EPB 138-094

WALKING ACCESSIBILITY TO PUBLIC TRANSPORT: AN ANALYSIS BASED ON MICRODATA AND GIS

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Acknowledgements

Founding from Consorcio Regional de Transportes de Madrid, Ministerio de Ciencia e Innovación (project TRA2008-06682) and Fundación Carolina is gratefully acknowledged.

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Abstract: This article analyses the role of walking accessibility to transit facilities. Microdata and GIS tools have been used to calculate distances walked by different population groups in the access to Metro stations. Distances walked by the population were used to determine the threshold distances of the station service areas and calculate the population covered by the Metro network. With respect to station ridership, different distance-decay functions were adjusted and the sensitivity of the population groups to the distance was measured. Two indicators were proposed, based on the distance-decay functions, to measure access quality and potential demand. The analysis was carried out on the Madrid Metro network. Results show that young people and adults, men, immigrants and public transit captives are willing to walk longer distances and are less sensitive to the effect of distance. When walking distances have been used in order to fix the limit of the catchment areas, the amount of population covered is lower than using a standard threshold (0.5 miles), but overestimations affect each age group in a different way. The access quality indicator shows both that the population group in the worst situation is that of children and stations in the centre have higher access quality values. However, the synthetic accessibility indicator shows that potential demand is lower in the most central and most peripheral stations than in the stations located in the intermediate areas. It has been proved that both indicators are sensitive to changes in the spatial distribution of population groups within the catchment areas. These results demonstrate some of the advantages of the proposed methodology and argue in favour of its use in public transport planning.

Key words: Accessibility, walking distance, coverage analysis, distance-decay functions, access quality, potential demand, public transport, Metro, GIS, Madrid

1. Introduction

The distance people walk to access bus stops or stations plays a fundamental role in the ultimate use made of public transit. The more people who live and/or are employed in close proximity to transit, the greater the likelihood the service will be used (Murray et al., 1998). Beimborn et al. (2003, cited in Biba et al., 2010) have found that spatial accessibility to the transit system is the primary determinant of transit use and only in the presence of such accessibility will a user consider other factors such as cost, comfort or security. The majority of transit users access transit systems by walking. For example, according to a mobility survey conducted in 2004 in Madrid, 80% of passengers accessing the Metro network did so on foot.

For this reason, in transit planning special attention has always been paid to analysing population and jobs with walking access to bus stops and stations. Walking accessibility to transit networks is usually studied by coverage analyses, which consider the number of people or jobs within certain limits of distance with respect to bus stops and stations. Estimates of the population with access to transit are an important input to estimates of transit use (Biba et al., 2010). Thus, this approach is essential for making decisions on future network extensions, enabling locations concentrated in areas of high potential demand to be chosen for new bus stops and stations. Furthermore, access to transit facilities should consider equity too. In this respect, analysis of accessibility is also important from a social exclusion standpoint, in that it aims to guarantee citizens equal opportunities for accessing transit networks. From this perspective, it is important to know which areas of housing or economic activity are located outside a certain distance limit and are therefore not covered by the network.

Walking distances for accessing Metro vary among the different population groups. Knowing these distances and using them for coverage analysis should make a more refined diagnosis of potential demand and population coverage possible. From the equity perspective, the use of the same distance threshold for all population groups ignores that some groups move slower or require greater effort and therefore cover shorter distances (for example, old people and children). It is also worth investigating the effect of distance deterrence (on the total population and by groups) to gain a better understanding of population behaviour regarding Metro access.

More and more microdata are available nowadays on public transport mobility. With these data, which are easily handled with a GIS, it is possible to carry out a systematic study of access to Metro stations by population groups. This article focuses on the analysis of walking access to the Madrid Metro using microdata from a mobility survey conducted by the Transport Authority of Madrid in November 2004. The paper has four aims. First, to calculate the actual distance walked to Metro stations by population groups in order to obtain the distance threshold for each group on an empirical basis. Since these distances are influenced by the spatial distribution of the groups, a procedure has been developed in order to neutralise this influence. Second, to apply these thresholds in GIS coverage analyses for determining the population with walking access to transit facilities. Third, to compute distance-decay functions that enable the decrease in demand with distance to be determined and use them to evaluate accessibility conditions for different population groups. And four, to propose an access quality indicator and a potential demand indicator, based on these distance-decay functions.

The article makes a contribution to the studies of access to public transport facilities based on the analysis of walked distances according to social groups. The proposal methodology will allow for better transit planning, including greater equity of service. In fact the results demonstrate some of its advantages and argue in favour of its use in the evaluation of transport networks, location of new stations and assessment of public transport plans.

The article is structured as follows. After this brief introduction, Section 2 reviews the literature in this area. Section 3 describes the data used and presents the methodology. Section 4 shows the main results; and Section 5 contains concluding remarks. The Madrid Metro is used as a case study.

2. Background

2.1 Distances walked to access transit facilities

The use of Geographic Information Systems (GIS) has made it easier to carry out coverage analysis of public transit networks. Research has been done on calculation methodologies, with differing results depending on how coverage areas are defined (straight-line or network distances), and on the effects of spatial units containing information on population (O´Neill et al., 1992; Peng and Dueker, 1995; Hsiao et al., 1997; Murray et al., 1998; Murray, 2001; Zhao et al., 2003; Moreno and Prieto, 2003; Horner and Murray, 2004; Wu, C. and Murray, 2005; Gutiérrez and García-Palomares, 2008; Biba et al., 2010).

However, in coverage analyses, transit planners tend to assume certain walking distance limits as the thresholds that people are willing to walk to access public transport. Most studies usually use distance thresholds of 0.25 miles (400 metres) for access to bus stops and 0.50 miles (800 metres) for metro or railway stations (see, for example, Untermann, 1984; O´Neill et al.; 1992; Hsiao et al.; 1997; Murray, 2001; Kuby et al., 2004; Biba et al., 2010). However, these distance thresholds are generally used without an empirical basis to justify them [1] and are applied equally to all population groups and urban spaces.

[1] One exception is Zhao et al. (2003), who found that farther than 0.5 mile away from a transit stop, transit use diminishes to three percent of that within 300 feet of a transit stop. This suggested that one half mile may be used as the upper limit when calculating the transit service catchment area and the service population.

Studies on access to public transport demonstrate that walking distances may vary according to different types of social groups, spaces and transit facilities. Lam and Morrall (1982) obtained an average distance for accessing bus stops of 327 metres (450 metres in the 75 percentile) in Calgary. They also observed that in residential areas longer distances were walked than in industrial ones. In the same city, O'Sullivan and Morrall (1996) obtained an average distance of 649 metres for accessing light rail stations in the suburbs (840 metres in the 75 percentile) but this fell to 326 metres in the CBD (419 metres in the 75 percentile).

