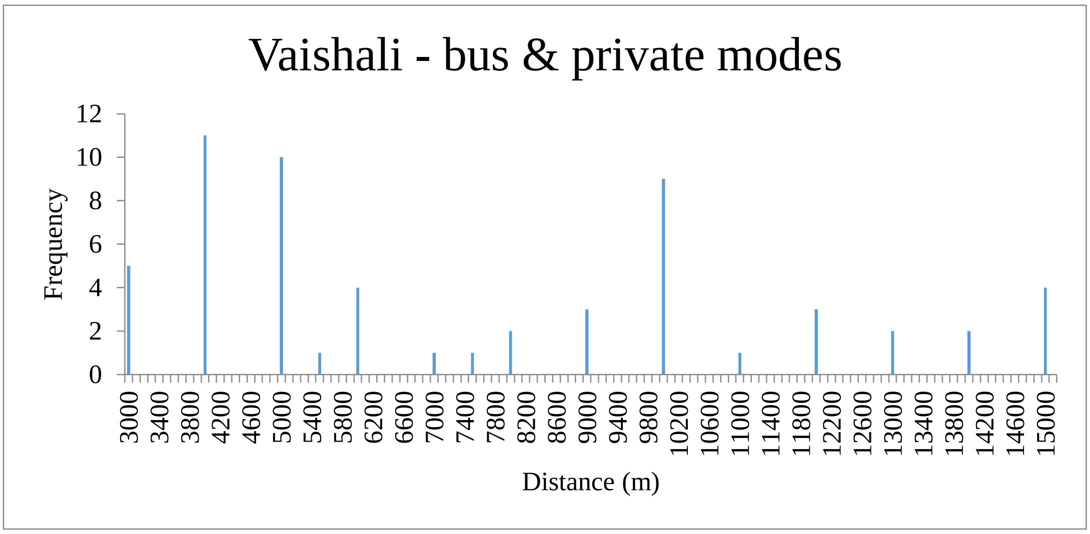


Histogram of reported distances for different stations – bus & private modes (Study 2)



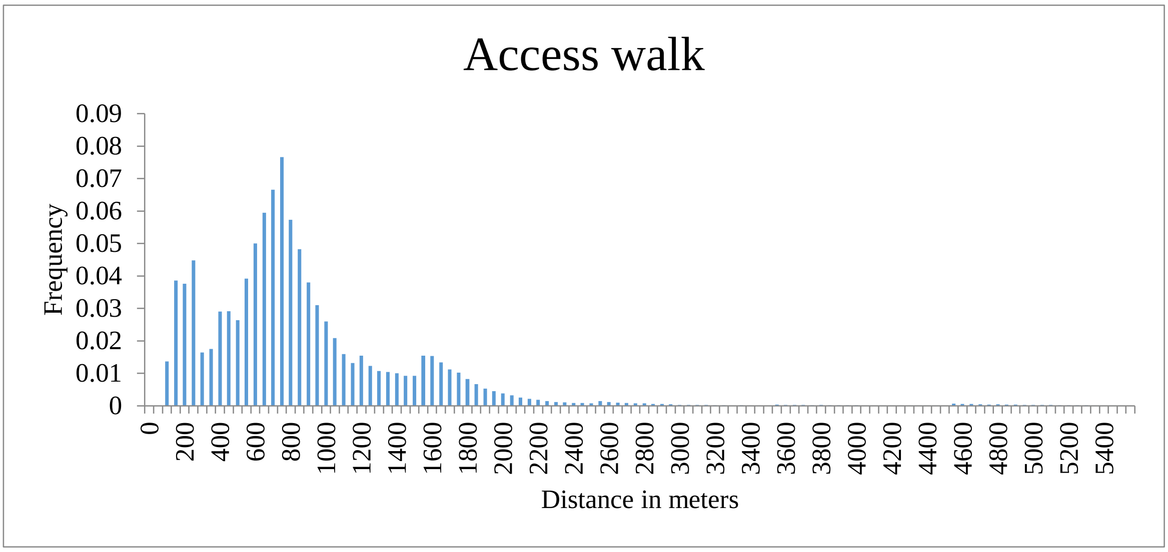

Dwarka mor - bus & private modes
Frequency
15
10
5
0
600
1100
1600
2100
2600
3100
3600
4100
4600
5100
5600
6100
6600
7100
7600
8100
8600
9100
9600
10100
10600
11100
11600
12100
12600
More
Distance (m)

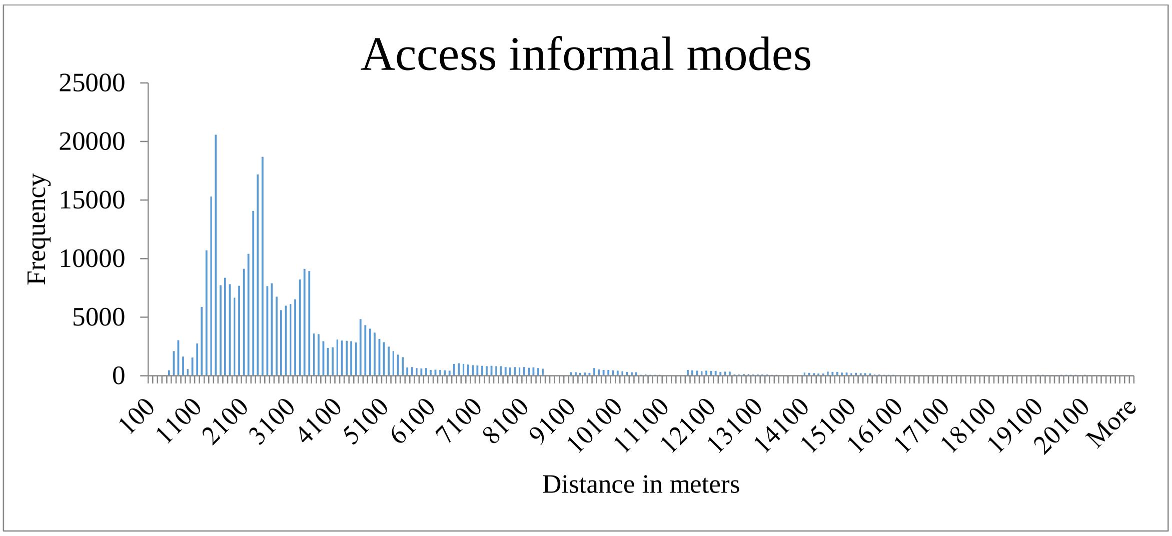

Lajpat Nagar - bus & private modes
Frequency
12
10
8
6
4
2
0
1200
1500
1800
2100
2400
2700
3000
3300
3600
3900
4200
4500
4800
5100
5400
5700
6000
6300
6600
6900
7200
7500
7800
8100
8400
8700
9000
9300
9600
9900
Distance (m)

