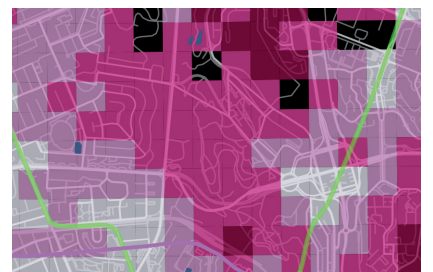# Linking People and Places

New ways of understanding spatial access in cities

Corporate Partnership Board Report

OECD

Linking People and Places

New ways of understanding spatial access in cities

About the International Transport Forum

The International Transport Forum at the OECD is an intergovernmental organisation with 57 member countries. It acts as a think tank for transport policy and organises the Annual Summit of transport ministers. ITF is the only global body that covers all transport modes. It is administratively integrated with the OECD, yet politically autonomous.

ITF works for transport policies that improve peoples' lives. Our mission is to foster a deeper understanding of the role of transport in economic growth, environmental sustainability and social inclusion and to raise the public profile of transport policy.

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Executive summary

What we did

Spatial accessibility relates to how, and how well, people access each other, jobs, services and opportunities. This report examines how different people and groups experience spatial accessibility in cities. It reviews the latest research findings, methodologies and data sources on urban accessibility and discusses how better data and computing power have improved accessibility analysis and mapping, and made it more relevant to people.

This study presents the results of several projects on accessibility measurement carried out by the International Transport Forum. They illustrate how new data sources can be used to refine accessibility analyses and ultimately transport planning. Building upon these experiments, general lessons on how to increase the relevance of accessibility studies are drawn. The findings were discussed and refined in a workshop with 15 experts from seven countries held in Mexico City in October 2016.

What we found

Increasingly, sophisticated measures of accessibility are being developed. Disaggregated metrics, calculated separately for different trip purposes, different travel modes and travel times, different age, sex and occupational groups, or distinct activities allow new insights into where, when and how people move through cities. Helped by previously unavailable data sets, more powerful computing and improved algorithms, these detailed metrics are becoming directly available to policy-makers, commercial actors and to the public and help inform planning and operational decisions.

On a global level, analysis of accessibility across cities reveals the interplay between travel speed and land use-based density of opportunities. For example, many cities in non-OECD member countries have better accessibility (measured as access to the rest of the population) than cities in the OECD, despite the latter having more extensive, faster and less congested transport networks. This is because the former concentrate more population (and, by proxy, opportunities) in a smaller area, which suggests that access through walking is higher and access through vehicle use lower in the non-OECD cities. This is a relevant finding for transport decision-makers in these cities, because investments in active mobility such as walking (or cycling) are typically not a high priority.

What we recommend

Design accessibility metrics to matter for people and policies

Accessibility metrics should be tailored to purpose so they are relevant to people affected by policies under consideration. Simple location-based metrics can be used for benchmarking cities. Person-based metrics can identify social groups and locations with poor levels of access and assess who would benefit from specific policies. Metrics that include the specificities of different travel modes are essential to compare travel options on a fair basis. Finally, utility-based metrics which focus on the welfare created by the transport system allow assessing the redistributive aspects of a project i.e. to identify winners and losers across neighbourhoods and social groups.

Leverage new data sources and methods for accessibility analysis

Authorities and the private sector should avail themselves of new possibilities to better understand how people experience and value accessibility. Historically, the high cost of data collection made accessibility studies infrequent and less timely. This is no longer the case as new data sources are becoming available.

The scale, scope and velocity of available data is increasing. Data science and analytic methods are improving. More and more volunteered or crowd-sourced data is becoming available. The general trend to open data is also increasing availability. Furthermore, reduced timespans between observation and analysis make it possible to use accessibility metrics nearly in real time to shape desired outcomes.

Invest in accessibility, not just roads, in fast growing cities

Road investments alone are not a sustainable option to guarantee adequate levels of accessibility in the world's rapidly growing cities. Today, these growing cities offer reasonable accessibility because of their high population density. But by 2050, density of Asian cities will fall by 19%, requiring the trunk road network to grow six-fold to maintain current accessibility by car. This underlines the crucial importance of stringent land use policies in maintaining accessibility.

Make use of accessibility analyses to support decision-making

Accessibility studies have tended to result in few direct policy impacts and have largely represented a way to gauge regional disparities in urban access. The main reason is that accessibility outcomes result from the complex interplay between land-use policies and transport supply. Although this interaction has not been easy to characterise in a policy-relevant manner in the past, this too is changing with better data and methodologies. Going forward, authorities should leverage these to design policy packages that effectively combine transport and urban planning interventions to improve accessibility in cities. Accessibility analysis should therefore form one of the essential tools that transport planners deploy when addressing transport investment and operational decisions.

1. Introduction

Urban access has sparked renewed interest among policy makers from various sectors. As a cross-cutting theme of the United Nations' Sustainable Development Goals (SDGs), better accessibility to essential services and opportunities for all citizens holds the promise of a more equitable, sustainable and economically viable future. While more generally, there is increasing consensus about the values of urban access, in areas of policy and planning the use of accessibility metrics still faces significant practical and methodological challenges.