Differences also appear depending on the type of station. In the case of suburban light rail stations, O'Sullivan and Morrall (1996) found a higher average walking distance for terminal and interchange stations (1.1 km) than for intermediate stations (450 metres). In CBD stations the average walking distance was shorter. Finally, they found somewhat greater distances for men than for women in suburban light rail stations. In the CBD, however, these differences were not significant.

In Montreal, El-Geneidy et al. (2009) analysed the differences in distances transit users were willing to walk to bus stops and stations according to their socio-demographic characteristics. Using a multiple regression model, they found that men walked greater distances than women; the same was true of young people with respect to old people. Another determinant was the nature of the ride; people walked farther if the ride involved a commute to work or a longer journey.

2.2 Decrease in demand with distance (distance decay)

Coverage analyses make it possible to obtain an initial approximation of the population served and from this, the potential demand for bus stops or stations. Its all-or-nothing function, however, is a disadvantage because it considers the population inside the area covered to be served by the network and the population outside it to be without service. This undoubtedly has its uses as it simplifies calculations and makes the results easier for the layman to understand. However, it assumes that all the population inside the coverage area has the same degree of accessibility to transit (living 100 metres from a station is not the same as living 600 metres away) and that accessibility outside it is non-existent, when some riders are willing to walk a distance that is somewhat greater than the pre-established coverage limit.

It is well known that the willingness to walk to a destination decreases with distance from it. The number of riders who walk to stations or bus stops decreases significantly with distance from these. If walking distances are increased and people have an alternative way to travel, there is a decline in transit ridership. Keijer and Rietveld (2000) showed there was a significant decrease with distance in the number of riders accessing train stations on foot, both in absolute terms and after adjustment to the population. Untermann (1984) found a close relationship between distance and the willingness to walk to access public transit; most people were willing to walk 500 feet, but this dropped to 40% for 1000 feet and scarcely 10% were willing to walk one and a half kilometres. In a review of distance-decay functions for transit access, Biba et al (2010) cited work by Loutzenheiser (1997) that showed that for every additional 500 m (1640 ft) from a station, the probability that an individual will walk to transit decreases by 50%, and by Dill (2003) that showed similarly every 10% increase in walking distance results in a 10% decline in transit use. Zhao et al. (2003) carried out an on-board survey in Miami to study the effects of walking distances on transit use. The data showed that transit ridership decreases exponentially with increased distance to the stops and ceases after 580 m (0.36 miles). Levinson and Brown-West (1984) used surveys carried out on board buses and classified riders into groups according to walking distance to bus stops and car ownership. The data obtained were compared with those of the resident population to give ridership penetration ratios (by dividing the number of riders in each group by the number of homes in that group). The correlations between distance and ratios had an explanatory power of over 90% with adjusted linear equations. In Madrid, it has been shown that with respect to riders per resident accessing on foot, Metro ridership decreases linearly as the distance from stations increases (Gutiérrez et al., 2011).

Baldwin (2009) studied the role of walking distance to bus stops and stations with respect to the frequency of transit ridership by people over 60 years old. This was done in two different areas (San José in California and Buffalo in New York State) and also multiple regression. It was found that walking distance to bus stops and stations in California has a statistically significant influence on the frequency of ridership. However, this is not the case in Buffalo; the difference here may be the consequence of an urban environment that is more closely related to pedestrian movement, which reduces the effect of decreased distance. It was also found that drivers are more sensitive to walking distance than nondrivers. In San José, each additional five minutes in perceived walking time to transit decreases transit ridership frequency by five percent for nondrivers and by 25 percent for drivers. Older adults are likely to ride transit more often if they are male, nonwhite, and low income.

Very few studies have in fact been done in relation to the analysis of walking distances to access transit and the decrease in ridership. This study not only analyses real walking distances, but also walking distances when the effect of the different spatial distribution of the groups is neutralised, thus providing information on the distance different groups are willing to walk. It proposes calculation of population covered using distance thresholds based on distances walked by the population groups. In addition, it proposes an access quality indicator calculation, which allows us to qualify the coverage results. This indicator is based on distance-decay functions.

3. Data and methodology

3.1 Data

The stations of the Madrid Metro were used as a case study for analysing walking distances and distance-decay functions in transit ridership. Data were provided by the Transport Authority of Madrid for the year 2004, the year in which the last household mobility survey took place. All the data were stored in a GIS. The software used was ArcGIS 9.3 (for GIS analysis) and SPSS19 (for statistical analysis).

2004 mobility survey provides a table showing x and y coordinates for the origin of trips using the Metro and the name of the station where the Metro was boarded. Madrid Metro stations and street network layers and socio-demographic data at transport zone level were also used in order to calculate network distances and population covered.

3.2 Georeferentiation of rides and calculation of distances

The places of origin (household locations) of all Metro rides accessed on foot were geo-referenced in the GIS. In all, some 17,000 records were used. Applying network analysis routines, the distance through the street network from each origin to each Metro station used was calculated. Expanded data were used to analyse the distances and neutralise the fact that the sampling fraction varies between transport zones. The results therefore represent the behaviour of the population as a whole. Basic statistics were obtained (average, standard deviation, percentiles) of the distances walked from home to the Metro station, both for riders as a whole and according to population groups.

Given that population groups are not evenly distributed spatially, distance statistics reflect both the willingness to walk to stations and the distribution of the different groups over the space. Groups found to be overrepresented in the nearest distance bands (usually the oldest established urban areas) tend to present lower average distances. In Madrid, for example, people over the age of 65 and foreigners tend to be concentrated in the more established areas of the city centre, which are those best served by the Metro. They have a much larger presence in the bands nearest the Metro than young people and adults or Spanish nationals respectively, which partly explains why their walking distances tend to be shorter.

In order to neutralise this effect, population distributions and Metro rides were considered in terms of distance bands from the stations. These data were then used to estimate spatial distribution of the groups according to distance bands if there was no type of *under*- or *over-representation* present (equation 1) and the rides corresponding to each group in each band were obtained (equation 2). With this information, the basic statistics on the distances walked by each group were obtained, thus neutralising the effect of the different spatial distribution of the groups:

$$Pc_{ki} = \frac{Pt_i \cdot Pt_k}{Pt} \qquad (1)$$

where:

Pc_{ki} = Population of group k in distance band i neutralising the different spatial distribution of the groups
Pt_i = Total population in band i
Pt_k= Total population of group k in the station catchment area (0 to 1500 metres[2])
Pt = Total population in the station catchment area (0 to 1500 metres)

$$Vc_{ki} = \frac{Pc_{ki} \cdot Vr_{ki}}{P_{ki}} \qquad (2)$$

where:
Vc_{ki}= Rides by group k in distance band i neutralising the different spatial distribution of the groups
Pc_{ki} = Population of group k in distance band i neutralising the different spatial distribution of the groups
Vr_{ki}= Rides by group k in distance band i
P_{ki}= Population of group k in distance band i

Figure 1 shows (in the example of age groups) the process to neutralise the different spatial distributions of the groups and to obtain the rides corresponding to each group in each band once these spatial distributions were neutralised.