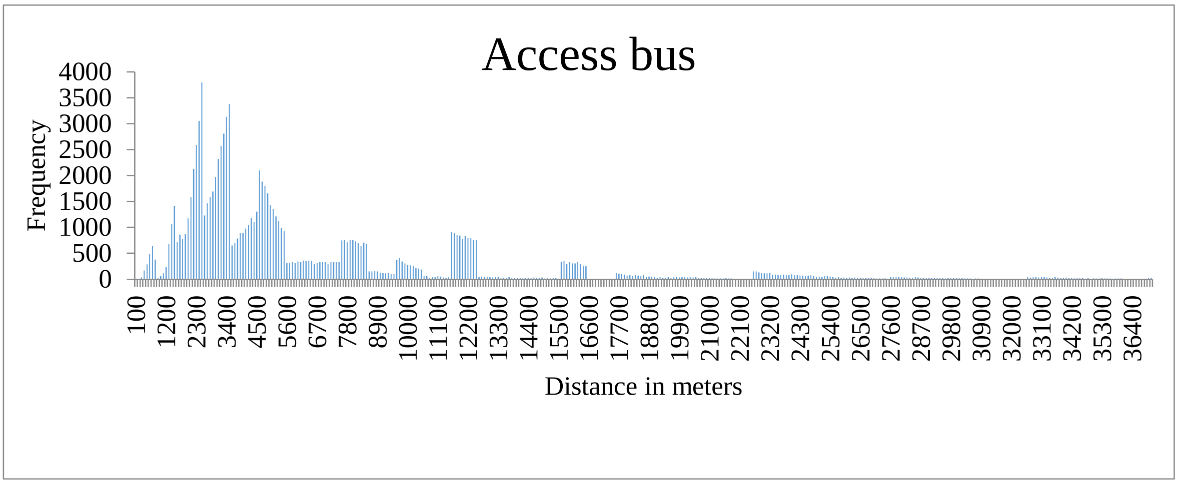

Vaishali - bus & private modes
Frequency
12
10
8
6
4
2
0
3000
3400
3800
4200
4600
5000
5400
5800
6200
6600
7000
7400
7800
8200
8600
9000
9400
9800
10200
10600
11000
11400
11800
12200
12600
13000
13400
13800
14200
14600
15000
Distance (m)

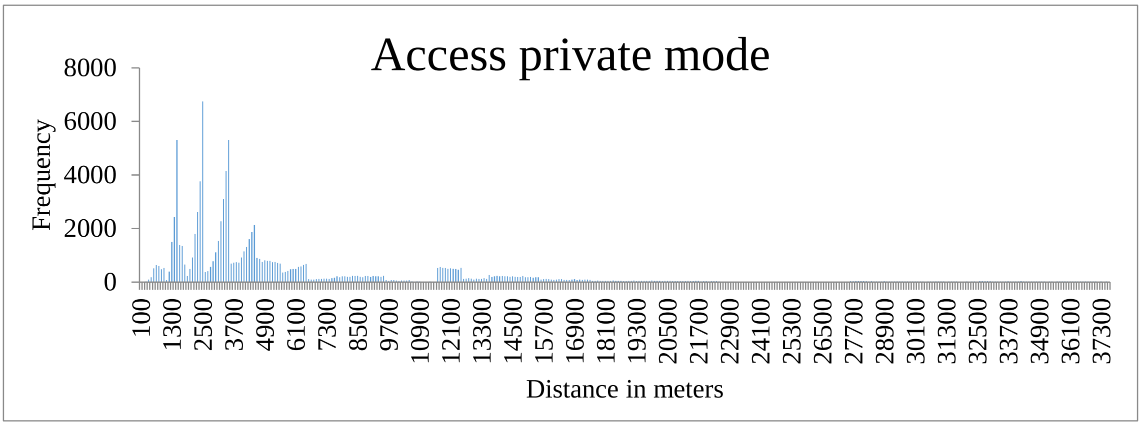
APPENDIX 7

Histogram of imputed distances for different modes for access (Study 1)

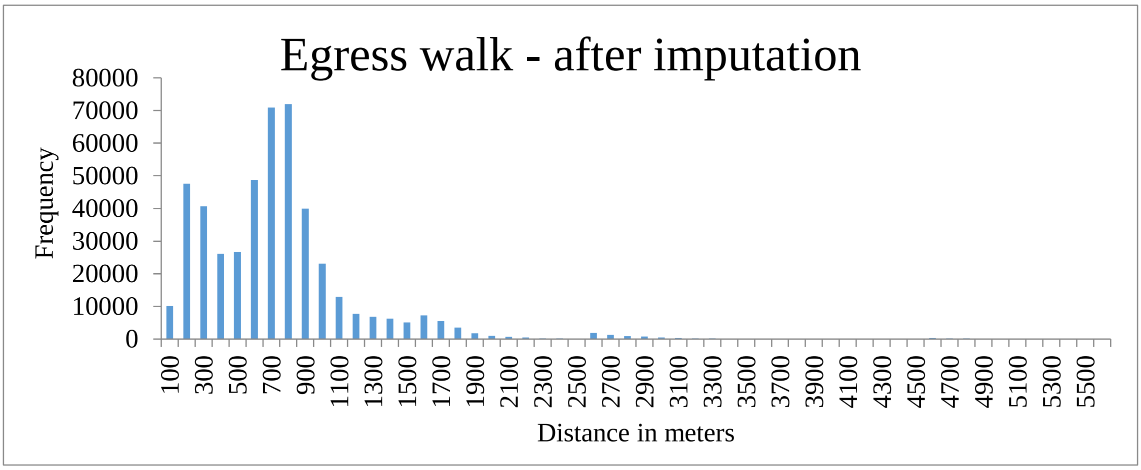


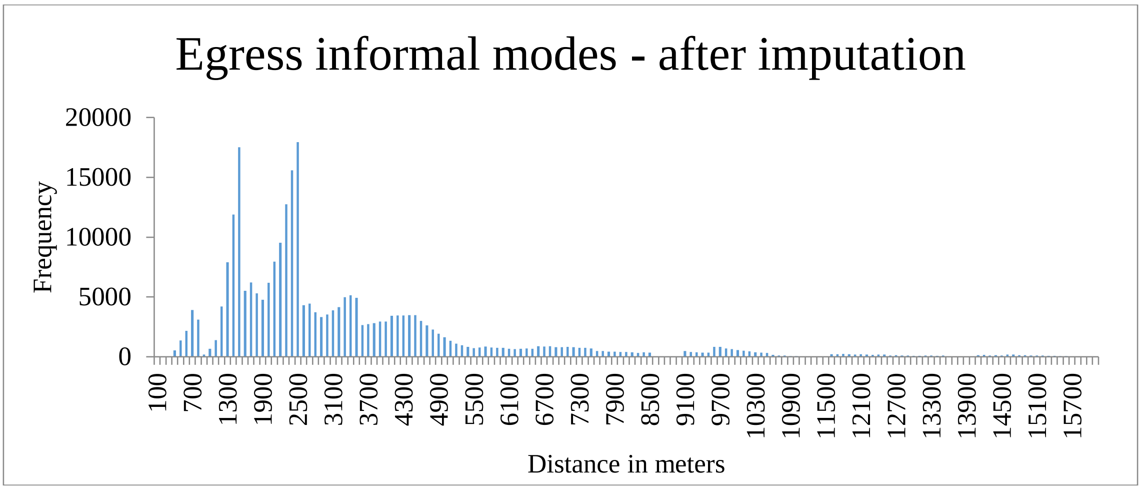


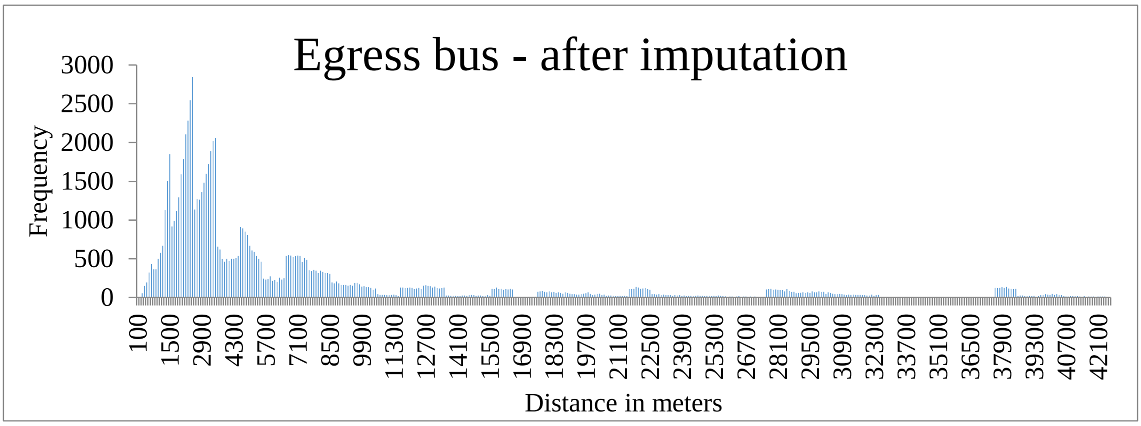




Histogram of imputed distances for different modes for egress (Study 1)