Accessibility can roughly be defined as the ease of reaching goods, services, activities and destinations (Litman, 2011). Accessibility is certainly not a new concept in the field of transport studies. While significant work has been achieved since Hansen (1959), this report argues it is time for reassessing accessibility for two main reasons.

Firstly, accessibility metrics are likely to become a central concept in transport planning over the years to come. Appraisal of transport projects has traditionally focused on travel time savings and congestion relief. However, there is a growing understanding that this misses the ultimate purpose of the transport system, which is to provide access to employment, goods, services and other opportunities. Consequently there is a new focus on measuring the accessibility provided by transport infrastructure and by the planning of cities.

Secondly, increasing data availability and computing power have made accessibility mapping much easier. Thanks to new models and platforms of data generation – based on satellite imagery or mobile phones, open and crowd-sourced – applications for accessibility mapping have been proliferating. By providing synthetic information and visual intuition, these maps are valuable tools for policy making.

Choosing the right measures and parameters for assessing accessibility is critical for policy guidance. When comparing the level of job accessibility by car and by public transport, for instance, should travel time be the sole criterion? Considering a city's layout, levels of road congestion and the perception of safety, is a 30-minute commute by bicycle (e.g. all uphill) comparable to driving? The same holds for predetermined thresholds for travel time: while some research puts forward a 60-minute travel time threshold for job accessibility as a proxy for the effective size of urban labour markets (Bertaud, 2014), other research considers individual perception in determining the willingness to reach a given destination, at a given time and a specific travel mode (Martinez and Viegas, 2013).

The aim of this report is to get accessibility measurement and mapping right for policy in this context. After reviewing the existing metrics in the literature (Chapter 2), the report presents how new data sources can help accessibility studies to be more relevant for transport planning decisions (Chapter 3). This potential is then illustrated on three practical examples. Chapter 4 illustrates how new data sources can be used to analyse and compare accessibility across global cities. Chapter 5 presents how data on cycling behaviours, e.g. GPS traces, can help understanding cyclists' preferences and why this is important to assess the best policies to improve accessibility. Finally Chapter 6 shows how to calculate the potential of accessibility improvement of the different neighbourhoods simply by improving their public transport connections, and to identify the corridors along which those new connections would be deployed.

2. Setting the scene: A policy-oriented literature review

Accessibility research has a long history and, overall, analytical approaches have been moving towards more detailed models accounting more adequately for complexity in travel behaviour (Geurs et al., 2012). Two main streams of works can be identified. On one side transport economists have been focusing on providing the microeconomics foundations behind the concept of accessibility (Ben-Akiva and Lerman, 1985). This allows accessibility to be interpreted as the benefit that people derive from the access to spatially distributed opportunities. On the other side, transport planners and geographers have increasingly analysed accessibility at an individual level. An example of these metrics can be found in the space-time geography of Häsgerstrand (1970) that incorporates spatial and temporal constraints, i.e. whether observed or assuming individual activity programmes can be carried out given time restrictions.

The wide variety of existing accessibility metrics in academic literature is certainly evidence of the interest of the subject, but has also created much confusion for practitioners. This has led to misuse of indicators and has made it difficult to compare studies. This chapter provides an overview of existing approaches to accessibility by introducing the relevant concepts and adopting a practical, policy-oriented point of view. It argues that, from a policy perspective, there is actually a limited number of metrics, although this is sometimes difficult to realise due to the diversity of terminologies and perspectives in the literature. The first section sets the basic concepts, while the second one presents the main trade-offs a practitioner faces to design metrics that are relevant for policies.

A common semantic toolbox of territorial accessibility

To ensure that accessibility metrics are addressed properly in policy and planning, it is important to establish clear and common terms and concepts. Ways of measuring accessibility abound and remain subject to wide discussion (Geurs and Wee, 2004). However, there is broad consensus about understanding accessibility as the ease or potential for reaching valued locations, such as services, goods, jobs or other forms of opportunities (Paez, 2016; see also Hansen, 1959; Owen and Levinson, 2014). To correctly define and understand the variety of existing metrics, it is first necessary to define the main underlying concepts. For this report, the terminology presented in Box 1 will be used.

Accessibility metrics can be analysed through three dimensions. The first dimension relates to transport costs. Here cost needs to be understood in the generalised sense i.e. it can include the non-monetary costs of a journey such as travel time but also reliability or comfort. The second dimension is how land use, or more precisely the spatial distribution of valued destinations, is represented. The choice of what is to be accessed will very much define the scope of the metric. When focusing on access to the labour market, it might be more interesting to focus on specific job types, like unqualified ones, or specific sectors, like services, depending on the policy goals. When focusing on access to education, the type of schools considered matters; for example, should universities be included? If so, should universities be weighted as heavily as primary schools in the final metric? Although these issues are often regarded as minor in academic literature, they are in fact at the heart of the practitioners' interests, as bad choices might lead to misleading results and wrong policy advice.