Figure 1

3.3 Calculation of the population covered according to walking distances

Distances walked by the population were used to determine the threshold distances of the station service areas and calculate the population covered by the Metro network. In order to do this, when it came to delineating the coverage bands, the specific threshold of each group (for example, children, adults, old people) was considered and the population covered obtained separately for each group. The results were then combined. For this study, we used the 75 and 90 percentiles for both walking distance statistics and corrected statistics, thus neutralising the effect of the different spatial distribution of the groups. The results were subsequently compared with those obtained with the standard 800 metre (0.5 miles) band usually used.

3.4 Calculation of rides per resident ratios and distance-decay functions

The distance-decay functions were calculated from the ratios of Metro rides per resident according to distance band every 100 metres from the stations up to a total distance of 1500 metres. The ride ratios were obtained from the home, dividing the total number of

[2] According to the 2004 household mobility survey, 1500 metres is the maximum distance that people are willing to walk to use the Metro in Madrid.

rides in each band by the number of residents. The spatial distributions of the population by groups were calculated every 100 metres (up to 1500 metres) from the coverage bands, which were computed using network distances (using the ArcGIS Network Analyst module). The bands were then overlaid on the layers containing the different population variables and these were distributed over the bands accordingly, using the areal weighting method (see O'Neill et al., 1992; Chakraborty and Armstrong, 1997).

The distance-decay functions of Metro ridership were obtained from the ride ratios by representing the ride ratios in relation to distances and adjusting functions by the least-squares method. The distance-decay functions were adjusted according to the characteristics of the different groups and spatial environments.

In order to analyse the effect of distance friction on Metro accessibility according to groups, the percentage decrease in demand every 100 metres was calculated. The gradient obtained in the different equations is heavily influenced by ratio value (Metro ridership). By calculating the percentage decrease in demand every 100 metres, we neutralise the effect of the different ratio values and obtain a value that is comparable between groups. The sensitivity of each group to the distance factor can be determined from this value.

3.5 Formulation of a quality indicator for station access.

Coverage analyses use cumulative opportunities measures to determine the amount of population living within a certain limit of distance with respect to stations. However, this population may be distributed over the catchment area in very different ways. This is reflected in the quality of station access, which is at its maximum for those who live near stations but diminishes as the distance between home and station increases. In order to take such circumstances into account, a simple procedure is proposed for obtaining a quality indicator for station access. This indicator is based on normalization of the distance-decay function, either in general terms or specific to each group, with a value of 1 given to the first band (maximum accessibility). In other words, population behaviour is used as a proxy for access quality. Once the normalized values of each band are known, the average is obtained, using the amount of population living in each band as a weighting factor, according to the equation [3]:

$$AQ = \frac{\sum_{i=1}^{n} \frac{R_{\max}}{R_i} P_i}{\sum_{i=1}^{n} P_i} \qquad (3)$$

[3] Equation 3 shows a general formula. It can be applied to different spatial or social contexts. In our case, the data for the calculation of specific distance-decay functions and the specific functions are presented in Section 4 (Results).

where:

AQ = Access quality

R_{max} = Ratio of rides per inhabitant in the band nearest the station (100 meters), calculated according to the distance-decay function (see section 4.3).

R_i = Ratio of rides per inhabitant in band i (also according to distance-decay function)

P_i = Population of band i

The bands may comprise those within the catchment area, or they may also include the band just outside the catchment area, depending on whether access quality is being analysed for the population served by the Metro or for the population in the study area as a whole.

This calculation can be done station by station or for the entire network. If the population is concentrated near a station or stations, access quality values will be higher than if it were situated in the outermost bands. Logically, the indicator will oscillate between 1 (all the population is concentrated in the first band) and 0 (station use is zero as the population lives in bands from which nobody accesses it). This indicator therefore gives relative values, which may be useful for comparing stations, networks and population groups or for evaluating changes over time (for example, new policies on population densification around stations). The information it provides (access quality) complements, rather than substitutes, that of classical coverage analyses (amount of population in the catchment area). In fact, the two sets of information can be combined as a synthetic indicator of accessibility to the network or station, according to the equation:

$$SAI = AQ \cdot P \quad (4)$$

where:

SAI = Synthetic Accessibility Indicator

AQ = Quality Access Indicator

P = Total population (covered by the network) in the station catchment area

This indicator therefore weights the number of people covered by their access quality. Results show the number of people in the service area once the distance effect, measured from distance-decay functions, has been discounted.

4. Results

4.1 Spatial distribution of the population and Metro ridership according to distance from the stations.

As the different spatial distributions of the groups will influence walking distances, the first essential is to know the characteristics of population distributions according to bands representing distances to the Metro. From the data in Table 1 the following patterns can be deduced:

- The population is concentrated in the first distance bands with respect to the stations. Of the people living less than 1500 metres away from the stations, 41.2% are found in the first 400 metres.
- Women tend to live a little nearer stations than men, with 42.1% of women living 400 metres from the stations, compared to 40.1% of men.
- The population in the first bands is much older. In the station catchment area, 46.8 % of people over that age of 65 live less than 400 metres from the station, whereas only 36.4% of children live at this distance.
- Immigrants tend to be concentrated near Metro stations, with 48.1% of foreigners living within a 400 metre distance compared to 40.6% of Spaniards.
- People living in households without cars also tend to live nearer stations, with 48.5% living less than 400 metres from a station, while for people with at least one car, the percentage is about 36% to 39%.

These distributions are well known in urban planning; in the older parts of the city the population is more aged and therefore more feminised. Such areas attract foreigners because of the supply of cheap rented flats and a better public transit service.

Table 1

With respect to ride distribution, the following patterns are observed (Table 2):

- The concentration of rides in the first bands is even higher than that of the population. Of Metro rides originating from home, 53.7% involve a walking distance of less than 400 metres.
- The differences in ride distribution between men and women according to distance from stations are similar to those found in the spatial distribution of the groups, although these are somewhat less in the first 400 metres.
- Rides by children and old people are particularly concentrated in the distance bands nearest the station, with 61.6% of boardings by children and 63.7% by old people concentrated in the first 400 metres, even though only 36.4% of children and 46.8% of old people live in this band.
- With respect to boardings by foreigners[4], 56.7% take place in bands less than 400 metres from the stations, compared to 53.4% for Spaniards, with 7.5% more foreigners living at this distance.
- When the number of cars per households is considered, the proportion of rides originating less than 400 metres from households without a car is about 7%

[4] In view of the different mobility patterns, foreigners originating from western Europe, the USA, Japan, Australia and New Zealand have been differentiated from those from Latin America, eastern Europe, Africa and Asia. The latter group makes up the majority, and comments on differences between Spaniards and foreigners always refer to this group.

higher than that of homes with a car, although at this distance the proportion of homes without a car is 10% higher than that of homes with a car.