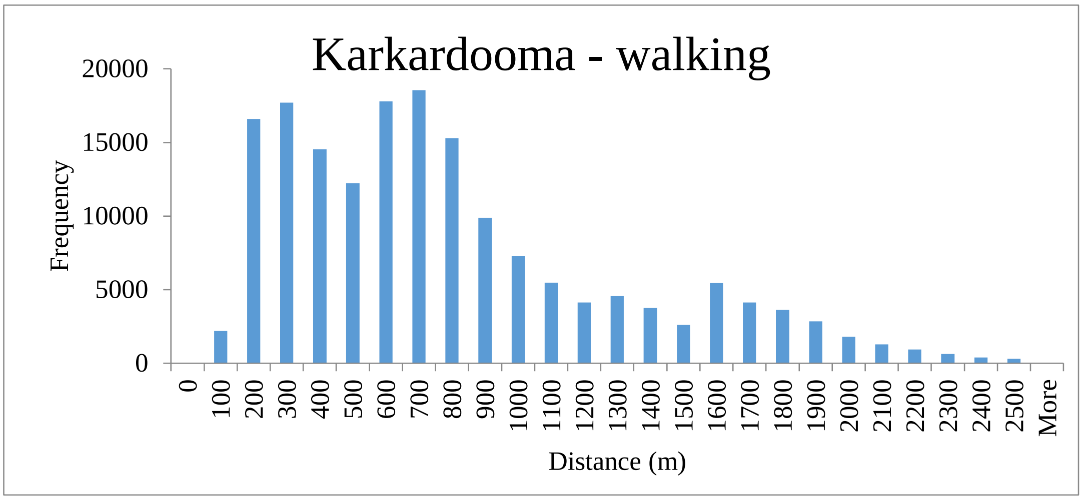


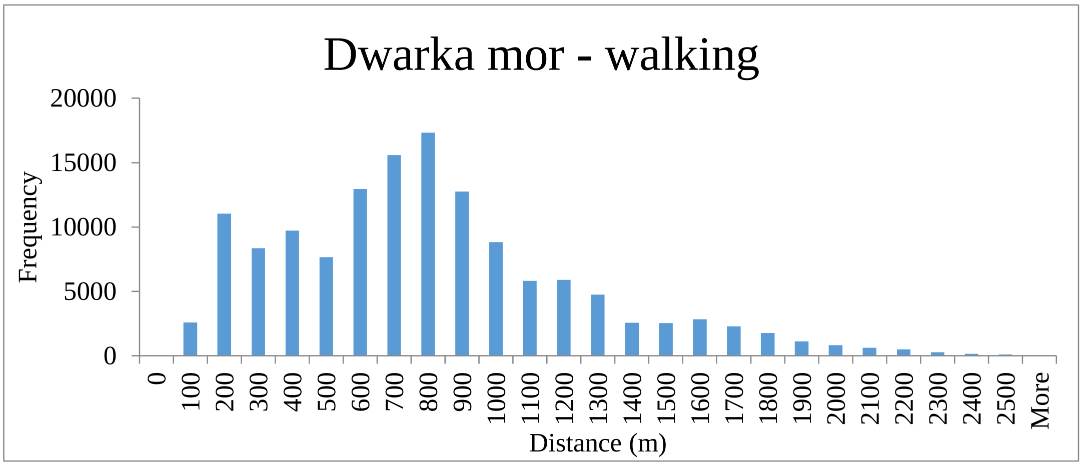

Egress informal modes - after imputation
Frequency
Distance in meters

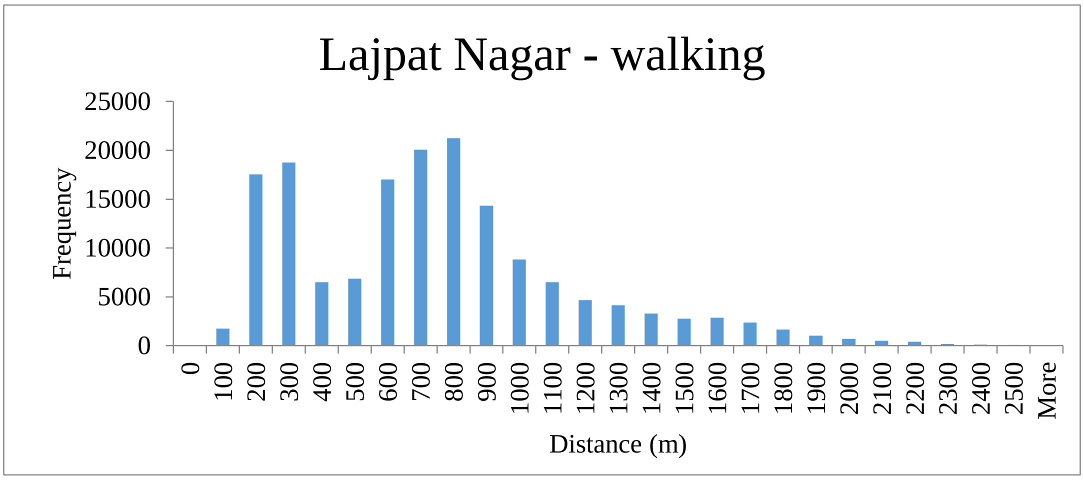

Egress bus - after imputation
Frequency
Distance in meters

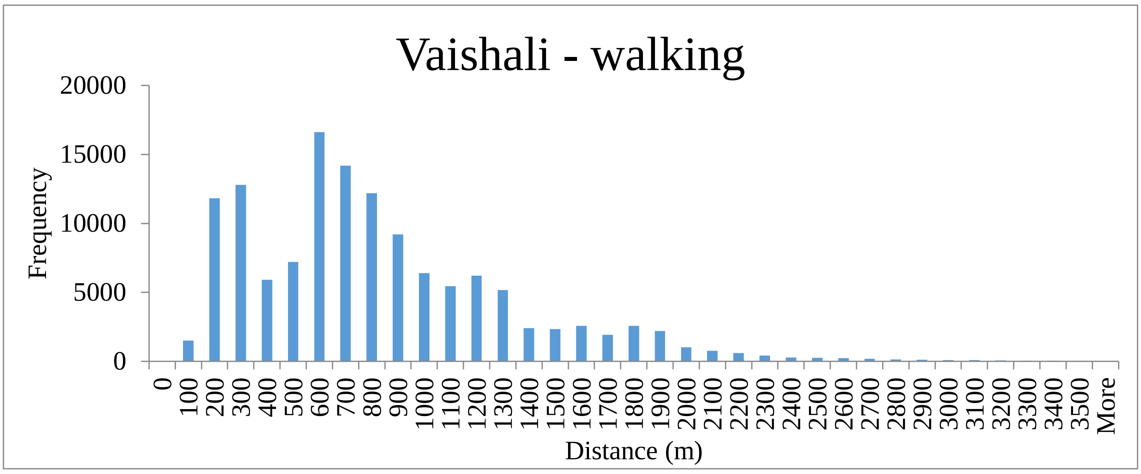
APPENDIX 8

Histogram of imputed distances for different stations – walking (Study 2)