The final dimension relates to how the individual perception of transport costs and opportunities are represented. In this report, this covers mainly two aspects. The first aspect is the cost decay function, which is defined as how the interest in a destination decreases as transport cost to reach it increases. In simpler terms, it specifies what is considered as "near" and what is considered as "far" (see Box 2). Of course, this definition varies across trip purposes, modes and more generally cities. The second aspect is the level of disaggregation considered. Individuals perceive accessibility based on their needs (depending on their age, gender or income) and their transport abilities (depending on their physical conditions, travel

budgets and if they own a vehicle). Increasingly sophisticated measures of accessibility can be made by computing disaggregated metrics separately for different trip purposes, travel modes and travel times, different age, sex and occupational groups, and distinct activity.

Box 1. **Key concepts to design accessibility metrics**

The general formula of an accessibility metric is:

$$A = \sum_d M_d . f(C_d)$$

The key concepts of this formula are:

- **Territorial units** define the zoning system and can be nodes in a network, cells in a grid or irregular polygons in a map. Typical examples include census block or administrative boundaries, at least when they make sense from a territorial perspective (denoted as d in the formula).

- The **mass of attractor** represents the value of the opportunities in the different territorial units. It can be jobs, square-metres of dedicated facilities or population (denoted as M in the formula).

- The **travel time** from the origin unit to the destination unit, including the time spent in transfer and waiting.

- **Latency** is the additional inconvenience due to non-continuous availability of service. When the connection between two units implies transfers, not only the entire time spent in the transfer must be counted, but possibly also some penalty for the inconvenience (and higher risk of delay). This concept is somewhat related to the more widely-used, but more specific, concept, that of schedule delay costs (Vickrey, 1969).

- The **cost or impedance** of a trip describes the difficulty to reach a destination unit to an origin unit. It can include monetary costs (marginal, average) as well as non-monetary (travel time, comfort, reliability, or different forms of negative externalities) (denoted as C in the formula).

- The **cost decay** is a monotonous function of impedance that represents the decreasing attractiveness of a place as it becomes more difficult to reach (denoted as f in the formula).

Numerous typologies of accessibility measures have been designed, often focusing on different aspects or targeting different academic communities. Considering the one proposed by Geurs and Wee (2004), a review that is relevant for transport planning, three streamlined perspectives can be distinguished:

- Infrastructure-based metrics typically analyse the performance of the transport infrastructure or service level. Typical examples include average speeds, number of people living near transit stations, or infrastructure densities. These metrics are not demanding in data but only provide information on the supply side of transport (i.e. do not include information about land-use or transport demand) and thus do not provide a proper measure of accessibility.

- Location-based metrics integrate the land-use dimension and assess the level of accessibility for an average user, thus neglecting most of the heterogeneity among users.

- Person-based and utility-based metrics analyse accessibility on the level of individuals/groups taking into account their characteristics and constraints to derive the level and value of accessibility. Thus they are the more complete and complex metrics.

Box 2. **Cost decay functions: Defining "near" and "far"**

When evaluating the attractiveness of an object, it is intuitive that objects that are located "near" are more attractive than objects located "far". This is known as the first law of geography: everything is related to everything else, but near things are more related than distant things. This concept is modelled in accessibility metric via the cost decay function that evaluates the loss of attractiveness of an object with impedance. A number of different cost decay functions have been introduced when evaluating accessibility, but they are essentially two options: threshold functions and smooth ones (see Figure 1).

Figure 1. **Different types of cost decay functions**
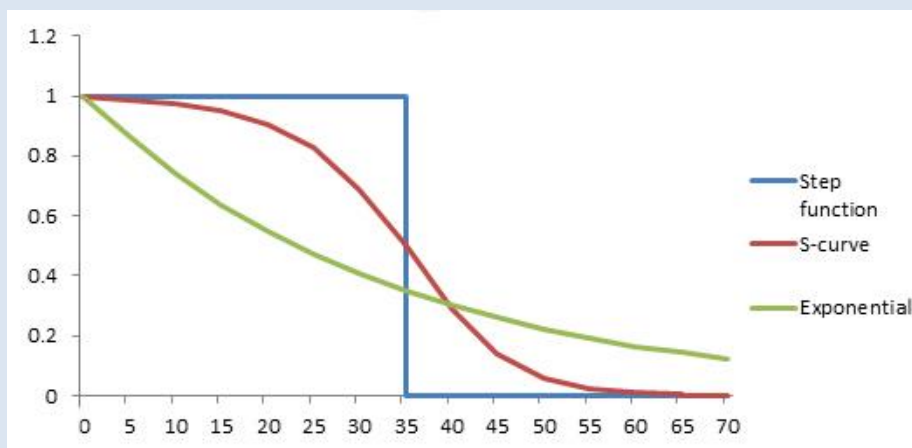
With a threshold function the attraction of objects drops at a certain interval (e.g. 30 or 60 minutes). This type of functions provides clear and easily readable results, such as number of hospitals accessible within 30 minutes. Thus this is our recommended choice for benchmarking, as explained in Chapter 4. However, threshold functions might work in a counterintuitive manor. Is an activity/opportunity located 31 minutes away from an origin much less significant than one located at 29 minutes? Furthermore, objects located in the "ends" of each step should not have the same attraction.