Table 2

4.2 Walking distances and coverage analysis

a. Real walking distances and walking distances neutralising the different spatial distribution of the groups.

The average distance walked from home to access stations is 420.5 metres (770.2 in the 90 percentile) (Table 3). If we examine the differences according to groups, we find that men on average walk a longer distance than women (428 metres as against 413). Similar behaviour is also shown by the percentiles. However, when the effect of the different spatial distribution of men and women is eliminated, the differences decrease (Table 4); averages become practically the same and there is a decrease in differences in the 90 percentile.

Greater differences are observed between different age groups. The distances walked by young people exceed those of adults and, obviously, those of old people and children (Table 3). However, when average distances are corrected for spatial distribution of the groups, taking the adult group as reference, the differences are more marked with respect to children (who live farther away) and less noticeable with respect to people over 65 (who live nearer). The differences between adults and young people disappear; young people walk more because they live farther away, but the willingness to walk to access the Metro is practically the same in both groups.

The role of the different spatial distribution of population groups is even more obvious in distances according to nationality. Surprisingly, Spaniards walk 23 metres more on average than foreigners (Table 3). However, distances neutralising the differences in location of the groups give a value of 22 metres more for foreigners, a distance that is maintained in the 90 percentile. Therefore, the willingness to walk is greater among foreigners (who make greater use of public transit and are largely captive).

In terms of car ownership, the group that walks the least distance to stations is the group from households without a car (Table 3). Once more, this is influenced by the fact that captives live nearer stations. When this effect is neutralised, it is the captives that walk the greater distances. Distances tend to decrease as the number of cars in the household increases, although these differences are small.

Table 3

b. Walking distances as coverage analysis inputs

Important differences between groups have been identified from analysing walking distances. These differences may be taken into consideration in analyses of population coverage or studies of potential demand of stations. In this section a coverage analysis is carried out using age groups as an example, based on the walking distances of each group, both real and corrected (neutralising the differences in their spatial distribution). Using the 75 percentile, the result is a total of 2.07 or 2.10 million inhabitants served by the Metro network, depending, respectively, on whether real or corrected distances are used. With the 90 percentile this number increases to 2.65 or 2.68 million respectively (Table 4).

Table 4

The standard distance threshold (800 metres) overestimates with respect to the two percentiles selected. Results obtained with percentile 90 are the most similar to those obtained with 800 metres. Also, when corrected distances are used, the overestimation is less than when real distances are used (3.5% compared to 4.6%) (Table 5). The most interesting aspect from a demand and social exclusion perspective is that this overestimation basically refers to children and old people, the groups that least use the Metro (see 4.3). A proportion of children and old people (the most disadvantaged groups), considered to be covered by the network using the 800 metre threshold, are not covered in accordance with the distances they are willing to walk. This is a serious overestimation from the perspective of social exclusion, but not from that of potential demand. When corrected distances are used, overestimation of the population over 65 decreases (their willingness to walk increases the distance threshold, which approaches 800 metres), but increases in the case of children (who are less willing to walk). Therefore, with respect to demand, overestimation of the standard threshold is significant, not only because it implies a different total population covered, but also because it has a different effect on groups with differing frequencies of Metro ridership and degrees of vulnerability.

Table 5

4.3 Distance-decay functions and estimate of network access quality

a. Distance-decay functions

The ratio of rides per person from home gradually declines with distance, from 0.55 rides per person in the first 100 metres to scarcely 0.06 at 1500 metres. Decrease is lineal with a very high adjustment (r^2 = 0.96), which proves the importance of spatial proximity to stations with regard to demand for the Metro. The adjusted line shows that the ratio of rides per inhabitant falls 6.9% with each additional 100 metres of distance, and that demand disappears beyond 1500 metres.

Differences according to population groups are observed in the decline in Metro ridership with distance (Table 6). In order to analyse these differences, linear adjustments to the decrease in Metro ridership have been adjusted for the different groups (for example, age groups, Figure 2). Table 7 shows the values of the β_0 and β_1 coefficients of the adjusted lines and their r^2 values. It also shows the ride ratio per person for the whole 1500 metre area (R_{VR}) and the percentage decrease in the ride ratio per person every 100 metres. The percentage decrease makes it possible to compare distance deterrence with respect to station access in the different groups. The following patterns can be observed from the data in Table 6:

- The differences between the sexes are again small. The Metro is used more by women, with 0.35 rides from home per resident, compared to 0.29 for men. The percentage decrease in the ride ratio every 100 metres is greater in women than in men, which means women are more sensitive than men to the increase in distance.
- The ride ratios per resident according to age group confirms the well-known fact that the Metro is used much more by adults (0.39 rides from home per resident) and young people (0.46) than by old people (0.14) and especially children (0.03). Percentage decreases in the ride ratio every 100 metres also indicate that old people and, above all, children are more sensitive to the effect of distance.
- Foreigners take more Metro rides (0.36 per person) than Spaniards (0.32). The value of the percentage decrease of the ride ratio every 100 metres for foreigners is much less, which confirms they are less influenced by the effect of distance.
- People living in households with cars not only ride less on the Metro but are also more sensitive to the effect of distance (the percentage decrease of the ride ratio every 100 metres is greater).

Table 6

Figure 2

Table 7

b. Network access quality

The network access quality indicator (equation 3) for the whole population (see Subsection 3.5) gives a value of 0.66, which means there is a certain tendency for the population to be concentrated in the inner bands of the service area. The values obtained from the specific functions of each age group (Table 7) range from 0.67 (old people and adults) through 0.64 (young people) to 0.57 (children). It is therefore children who have the poorest accessibility to stations.

The total population covered by the network within a 1,500 metre limit is 3,467,000 inhabitants. The synthetic accessibility indicator (equation 4) gives a value of

2,280,000, which better expresses potential demand (since it considers the distance-decay effect). In terms of demand, this can be interpreted as 3,467,000 inhabitants distributed over different bands being equivalent to 2,280,000 concentrated in the first band. If the 509,000 inhabitants living between 1,000 and 1,500 metres away from stations (see Table 1) were found in the first band (0-100 metres), the quality indicator would then reach a value of 0.73 and the synthetic indicator would rise to 2,538,000. These indicators are therefore sensitive to the different locations of the population within station catchment areas; they can be used to make comparisons in time and, among other things, measure the effects of redensification policies.