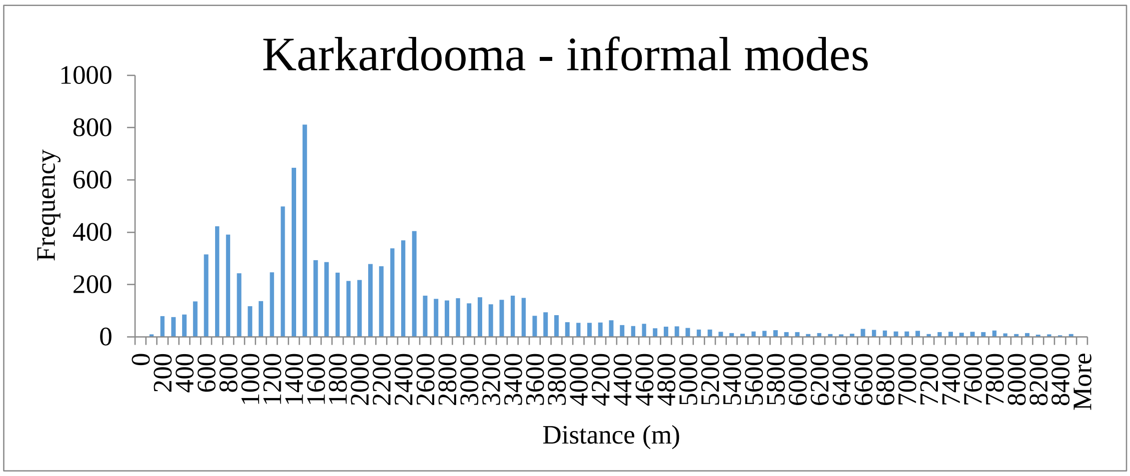


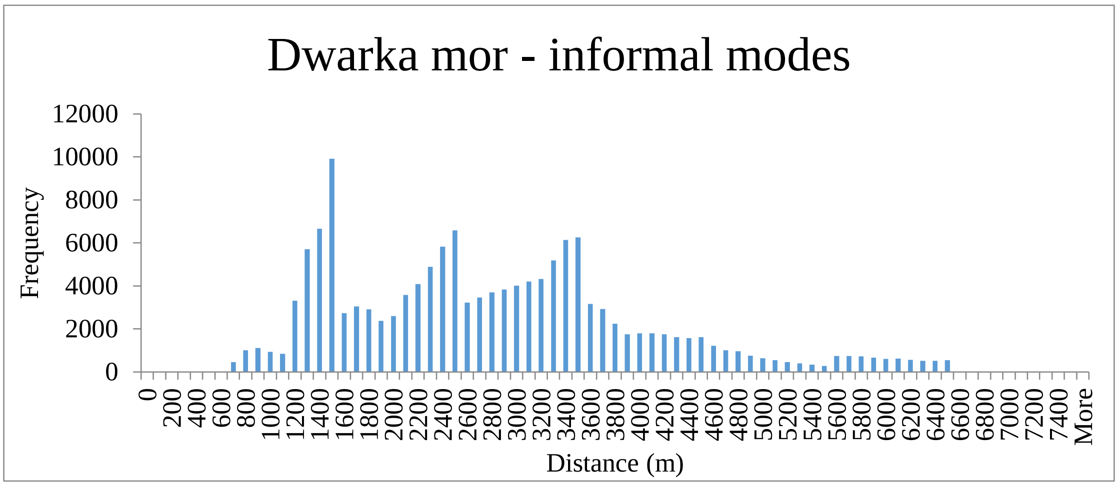


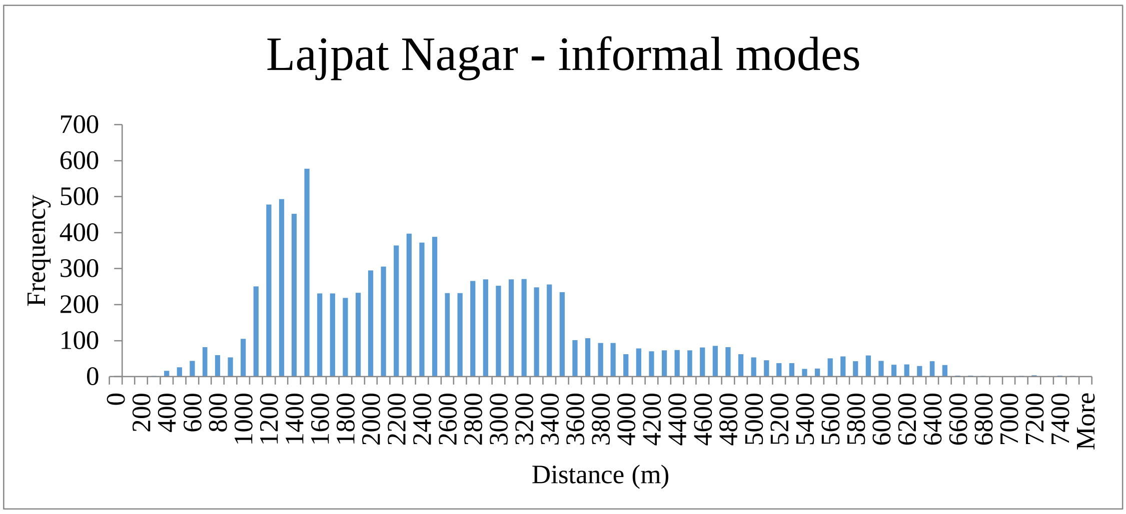


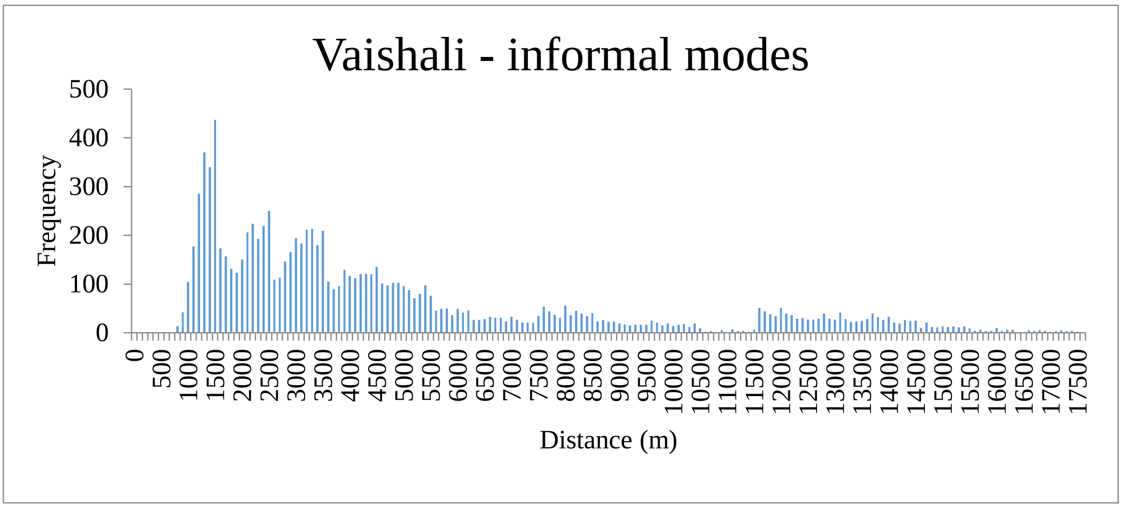


Histogram of imputed distances for different stations – informal modes (Study 2)