This led researchers to employ smooth cost decay functions to measure accessibility. Commonly used functional forms are negative exponential, Box-Cox or Tanner functions. In this report, the retained option for case studies (Chapter 5 and 6) is the generalised logistic function, or the S-curve, in which the concepts of near and far are quite clear, based on the recommendations of Martinez and Viegas (2013).

Designing metrics that matter for people and policies

Building on the previous definitions, Figure 2 introduces a simple framework. Rather than an additional typology, this is to be seen as a straightforward tool for the practitioners to choose between the available categories of metrics.

The main trade-off expressed here is between having a comprehensive and exhaustive set of accessibility metrics without ending up with results that are too complex. Starting from a very simple metric to measure access to jobs (i.e. the number of jobs that can be reached within 30 minutes), there are two main ways for improvement. First, this location-based metric can be turned into a person-based metric by disaggregating it in several group-specific metrics. Two simple examples include considering different travel times depending on the ownership of a vehicle or considering access to specific types of jobs depending on the level of education. Second, travel time can be replaced by a generalised cost in order to take into account other aspects of a trip. For instance, discomfort and low frequency have an impact on the level of accessibility provided by a transport system.

Figure 2. **Available options for the practitioner**

Transport dimension

	Travel-time-based	Generalised-costs-based
Location-based	Compare cities *Ex: Number of jobs within 30 min*	Identify improvements of the transport system *Ex: Number of opportunities within 1 hour of generalised travel times*
Person-based	Study equity and distributionnal aspect of projects and policies *Ex: Number of jobs of a specific type weighted by a S-function*	Assess large projects *Ex: Utility based metrics*

Individual dimension

This leaves us with four possibilities, each being relevant for a specific usage. The following subsections give a quick description of each one as well as an overview of the new perspectives offered by new data sources.

Simple location-based metrics: Benchmarking cities

Comparing cities and how their transport system provides accessibility is important for identifying best practices. This has long been a very difficult task, mainly because data was neither standardised, nor available. However, as globally available datasets are appearing, this is no longer an issue.

Using simple, location-based metrics is a recommended option for large scale benchmarking. Indeed, complex person-based metrics limit the potential for comparison. An example of a large scale benchmark, as well as recommendations for such an analysis, is given in Chapter 4.

Person-based metrics: Analysing equity issues

Accessibility measures and maps are useful in helping to identify social groups and locations with poor levels of access to services but also to assess who would benefit from a policy to be implemented. However aggregated, location-based metrics don't account for differences in physical capabilities and mobility levels of different social groups of people and are thus of limited use in analysing equity outcomes. This explains why academics have long argued the interest of person-based metrics to assess transport project and policies.

However, two reasons explain why this has hardly been done in practice. First, the data requirements and computational needs have stopped practitioners from implementing person-based metrics. We believe that, as more and more data is available, this is no longer the case for many cities. Even in the developing world the amount of data available through remote sensing and mobile phone data is now impressive (see Chapter 3 and 4).

Second, person-based metrics are less aggregated and thus more difficult to analyse. Analysing the effect of an infrastructure on several user groups depending on their socio-economic characteristic as well as their

location quickly becomes a tedious task and deriving policy recommendations out of this large amount of data is usually difficult. There again we believe that this, along with the development of new data visualisation techniques, is likely to change. Interactive mapping techniques now allow analysts to explore large data sets in a user-friendly way (see Box 3 for a detailed example).

Box 3. **Potential job accessibility in wider New York City**

The Regional Plan Association, an urban research and advocacy organisation based in New York City, has developed an interactive mapping website displaying job accessibility. The tool displays the number of accessible jobs from different locations for wider NYC, choosing the industrial sector, educational profile, transport mode and maximum travel time. While more than 9.6 million jobs are available in wider NYC, a typical resident living in East Flatbush, Brooklyn, can reach 1 261 000 jobs within a 30-minute drive (Figure 3, upper left). Using public transport, the number of potential employment locations drops to 108 000 for the same place (upper right). However, 663 000 jobs could be reached by bicycle (lower left); walking enables a reach to just 35 000 job locations.