Table 8

These indicators can also be used at station level. The average population covered at 1,500 metres at the stations is 18,700 inhabitants, with an access quality of 0.69 (standard deviation of 0.15) and a synthetic accessibility indicator of 12,400 (Table 9). In general, stations in the centre have high access quality values, which decrease towards the periphery (Figure 2). Station density is at its greatest in central zones and the catchment area of stations is reduced by competition between them. Nevertheless, the highest values on the synthetic accessibility indicator are found in intermediate districts, where catchment areas are large and there is no competition between stations; at the same time, they have high population densities and average access quality indicators. Potential demand values (synthetic accessibility indicator) are low in the periphery because of the lower population density and access quality, although this is also the case with many stations in the centre, which have a smaller catchment area and lie in commercial zones.

Figure 3

Table 9

5. Final remarks

Ease of access to stations constitutes a key element in explaining public transit demand. Until now, however, there have been few systematic studies on the distance people walk to access public transit networks and even fewer on differences according to socio-demographic group. These data are important when it comes to carrying out coverage analysis, because they enable empirically based distance thresholds to be defined.

The walking distance to access Madrid Metro stations is 770.2 metres (percentile 90), which is slightly lower than the 800 metre threshold usually used. Certain groups of population (old people, women, immigrants, public transport captives) are concentrated around the stations and this influences the distances walked; immigrants and captives therefore walk less distance than Spaniards and car owners. However, once the effect of the different spatial distribution of population groups is neutralised, it is observed that young people and adults, men, immigrants and transit captives are willing to walk greater distances.

Information from the analysis of walking distances is important in that it enables data on distances to stations according to population group to be combined with coverage analyses in order to obtain information according to the walking distances of different population groups. This is particularly critical in the case of disadvantaged groups, such as old people without cars, who are not only captive but also have reduced walking mobility. It is also important with respect to capturing demand from groups who have the alternative of private transport and are therefore more demanding with respect to conditions of access to the Metro.

A close inverse relationship has also been observed between distance to stations and frequency of Metro ridership; those who live nearest the stations tend to use the Metro more often. The cause-effect relationship is not one-way, however. Although the most direct explanation is that the Metro is used more by those living near a station, in many cases the choice of where to live is influenced by the wish to use Metro; certain groups choose to live near a station for this very reason. This is known as self-selection. The particular distance-decay functions of each group make it possible not only to identify groups that make more use of the Metro (women, young people and adults, immigrants and captives) but also, above all, to know how sensitive they are to the distance deterrence effect. Men, young people, adults, captives and immigrants are less sensitive to the effect of distance than women, children, old people, car-drivers and non-immigrants.

Two indicators have been also proposed in order the measure access quality and potential demand. It has been demonstrated that both are sensitive to changes in the spatial distribution of population groups within the catchment areas. The access quality indicator shows that children make up the group in the worst situation, considering both the spatial distribution of the groups and the specific effect of distance friction on each of these. In addition, stations in the centre have high access quality values, since the catchment area of these stations is reduced by competition between them. However the synthetic accessibility indicator shows that potential demand is lower in the most central (small catchment areas) and most peripheral stations (lower population densities) than in the stations located in the intermediate areas. On the other hand, the synthetic accessibility indicator is more expressive of potential demand than the mere consideration of the amount of population covered. This indicator in effect has the advantage of incorporating the specific distance-decay function for each group in a way that reflects the greater or lesser use they make of public transit depending on which distance band they live in.

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Table 1. Population distribution according to groups and distance to the Metro stations

	Distance to the station (km)														
Groups	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
Total population															
Population	108727	334584	470746	512871	511121	338506	289856	214668	175871	156018	91811	85090	68924	55876	51454
Accumulated percentage	3.1	12.8	26.4	41.2	55.9	65.7	74	80.2	85.3	89.8	92.5	94.9	96.9	98.5	100
Sex (total)															
Women	59147	181645	255200	275226	271074	177271	149748	109633	89807	79978	47281	43865	35457	28516	25893
Men	49580	152939	215546	237645	240047	161235	140108	105035	86064	76040	44530	41225	33467	27360	25561
Sex (accumulated percentage)															
Women	3.2	13.2	27.1	42.1	57	66.7	74.8	80.8	85.7	90.1	92.7	95.1	97	98.6	100
Men	3	12.4	25.5	40.1	54.7	64.6	73.2	79.6	84.8	89.5	92.2	94.7	96.8	98.4	100
Age (total)															
4 - 12	8436	25829	36818	41438	43375	29799	26303	20960	17657	16171	10132	9561	8222	7194	6915
13 - 23	14627	44697	62480	69421	71468	50177	44847	33375	26695	23464	14078	13031	10750	8333	7574
24 - 65	64054	196740	276094	299680	300565	200274	172440	128091	105769	94363	55679	51605	41017	33427	30594
> 65	21610	67319	95354	102331	95713	58255	46266	32241	25750	22021	11922	10893	8935	6922	6372
Age (accumulated percentage)															
4 - 12	2.7	11.1	23	36.4	50.5	60.1	68.6	75.4	81.1	86.4	89.7	92.8	95.4	97.8	100
13 - 23	3	12	24.6	38.6	53	63.2	72.2	79	84.4	89.1	92	94.6	96.8	98.5	100
24 - 65	3.1	12.7	26.2	40.8	55.4	65.2	73.6	79.9	85	89.6	92.4	94.9	96.9	98.5	100
> 65	3.5	14.5	30.1	46.8	62.5	72	79.5	84.8	89	92.6	94.6	96.4	97.8	99	100
Number of cars per household (total)															
0	18850	57144	77615	79148	73180	45166	35540	24500	19128	16267	9274	8029	6790	5142	4491
1	15806	49036	69890	77531	79766	54506	47705	35553	29103	25838	15040	14176	11369	9349	8672
2	5058	16210	23421	26489	27268	18498	16640	12912	11093	10275	6503	6247	4770	4185	3816
3 or more	1533	4637	6790	7912	8173	5457	5045	3952	3428	3027	1806	1710	1341	1138	1155
Number of cars per household (accumulated percentage)															
0	3.9	15.8	32	48.5	63.7	73.1	80.5	85.6	89.6	93	94.9	96.6	98	99.1	3.9
1	2.9	11.9	24.8	39.1	53.7	63.8	72.6	79.1	84.5	89.2	92	94.6	96.7	98.4	2.9
2	2.6	11	23.1	36.8	50.9	60.5	69.1	75.8	81.5	86.8	90.2	93.4	95.9	98	2.6
3 or more	2.7	10.8	22.7	36.6	50.9	60.4	69.3	76.2	82.2	87.5	90.6	93.6	96	98	2.7
Nationality (total)															
Spaniards	97318	301557	425959	468560	471932	313037	268368	198903	162871	145649	86306	80771	64203	52722	48976
Foreigners (Latin America, Africa, Asia…)	10207	29254	39824	39151	34488	22324	18494	13681	11657	9478	4897	3772	4249	2723	2048
Foreigners (Western Europe, North America…)	1202	3773	4963	5160	4701	3145	2994	2085	1343	892	607	547	472	431	429
Nationality (accumulated percentage)															
Spaniards	3.1	12.5	25.9	40.6	55.4	65.2	73.6	79.9	85	89.6	92.3	94.8	96.8	98.5	100
Foreigners (Latin America, Africa, Asia…)	4.1	16	32.2	48.1	62.1	71.2	78.7	84.2	89	92.8	94.8	96.3	98.1	99.2	100
Foreigners (Western Europe, North America…)	3.7	15.2	30.3	46.1	60.5	70.1	79.2	85.6	89.7	92.4	94.3	95.9	97.4	98.7	100