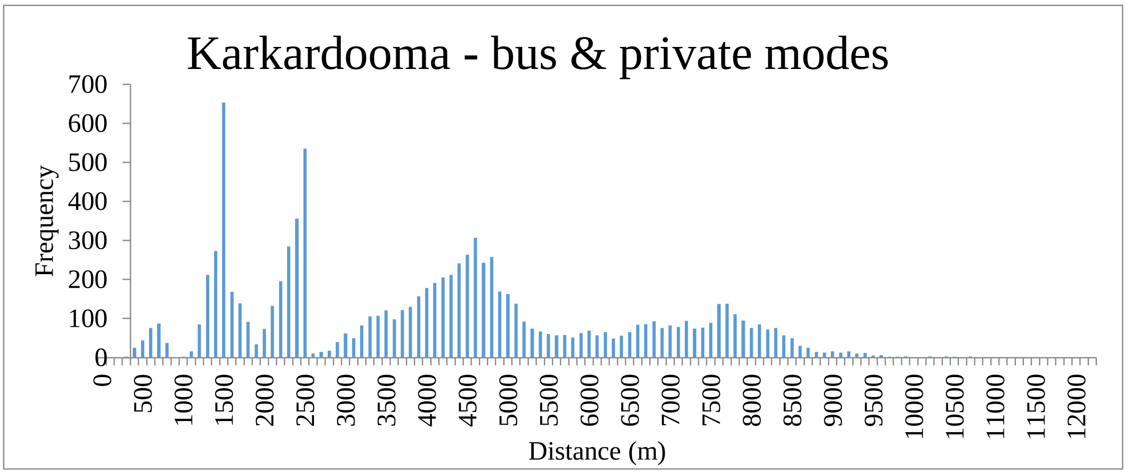


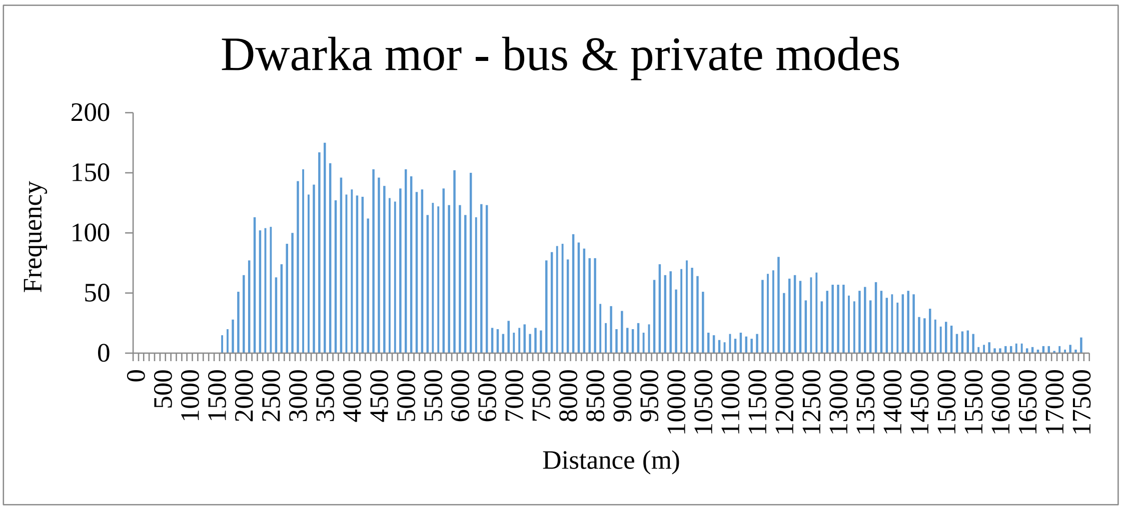


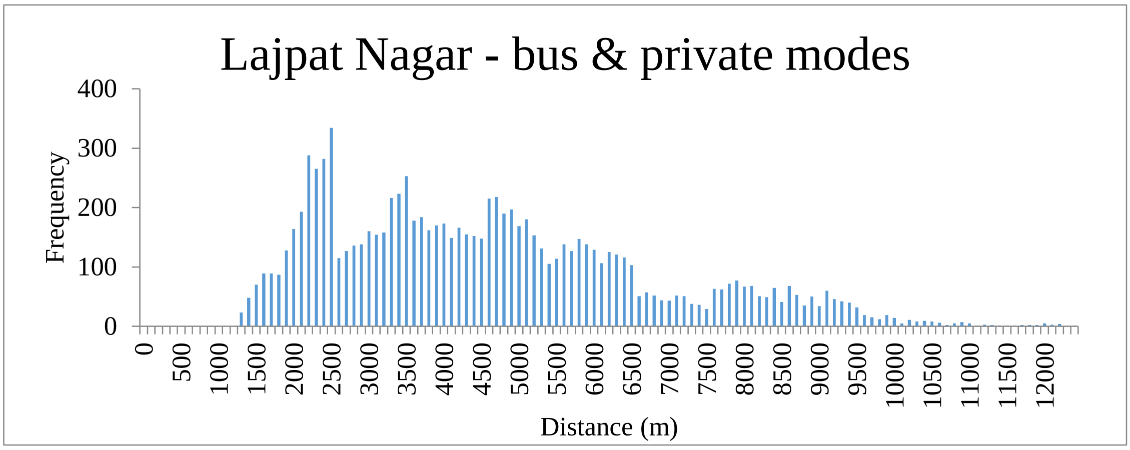


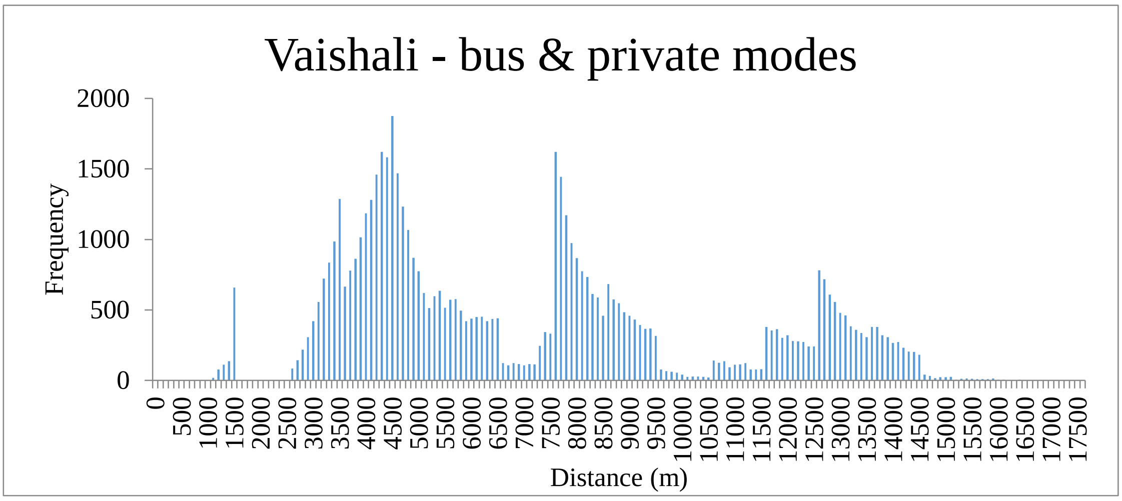


Histogram of imputed distances for different stations – bus & private modes (Study 2)



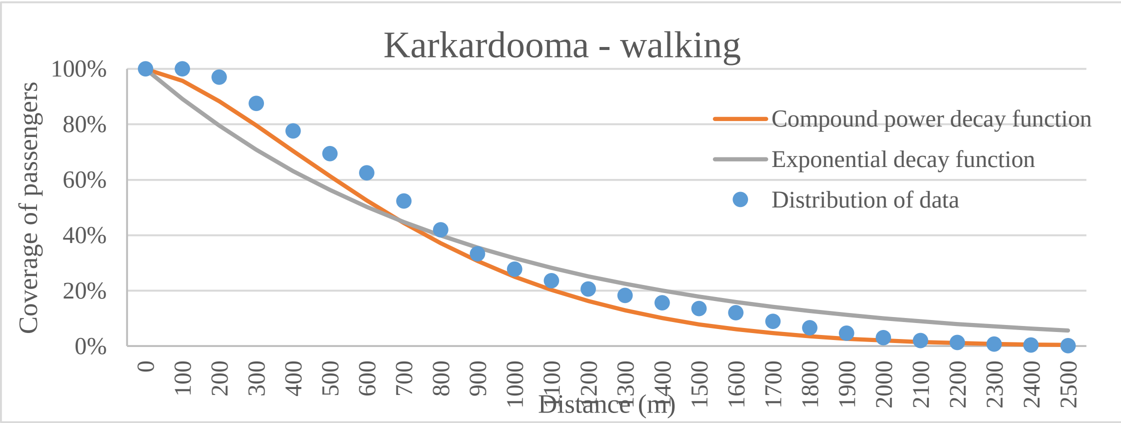

Dwarka mor - bus & private modes
Frequency
Distance (m)