Figure 3. **Job accessibility in New York**
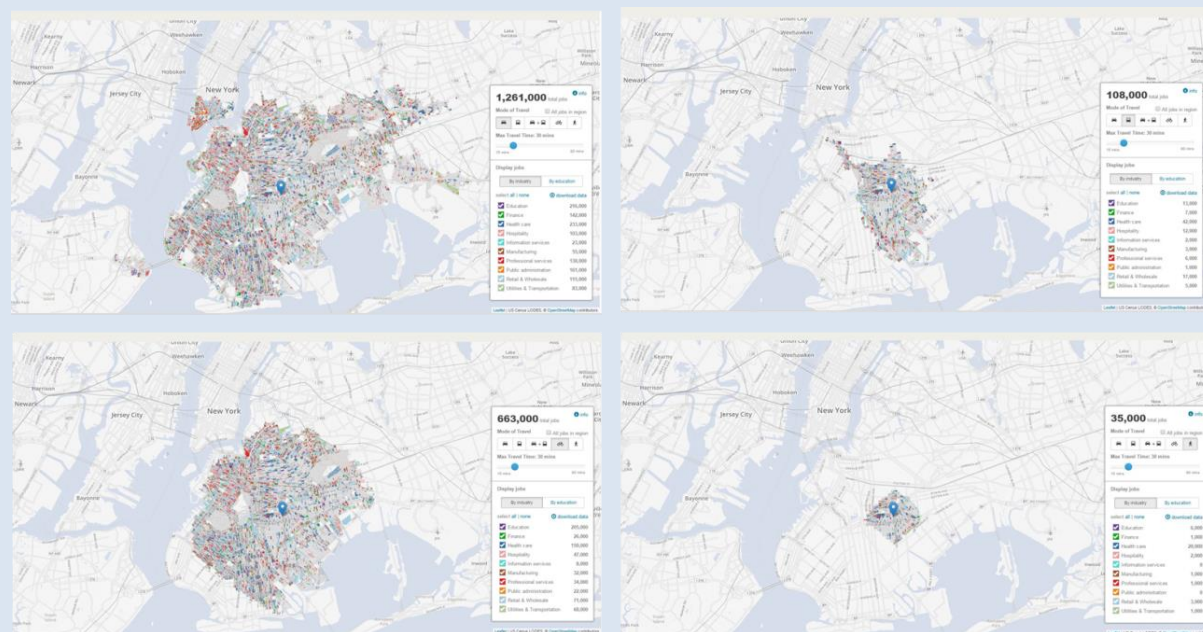
Source: New York Regional Planning Association (2017).

Generalised-costs metrics: Taking into account the specificities of each mode

Travel time is usually an imperfect proxy to impedance. A trip can be fast but inconvenient and expensive; thus a person might prefer to take a longer route or a slower mode if it is less expensive and more comfortable. Correctly assessing accessibility implies understanding the route and mode choice strategies of the transport system users. This requires surveys to describe travel behaviours as well as significant analytical work.

Nevertheless, when trying to identify how the transport system can be improved to provide better accessibility, taking into account generalised costs is essential. Chapter 3 and 5 illustrate this point for cycling and show that, when it comes to designing cycling policies, a simple location-based metric would lead to incorrect policy recommendations. It illustrates how GPS traces can help understanding cyclists' preferences and why this is important to assess the best policies to improve accessibility.

Utility-based metrics: Assessing large projects

Accessibility is usually poorly or indirectly taken into account when assessing transport policies. Traditional appraisal frameworks tend to favour projects leading to large travel-time saving rather than projects actually providing access. Better accounting for accessibility improvements is thus regarded as an important and required evolution in the way transport planning is conducted. In particular large transit investments, such as the Crossrail project in London and Grand Paris Express, often offer limited travel-time savings compared to the investments costs required, but significantly increase access.

Utility-based metrics interpret accessibility as the welfare created by the transport system and are thus particularly well-fitted for decision-making. As they are person-based, utility-based metrics allow assessing the redistributive aspects of a project, i.e. to identify winners and losers across neighbourhood and social groups. This is important as the traditional approach to assessment, costs benefit analysis (CBA), is based on aggregate welfare maximisation and often neglects equity issues. As they are based on generalised costs, utility-based metrics allow taking into account all the relevant attributes of a transport service, e.g. comfort, reliability and affordability, which is an important requirement for any project assessment. Finally utility-based metrics have strong microeconomic foundations and can thus be directly used in traditional CBA.

On the other hand, utility-based metrics are difficult to interpret and communicate. That is to say, the measure cannot be easily explained without reference to relatively complex theories which most planners and political decision-makers do not completely understand. As utility-based metrics is a wide and still controversial field, it will not be studied in detail in this report. However it is important to remember that they are considered by many academics as the appropriate way of taking in account accessibility for project assessment.

3. Increasing the relevance of accessibility: New data sources for improved insights

Data requirements for accessibility analysis

Measuring accessibility requires a broad range of data inputs in order to deliver accurate and relevant results. These data inputs help define the multiple components referenced in earlier chapters that inform accessibility metrics. Typically, these data have been relatively expensive to gather which has limited the frequency with which they are collected – reducing, in turn, their relevance. This has implications regarding the ease with which accessibility can be calculated and the relevance of those calculations to people's actual experience.

For instance, data on where people are travelling from, where they are travelling to, how they travel and for what purpose are typically collected via expensive and infrequent (yet bias-adjusted and generally high-quality) origin-destination (OD) household travel surveys. Because of their periodicity and because they rely on data collection methods that may not adequately reflect current lifestyles (e.g. a reliance on land-line interviews when many people no longer subscribe to these in favour of cellular phones), they may not adequately capture travel behaviour – especially when it is undergoing rapid changes. For instance, many current national and regional household travel surveys were conducted before the emergence of ride services like Didi Chuxing, Uber, Lyft and Grab – yet these and other emerging travel options are already impacting and will plausibly continue to change the mobility landscape in many cities before the next round of household travel surveys are completed. Likewise, data on population and employment is collected via national censuses that are equally periodic and may not accurately reflect reality due to rapid growth and a large share of informal settlements and employment in many parts of the world. Even the digital maps that are necessary for routing calculations in accessibility analysis have historically been produced by national cartographic agencies and updated on a variable basis. In many cities, especially in emerging economies and low-income countries, these maps may be outdated or missing altogether.