Table 2. Walking access to the Metro station according to distance bands

	Distance to the station (km)														
Groups	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
Total population															
Population	60087	155739	203707	181497	165012	119507	87710	50055	37329	24608	11291	9245	5632	4386	3202
Accumulated percentage	5.4	19.3	37.5	53.7	68.5	79.1	87.0	91.5	94.8	97.0	98.0	98.8	99.3	99.7	100
Sex (total)															
Women	36738	88180	115943	104782	97909	67716	47918	26580	20441	12573	6337	4866	2681	2439	1342
Men	23349	67559	87764	76715	67103	51791	39792	23475	16887	12035	4954	4379	2950	1948	1860
Sex (accumulated percentage)															
Women	5.8	19.6	37.8	54.3	69.7	80.3	87.9	92.0	95.3	97.2	98.2	99.0	99.4	99.8	100
Men	4.8	18.8	37.0	52.9	66.8	77.6	85.8	90.7	94.2	96.7	97.7	98.6	99.2	99.6	100
Age (total)															
4 - 12	198	2470	2054	1298	1226	1234	621	194	319	0	0	42	122	0	0
13 - 23	12555	25116	40415	37556	35806	21669	20701	11040	9257	5778	2377	1790	673	652	284
24 - 65	40962	116386	140159	127440	118275	87590	61602	35682	25493	17935	8594	6806	4836	3734	2592
> 65	6371	11765	21078	15203	9703	9015	4786	3141	2262	896	320	609	0	0	325
Age (accumulated percentage)															
4 - 12	2	27.3	48.3	61.6	74.1	86.8	93.1	95.1	98.3	98.3	98.3	98.8	100	100	100
13 - 23	5.6	16.7	34.6	51.2	67.1	76.7	85.9	90.8	94.9	97.4	98.5	99.3	99.6	99.9	100
24 - 65	5.1	19.7	37.3	53.2	68.1	79	86.8	91.2	94.4	96.7	97.7	98.6	99.2	99.7	100
> 65	7.5	21.2	45.9	63.7	75	85.6	91.2	94.8	97.5	98.5	98.9	99.6	99.6	99.6	100
Number of cars per household (total)															
0	24252	69251	84634	70203	65512	44650	29944	13442	11870	7096	3558	3348	950	1689	1041
1	25053	62537	86177	79589	68687	54544	41989	25671	17911	11792	5127	4175	2987	1722	1934
2	8934	18863	27023	23396	24408	17116	13593	9623	5823	5054	2038	1373	1328	592	
3 or more	1848	5087	5873	8310	6403	3196	2183	1319	1725	669	568	349	365	385	227
Number of cars per household (accumulated percentage)															
0	5.6	21.7	41.3	57.6	72.7	83.1	90	93.2	95.9	97.5	98.4	99.1	99.4	99.8	100
1	5.1	17.9	35.5	51.7	65.7	76.9	85.4	90.7	94.3	96.7	97.8	98.6	99.3	99.6	100
2	5.6	17.5	34.4	49.1	64.5	75.2	83.8	89.8	93.5	96.7	97.9	98.8	99.6	100	100
3 or more	4.8	18	33.3	54.8	71.5	79.8	85.4	88.9	93.3	95.1	96.6	97.5	98.4	99.4	100
Nationality (total)															
Spaniards	54753	141325	183584	163138	149153	108745	80801	47190	32888	22930	10468	8714	5217	4023	3061
Foreigners (Latin America, Africa, Asia…)	4465	13013	17173	15313	14772	8991	4881	2281	3772	1585	533	488	413	231	140
Foreigners (Western Europe, North America…)	870	1399	2951	3046	1088	1772	2027	585	669	93	290	42	0	132	0
Nationality (accumulated percentage)															
Spaniards	5.4	19.3	37.4	53.4	68.1	78.8	86.8	91.4	94.6	96.9	97.9	98.8	99.3	99.7	100
Foreigners (Latin America, Africa, Asia…)	5.1	19.9	39.4	56.7	73.5	83.7	89.3	91.9	96.2	98.0	98.6	99.1	99.6	99.8	100
Foreigners (Western Europe, North America…)	5.8	15.2	34.9	55.2	62.5	74.4	87.9	91.8	96.3	96.9	98.8	99.1	99.1	100	100

Table 3. Basic statistics on walking distances (in metres) from home to the Metro stations. In bold, walking distances neutralising the effect of the different distribution of groups according to bands

Groups	Mean	Median	Standard deviation	Coeficient of variation	P 75	P 90	P 95
Total	419.6 / **420.5**	375 / **378.4**	253.4 / **255.3**	60.4 / **60.7**	554 / **563**	763 / **770.2**	905 / **918.1**
Sex							
Women	412.9 / **418.6**	373 / **380**	248.3 / **251.8**	60.1 / **60.2**	542 / **558.3**	751 / **761.5**	885 / **909.2**
Men	428.4 / **423.6**	380 / **377.1**	259.7 / **259.6**	60.6 / **61.3**	569 / **570.2**	783 / **782.9**	933 / **929.3**
Age							
4 - 12	368.8 / **350.8**	318 / **305.1**	225.6 / **210.5**	61.2 / **60**	501 / **484.6**	655 / **631.6**	769 / **741.1**
13 - 23	430.9 / **419.3**	395 / **379.7**	248.3 / **246.2**	57.6 / **58.7**	576 / **559.4**	782 / **768.1**	910 / **903**
24 - 65	422.1 / **421.4**	377 / **379.2**	257.4 / **257.9**	61 / **61.2**	556 / **562.1**	767 / **771**	920 / **925.8**
> 65	372 / **396.4**	322 / **345.6**	225.1 / **245.2**	60.5 / **61.9**	493 / **539.1**	667 / **735.6**	801 / **859.5**
Cars per household							
0	394.6 / **428.2**	354 / **386.4**	241.2 / **260.8**	61.1 / **60.9**	518 / **569.5**	699 / **784.5**	858 / **939.2**
1	433.3 / **418.3**	389 / **373.8**	258.1 / **255.1**	59.6 / **61**	582 / **563.1**	786**767.6**	921 / **912.4**
2	442 / **413.8**	403 / **375.8**	260.7 / **249.2**	58.9 / **60.2**	594 / **560.1**	805**760.1**	938 / **899.1**
3 or more	433 / **401.3**	380 / **357.3**	272.6 / **255.2**	62.9 / **63.6**	541 / **510.5**	829**746.6**	972 / **921.8**
Nationality							
Spaniards	421.3 / **419.1**	376 / **376.4**	254.7 / **255.7**	60.5 / **61**	559 / **562.6**	763 / **768.3**	911 / **917.3**
Foreigners (Latin America, Africa, Asia…)	398.5 / **431.5**	361 / **394.6**	237.7 / **250.8**	59.6 / **58.1**	502 / **552.7**	718 / **789.4**	858 / **925.2**
Foreigners (Western Europe, North America…)	429.2 / **457.2**	357 / **410.4**	250.2 / **261.5**	58.3 / **57.2**	632 / **623.8**	777 / **816.8**	851 / **949.4**