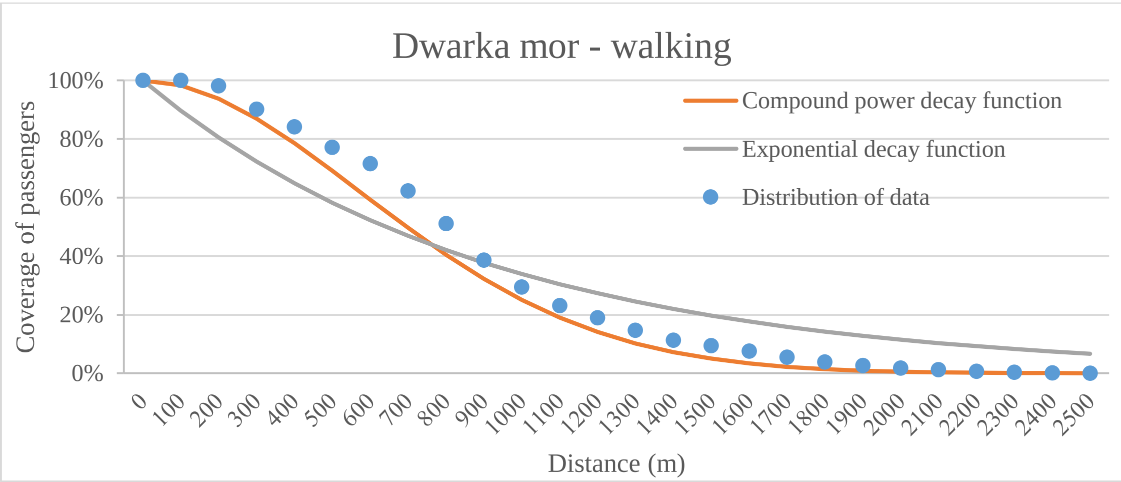

Lajpat Nagar - bus & private modes
Frequency
Distance (m)

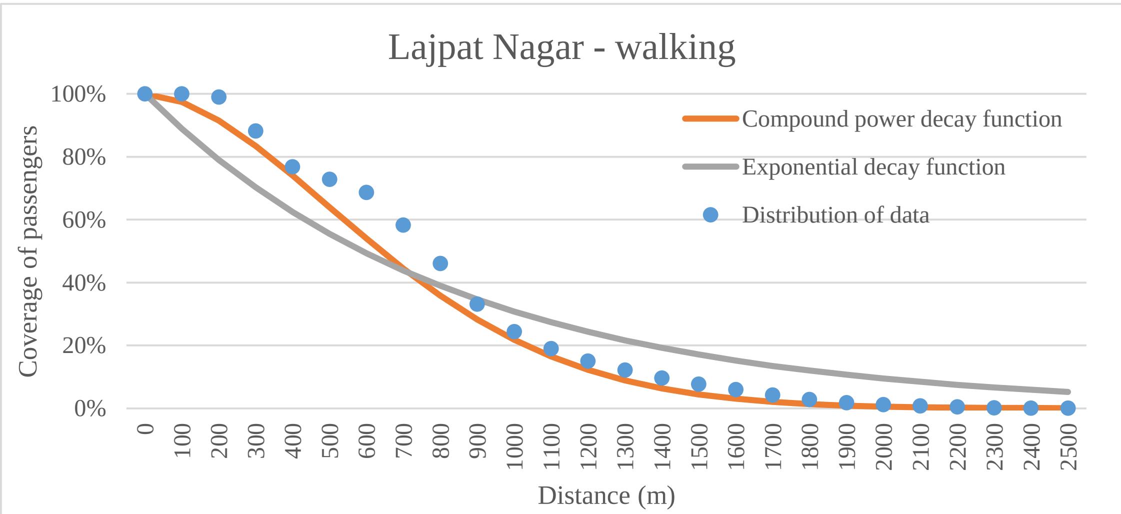

Vaishali - bus & private modes
Frequency
Distance (m)

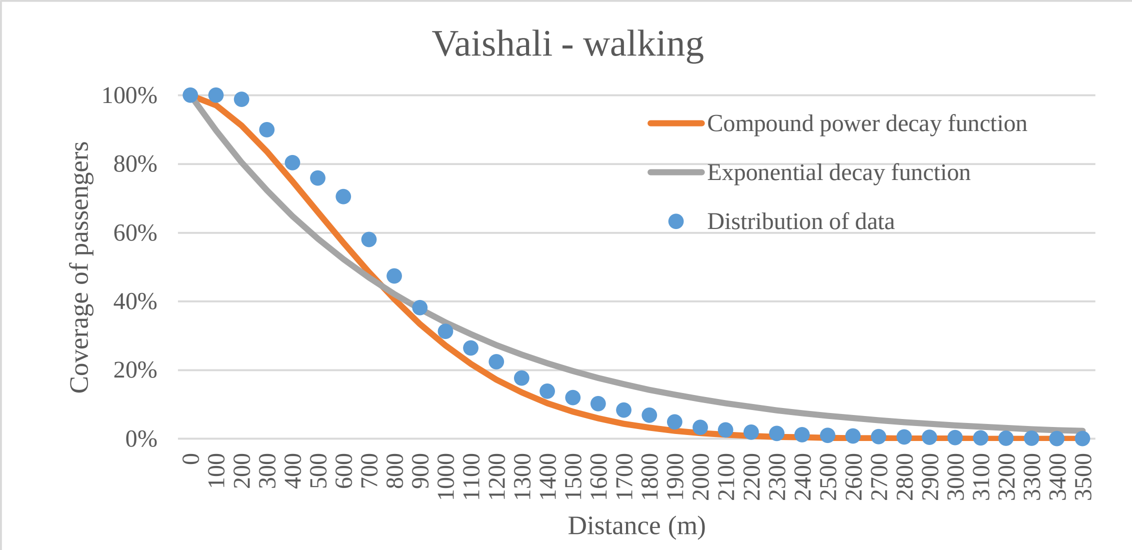
APPENDIX 9

Distance decay curves (exponential decay function and compound power exponential decay function) for walking for various stations (Study 2)