These are not necessarily insurmountable challenges since a lot of what is necessary for accessibility calculations can be modelled both on the basis of real-world data as well as on the basis of assumptions based on smaller sample observations, micro-data sources and reasoned guesses. Nonetheless, there are a number of new and emerging data sources that should allow timelier and more relevant accessibility metrics.

Changes in terms of accessibility-relevant data

Four factors are rapidly changing in terms of accessibility-relevant data.

Scale, scope and velocity of data

The first, and potentially the most important by far, is the scale, scope and velocity of data being produced that can better inform accessibility analysis. This is a result of the deployment and growing ubiquity of connected data-producing and data-logging devices – many with multiple sensors and on-chip computing capability. These devices are rapidly increasing in number from less than 20 billion today to anywhere from 50 to 80 billion in 2025 (Nordrum, 2016; Press, 2016). Among these objects are various embarked devices in connected cars, smartphones, personal activity-measuring devices, surveillance cameras, condition sensors, Wi-Fi routers, etc. These devices produce data that can be used to infer a number of accessibility-relevant indicators; trip origins and attractors, population distribution, effective travel speeds, dynamic changes in travel patterns and flows over the course of the day, the value of certain destinations to travellers, routing heuristics used by travellers, service schedules, frequency, reliability, etc. The amount of

data produced by the internet of things will be massive – one estimate puts it at 2 zettabytes by 2025, or 2 trillion gigabytes (Machina Research, 2016) – though this represents only a small fraction of the estimated 180 zettabytes (180 trillion gigabytes) of data produced globally in 2025. Extracting actionable insight from this raw data is not trivial but this is another area where change is underway.

Data science and analytics

The change in data science and data analysis is the second factor to consider going forward and this will enable more and more useful information to be derived from the rapidly rising amount of raw data. Instead of managing the vast amount of data via isolated databases, increasingly data will be stored on cloud servers with remote access and analysis features. This move, in itself, does little to increase the availability of access-relevant data since much of the data thus produced is commercially sensitive for the companies deploying the sensing devices generating the data. Additionally, these companies often have a commitment to preserve the privacy of their clients whose identities could be compromised by the release of the data. Nonetheless, the volume and nature of actionable data to inform accessibility analysis could increase the relevance and timeliness of accessibility analysis if this analysis can take place without compromising commercial secrets and privacy concerns.

Furthermore, the deployment of increasingly "smart" sensors (sensors tethered to micro-chip-level processing and storage capabilities) opens up new opportunities in "edge computing". Sensors typically generate much more data than they log and transmit. Only a very small share of that data is logged, stored and eventually transmitted for analysis – typically to a local, non-cloud-connected database. Rather than bringing data to physical or cloud databases where it then undergoes analytical operations, the new capabilities offered by smart sensors means that the code can be brought to the data where it is being sensed – at the "edge". The analytical output of that data could be greatly enriched in certain circumstances by moving the code directly "in stream" within the sensing chip itself. This distributed analytical capacity opens new, more flexible possibilities for treating raw data (the code can be pushed to devices according to analytical needs) and because of the low latency for data treatment, this increases the possibility for accessibility to eventually be monitored in near real-time.

The rise of volunteered or crowd-sourced data

A third changing factor is the growing volume of volunteered or crowd-sourced data that can usefully inform accessibility analysis. Individuals are increasingly willing to provide data to commercial entities in return for services they value. These may include location details for restaurant and bar reviews, ride-sourcing services, social media updates or route search behaviour in online map and navigation platforms. These may be useful to infer certain accessibility metrics – especially when they reveal preferences for locations or routes that deviate from those that are the most obvious or display differences in the way in which various demographic or income groups access opportunities.

Crowd-sourcing certain basic data required for accessibility analysis – especially data regarding travel behaviour, networks, services and amenities – has opened new possibilities for understanding accessibility in a much more detailed and timely way. This is especially true in regions of the world where this data has been notoriously flawed or missing. Foremost among these types of data is the crowd-sourced and editable digital atlas of the world, OpenStreetMap, which is at the base of much of our own global analysis of accessibility.

A move to open data

Finally, the fourth rapidly changing variable in the datascape surrounding accessibility is the move to more open access to much of the data that can be useful for analysis. Governments at all levels increasingly adhere to open data principles. They put in place policies that promote transparency, accountability and

value creation by making government data available to all as per recommendations from the OECD's Open Government Data initiative (OECD, 2017). Much of this data – including census, household travel survey, geographic, and transport-related data – is useful, and even necessary, for accessibility analysis. Open data initiatives may also extend to data held by the private sector or quasi-public companies like those that provide public transport services in some cities. In these cases, some data may be made completely open while other data is made available via the controlled use of application programming interfaces (APIs) that allow access to the data held by commercial entities – though access may be restricted in terms of the amount of data that can be transferred at no cost.