Table 4: Population covered using distance thresholds of the 75 percentile and 90 percentile (**in bold data neutralising the effect of the different distribution of groups according to bands**)

Age groups	4 - 12	13 - 23	24 - 65	> 65	Total
Distance thresholds	501 m / **655m**	576 m / **782 m**	556 m / **767 m**	493 m / **667 m**	-
Population covered	153622 / **202173**	301951 / **385513**	1249102 / **1597440**	371649 / **473906**	2076324 / **2659032**
Distance thresholds (corrected distance)	485 m / **632 m**	559 m / **768 m**	562 / **771 m**	539 m / **735 m**	-
Population covered (corrected distance)	147935 / **196868**	294684 / **383330**	1262776 / **1607573**	404595 / **500145**	2109990 / **2687916**
Differences	-5687 / **-5305**	-7267 / **-2183**	13674 / **10133**	32946 / **26239**	33666 / **28884**
Differences (%)	-3.8 / **-2.7**	-2.5 / **-0.6**	1.1 / **0.6**	8.1 / **5.2**	1.6 / **1.1**

Table 5: Population covered: comparison between standard coverage distance (800 metres) and real/corrected distances

	Age groups	4 - 12	13 - 23	24 - 65	> 65	Total
Population covered (800 metres)		232958	391092	1637938	519089	2781077
Population covered: overestimations of the 800 m standard distance compared with real/corrected distances						
Percentile 75 (real distances)	Total	79336	89141	388836	147440	704753
	%	51.6	29.5	31.1	39.7	33.9
Percentile 75 (corrected distance)	Total	85023	96408	375162	114494	671087
	%	57.5	32.7	29.7	28.3	31.8
Percentile 90 (real distances)	Total	30785	5579	40498	45183	122045
	%	15.2	1.4	2.5	9.5	4.6
Percentile 90 (corrected distance)	Total	36090	7762	30365	18944	93161
	%	18.3	2.0	1.9	3.8	3.5

Table 6: Ride ratios according to distance bands from stations and groups

	Distance to the station (km)														
Groups	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
Total	0.55	0.47	0.43	0.35	0.32	0.35	0.30	0.23	0.21	0.16	0.12	0.11	0.08	0.08	0.06
Sex															
Women	0.62	0.49	0.45	0.38	0.36	0.38	0.32	0.24	0.23	0.16	0.13	0.11	0.08	0.09	0.05
Men	0.47	0.44	0.41	0.32	0.28	0.32	0.28	0.22	0.20	0.16	0.11	0.11	0.09	0.07	0.07
Age															
4 - 12	0.02	0.1	0.06	0.03	0.03	0.04	0.02	0.01	0.02	0	0	0	0.01	0	0.02
13 - 23	0.86	0.56	0.65	0.54	0.5	0.43	0.46	0.33	0.35	0.25	0.17	0.14	0.06	0.08	0.04
24 - 65	0.64	0.59	0.51	0.43	0.39	0.44	0.36	0.28	0.24	0.19	0.15	0.13	0.12	0.11	0.08
> 65	0.29	0.17	0.22	0.15	0.1	0.15	0.1	0.1	0.09	0.04	0.03	0.06	0	0	0.5
Cars per household															
0	1.29	1.21	1.09	0.89	0.9	0.99	0.84	0.55	0.62	0.44	0.38	0.42	0.14	0,33	0,23
1	1.59	1.28	1.23	1.03	0.86	1	0.88	0.72	0.62	0.46	0.34	0.29	0.26	0.18	0.22
2	1.77	1.16	1.15	0.88	0.9	0.93	0.82	0.75	0.52	0.49	0.31	0.22	0.28	0.14	0
3 or more	1.21	1.1	0.86	1.05	0.78	0.59	0.43	0.33	0.5	0.22	0.31	0.2	0.27	0.34	0.2
Nationality															
Spaniards	0.56	0.47	0.43	0.35	0.32	0.35	0.3	0.24	0.2	0.16	0.12	0.11	0.08	0.08	0.06
Foreigners (Latin America, Africa, Asia…)	0.44	0.44	0.43	0.39	0.43	0.4	0.26	0.17	0.32	0.17	0.11	0.13	0.1	0.09	0.07
Foreigners (Western Europe, North America…)	0.72	0.37	0.59	0.59	0.23	0.56	0.68	0.28	0.5	0.1	0.48	0.08	0	0.31	0

Table 7. Decrease in ridership and distance decay according to groups (lines adjusted to the relationship between the ride ratio per person and distance in kilometres from the station)

Groups	β_0	β_1	r^2	R_{VR} (rides/person)	Percentage decrease of the ride ratio every 100 metres
Total	0.5124	-0.3418	0.9626	0.32	-6.90
Sex					
Women	0.5561	-0.3779	0.9573	0.35	-7.03
Men	0.4617	-0.2997	0.9609	0.29	-6.56
Age					
4 - 12	0.0559	-0.0438	0.5625	0.03	-8.15
13 - 23	0.7536	-0.5240	0.9466	0.46	-7.20
24 - 65	0.6112	-0.4006	0.9580	0.39	-6.78
> 65	0.2298	-0.1679	0.8152	0.14	-7.58
Cars per household					
0	1.2813	-0.792	0.9331	0.90*	6.38
1	1.4479	-0.956	0.9536	0.90*	6.83
2	1.4495	-1.015	0.9231	0.82*	7.26
3 or more	1.0969	-0.716	0.8305	0.67*	6.75
Nationality					
Spaniards	0.5126	-0.3439	0.958	0.32	-6.94
Foreigners (Latin America, Africa, Asia…)	0.4995	-0.3153	0.881	0.44	-6.52
Foreigners (Western Europe, North America…)	0.6566	-0.3868	0.4959	0.46	-6.07