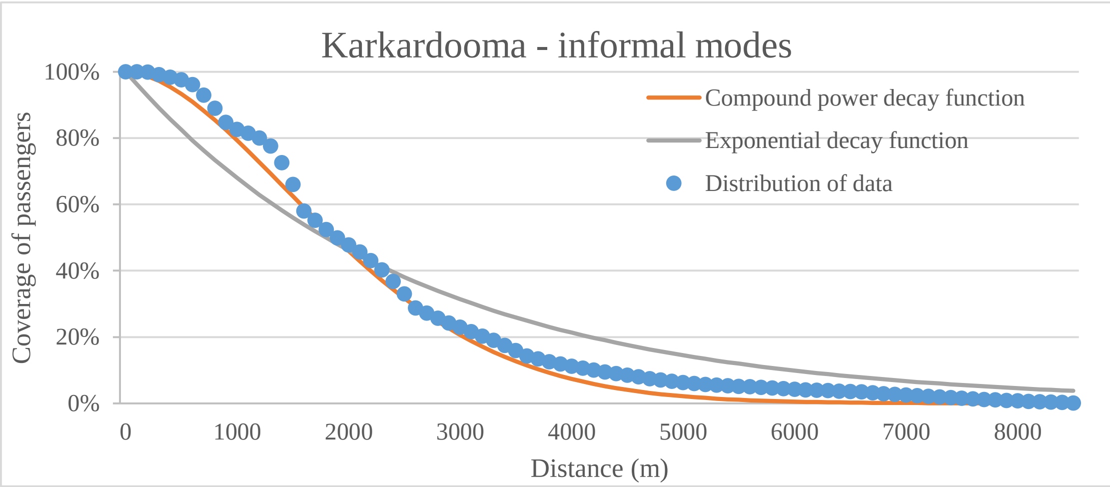


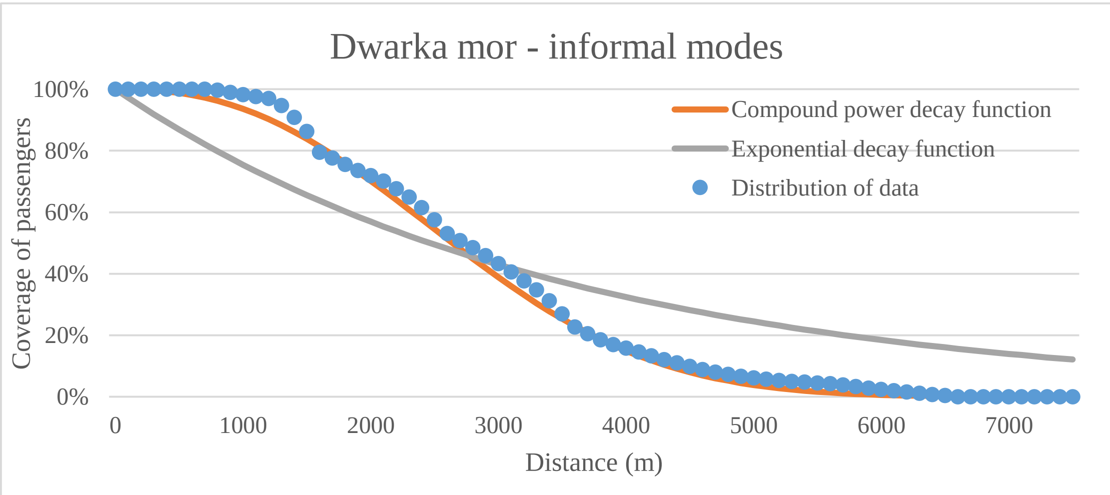


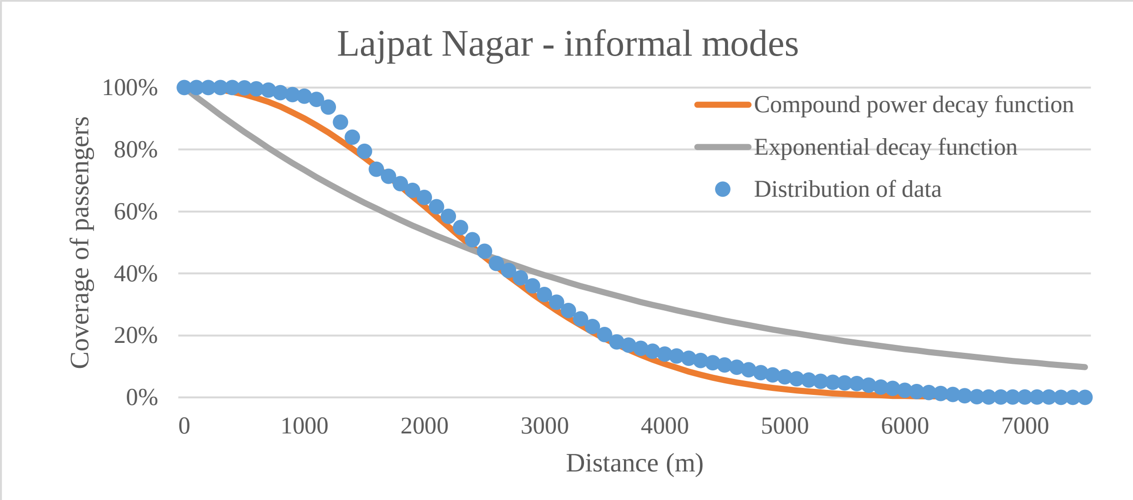


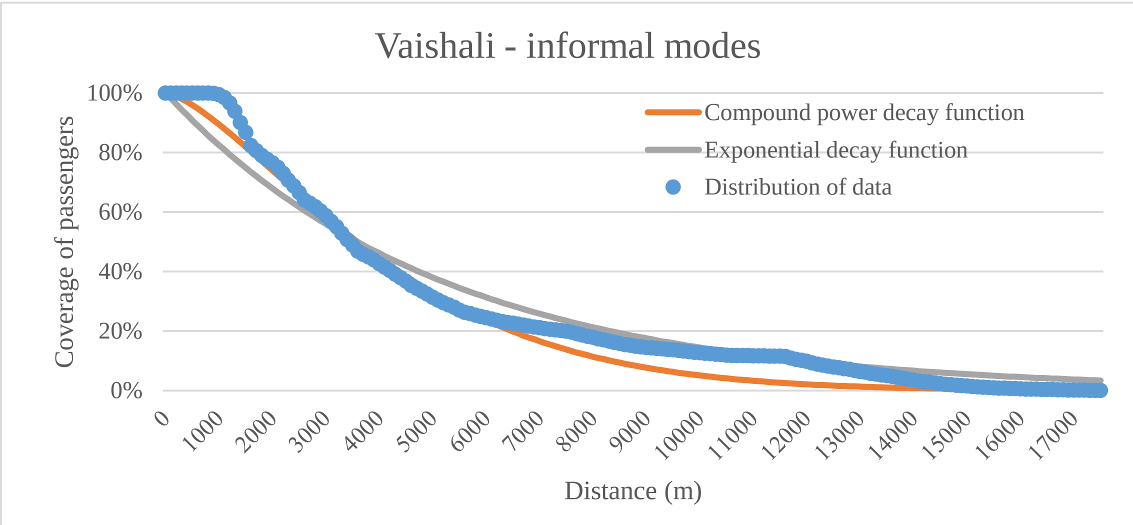


Distance decay curves (exponential decay function and compound power exponential decay function) for informal modes for various stations (Study 2)