Parallel to the move to open datasets is a similar move towards the development of crowd-built open-source data analytic tools – for example QGIS (geographic analysis) and Transport Analyst (accessibility analysis). These, and various open programming frameworks (e.g. Python, Java, R), are increasing the speed with which novel data analytic approaches can be tested and are rapidly becoming default tools in the accessibility toolbox.

New data sources and approaches for improved accessibility analysis

The four mega-trends described in the previous section are changing both the practice of measuring accessibility and widening its scope. While many of the ways in which accessibility is measured will remain as they were in the past, much of what was thought to be too difficult to carry out due to lack of adequate data or sufficient computing ability is now newly possible. The scope and pertinence of accessibility analysis is thus improved and better policy-oriented insight can be derived. Furthermore, the decrease in latency between observation and analysis is leading to a situation where real-time accessibility metrics support operational outcomes for the private sector and real-time control capabilities for public authorities. Perhaps most important is the manner in which a lot of newly available data gives rise to a better understanding of the contextual and chronological variability of access which better reflects how people actually experience and value destinations (Chen et al., 2016).

The following sections illustrate how and where this is happening and points to where further changes may be expected by looking at recent developments regarding data necessary to calculate accessibility in the following areas:

- availability and quality of transport networks
- availability and quality of transport service and measuring outcomes
- understanding where people are going and how they travel
- calculating travel times
- understanding why people travel
- gauging the subjective travel experience.

Data regarding the availability and quality of transport networks

As noted before, accessibility calculations rest on two major components: information regarding transport networks and information regarding where people are travelling to and from. Traditionally the former has been built on official cartographic data – typically from national cartographic agencies, augmented by regional and local geographic data held in agency geographic information system (GIS) databases. In many countries and cities, these were not accessible to the public or available for open use. This has changed in many (but not all) OECD and ITF member countries (see Figure 4). According to the Global Open Data Index (itself crowd-sourced), much of the national cartographic data in the world – including in OECD and ITF member countries – cannot be considered truly "open" (Global Open Data Index, 2016). Though

progress is being made, there is still much to be done in order to make this data useable, especially for global and comparative accessibility analyses.

Some countries collect and disseminate global spatial datasets that are useful for understanding how to integrate certain transport networks into accessibility analysis. For instance both the US National Aeronautics and Space Administration and the European Space Agency distribute digital elevation data based on space-borne synthetic aperture radar platforms. These global high-resolution digital elevation models are useful in calculating some accessibility metrics – especially for active modes where slope is an important factor to consider.

Cities are increasingly opening up local geographic datasets for public use – including data on road networks, rail networks, bicycle infrastructure, public transport-related infrastructure. This data, however, is not easy to aggregate across cities let alone countries which complicates broad cross-regional comparison of accessibility. This data is also typically not easily updated by users, which limits its usefulness for bespoke accessibility calculations that require data not be included in official maps.

At a global scale, several commercial platforms provide and update very detailed maps that generate substantial revenue by enabling consumers to use navigation and location-aware services. These include map-based platforms from Apple, Baidu, Google, Here and Microsoft Bing. These and certain regional map platforms like Tencent in China and Naver in Korea may allow access to some geographic data via API calls, though these are typically limited in volume and generally are not free. Some platforms, like Microsoft's Bing, allow more open access to (and use of) the aerial photography/satellite layer which can help determine the presence of objects in the real world – including buildings and networks.

Figure 4. **2015 Global Open Data Assessment of National Map Data**

Source: ITF based on Global Open Data Index (2016).

One key change that has opened up new horizons for accessibility analysis is the creation of several fully open global spatial datasets - largely in response to the lack of availability of detailed, harmonised and user-responsive geographic data. Fully open spatial data platforms like Natural Earth's and crowd-sourced mapping platforms like OpenStreetMap (OSM) have significantly expanded the scope of possible analysis in terms of measuring accessibility, especially across different jurisdictions and in areas where spatial data is lacking.

Initiated in 2004, OSM is a global collaborative project leveraging volunteered geographic information in order to construct a fully editable map of the world. It builds on widespread internet penetration, broad dissemination of GPS-enabled data logging devices (including smartphones), open-source software and open access to remote sensing resources including aerial photography. Inspired by Wikipedia, it has grown from a discontinuous map of uncertain quality in many regions to a relatively high-quality map constantly fed and edited by a community of 3.5 million members. Data checking is robust, errors easy to discern and rectify and, at least for the general topology and geometry of transport networks in many regions, OSM data is indiscernible from official mapping resources – especially since certain national mapping agencies and local mapping departments upload their data directly to the platform.

Based on GPS traces, measurements and geocoding from screen images of aerial photography, OpenStreetMap cannot match the positional accuracy of many national or commercial mapping platforms that use several sources for location fixes (laser scanner, GPS, etc.). Reviews of OSM quality and exactitude find that these differ by region and country with OSM data quality exceeding that of national or proprietary databases in certain cases (Brovelli et al., 2016). Strict positional accuracy, however, is not a critical component in accessibility analysis – unlike topological correctness and network completeness. For the latter, and sometimes for the former – depending on the region – OSM provides generally acceptable data for routing calculations across transport networks. In any case, simple tests can help discern the representativeness of OSM data.