* Rides/Home

Table 8. Access quality indicator and synthetic accessibility indicator according to age groups. Sensitivity to changes in spatial distribution of the population groups

Age groups	4 - 12	13 - 23	24 - 65	> 65	Total
Present situation					
Access quality (AQ)	0.57	0.64	0.67	0.67	0.66
Synthetic accessibility indicator (SAI) (potential demand)	176898	317235	1375868	409707	2279709*
Relocation of the population living between 1,000 and 1,500 metres to the 0-100 metre band					
Access quality (AQ)	0.69	0.72	0.74	0.72	0.73
Synthetic accessibility indicator (SAI) (potential demand)	212176	357476	1526345	442800	2538796*

* Total for the row

Table 9: Statistics of population covered at 1,500 metres; access quality and synthetic accessibility indicator according to stations

	Population covered	Access quality (AC)	Synthetic accessibility indicator (SAI)
Stations*	182	182	182
Minimum	6	0.14	1
Maximum	79530	0.93	39145
Mean	18705.6	0.69	12424.8
Standard Deviation	12362.2	0.15	7126.2

* Stations with population within the 1,500 metre catchment area

Figure 1: Process to neutralise the different spatial distributions and rides

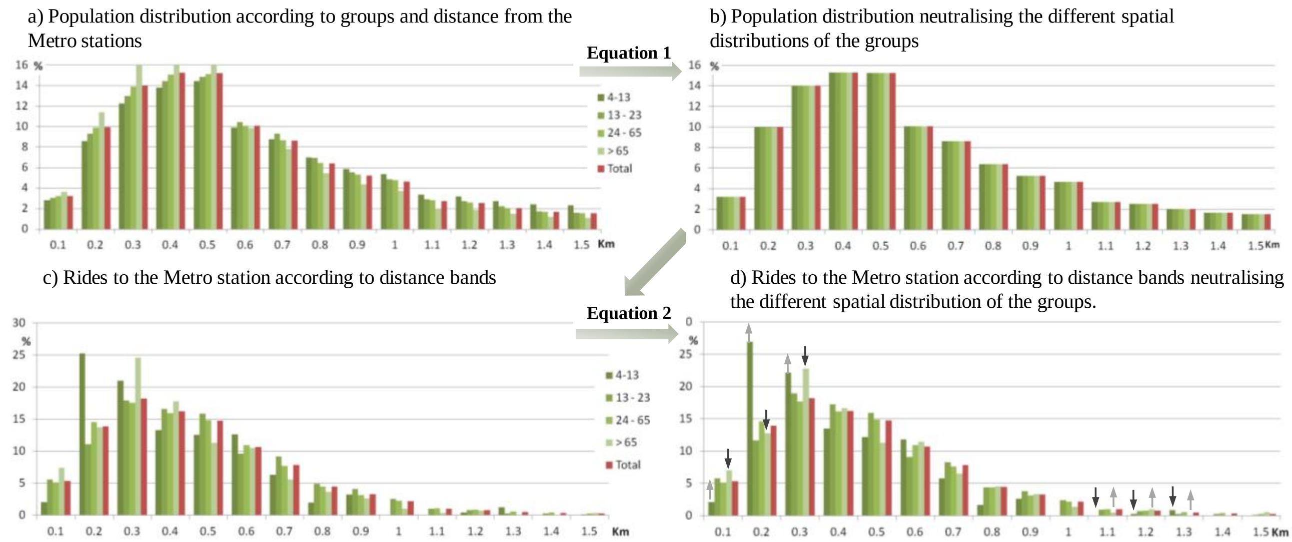

Figure 2: Metro ridership (rides/resident ratios) according to distance from the station and age groups

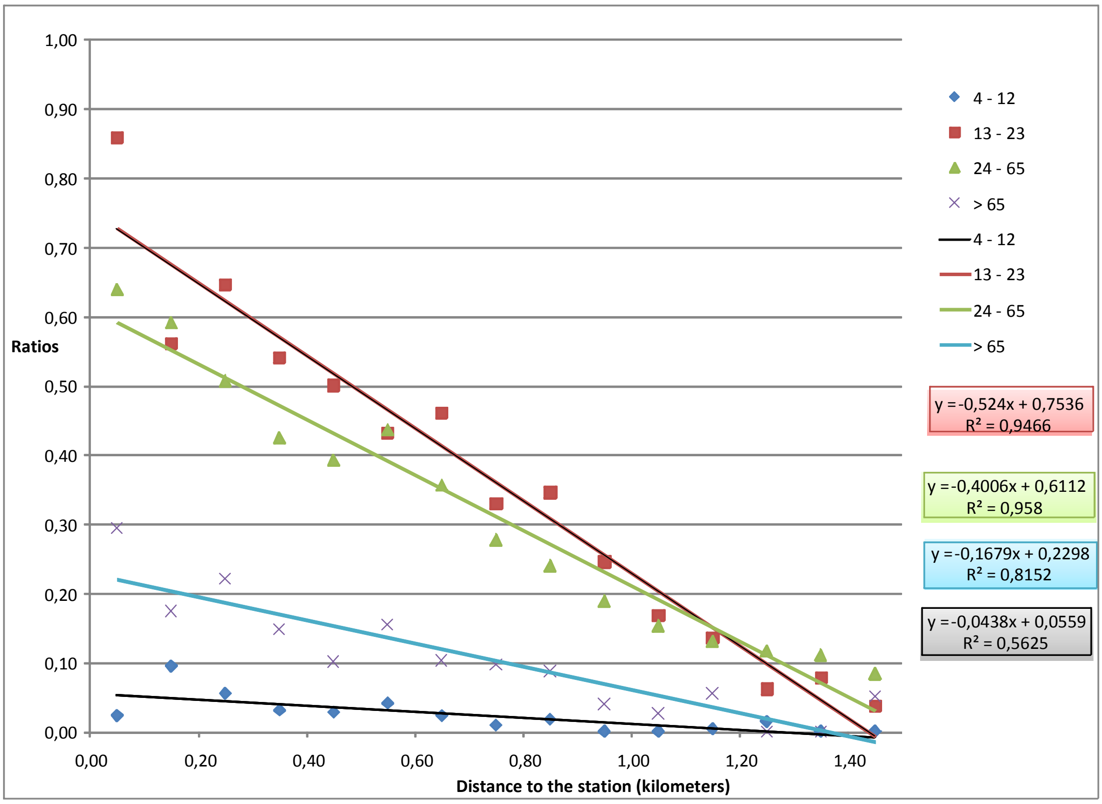

Figure 2. Access quality (AQ) and synthetic accessibility indicator (SAI) according to stations