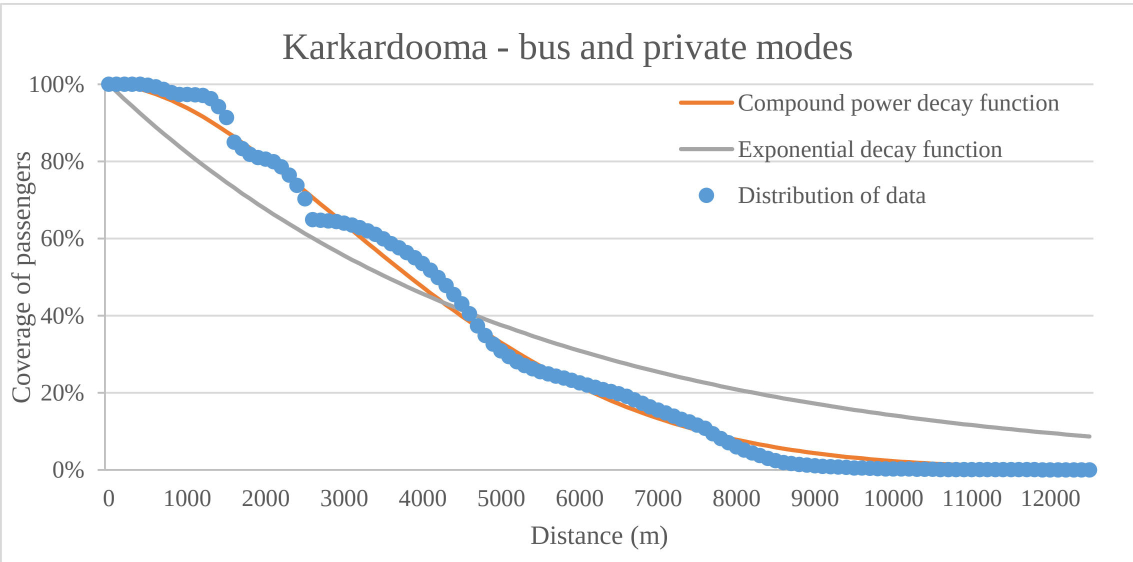


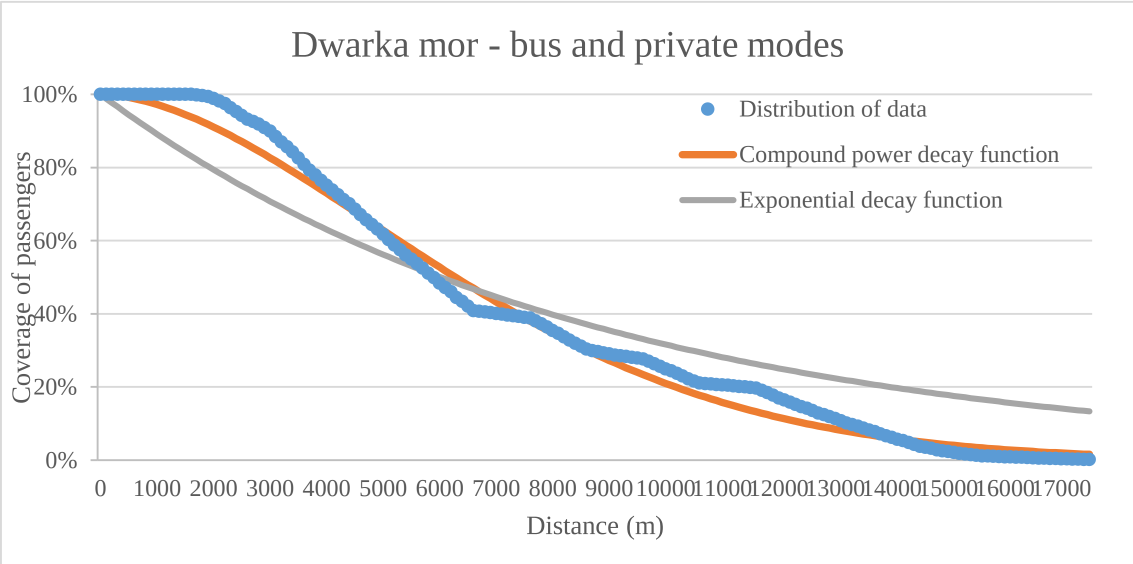


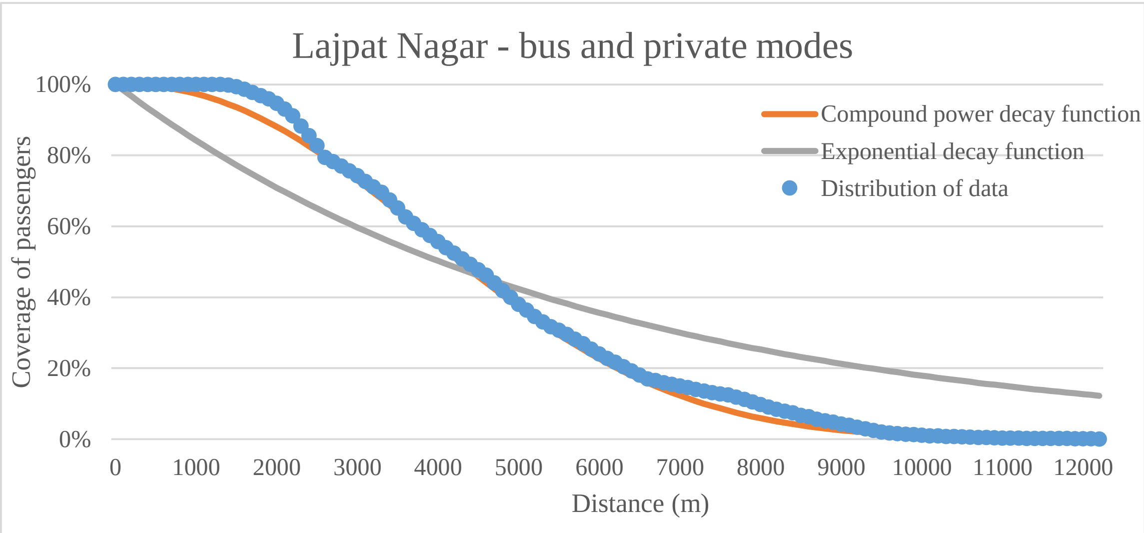


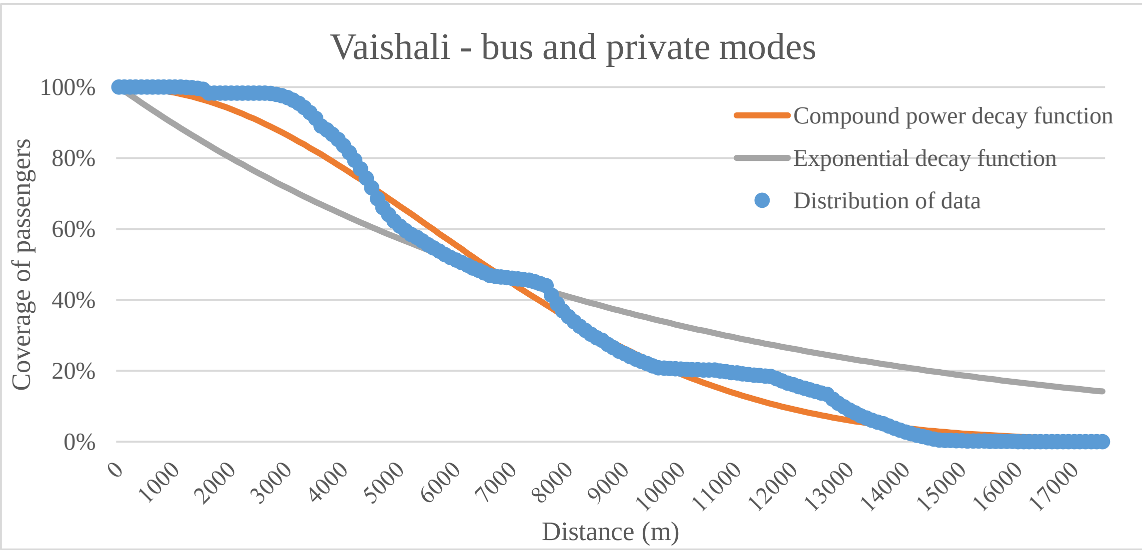


Distance decay curves (exponential decay function and compound power exponential decay function) for bus & private modes for various stations (Study 2)




Dwarka mor - bus and private modes
100%
80%
60%
40%
20%
0%
Coverage of passengers
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000 15000 16000 17000
Distance (m)
Distribution of data
Compound power decay function
Exponential decay function


Lajpat Nagar - bus and private modes
100%
80%
60%
40%
20%
0%
Coverage of passengers
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000
Distance (m)
Compound power decay function
Exponential decay function
Distribution of data


Vaishali - bus and private modes
100%
80%
60%
40%
20%
0%
Coverage of passengers
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000 15000 16000 17000
Distance (m)
Compound power decay function
Exponential decay function
Distribution of data