In the global accessibility work described in the previous chapter, two such tests were applied to the raw OSM street network extracts. The first was to compare the density of junctions across similarly-sized urban areas within and between regions. If one city displayed a much lower junction density profile, chances were that the city in question had not been adequately mapped and the city was dropped from the analysis. Another test was to see if the network was topologically complete and if each grid used in the analysis could be connected and routed to the network. These tests help make up for some of the inherent data quality issues in OSM though these are generally becoming less numerous over time.

One of the most interesting features of OSM in terms of novel types of accessibility analysis is the ability for users to edit the map and create new map categories ("tags") which, after validation by the OSM mapping community, can be used for more detailed accessibility analysis (see Figure 5). Tags for sidewalk kerb-cut locations help map wheelchair accessibility and cycling-specific tags have enabled a new understanding of cycling accessibility in many cities. The editing function of OSM can help provide a more detailed understanding of the location and quality of transport networks ensuring that results accessibility analysis reflect up-to-date conditions.

National cartographic data and commercial mapping platform data typically does not encode or represent the "quality" of transport infrastructure or networks beyond simple geometric measures (lanes, track width, etc.). City data may include more information on those aspects of the network that are useful for calculating impedance and travel speeds in accessibility analysis. And as noted above, OpenStreetMap allows users to edit and update map data to include a number of accessibility-relevant variables. However, with the deployment of more and more sensor- and video camera-equipped cars, an increasing number of vehicles will capture, encode and transmit detailed high-definition map information that extends beyond just the simple geometric representation of the road to a more holistic and detailed view of the road

environment. Coupled with the move to edge computing that pushes analytic and processing code into the data capture stream, the type of data derived from these vehicles can ensure timely, highly detailed and self-updating maps which start to replicate human vision and cognitive processing.

Figure 5. **Example of map editing interface in OpenStreetMap**
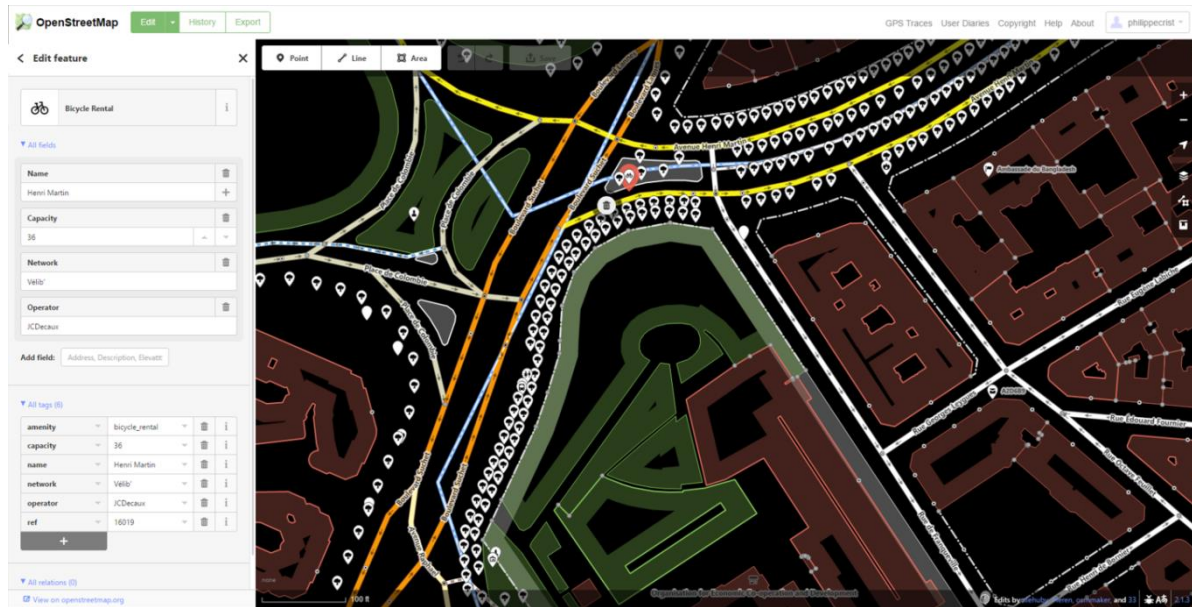
Source: OpenStreetMap (2017).

This development will be important for the deployment of more automated vehicles and will be a requirement for fully automated vehicles. It may also allow a better understanding of accessibility. At a very basic level, the route tracks generated by on-board location-aware sensors give an indication of where roads are located. However, in contexts where many vehicles are provided multiple location fixes, this same data can be used to determine the geometry and extent of the road footprint. Figure 6 shows the result of calculating road footprints and centre lines based on GPS-derived taxi tracks in Beijing (Ai and Yang, 2016).

For instance, what vehicles "see", especially with light detection and ranging sensors (LIDAR), provide important insight into the quality of pedestrian travel on pavements and sidewalks. Much of the deployment of vehicle-embarked LIDAR has focused on determining features of the road that are important for automated driving – markings, road quality, other vehicles, pedestrians and cyclists and roadside signs. These LIDAR plots and video scans help companies like Apple, Baidu, Here, Google and Microsoft to extract contextual spatial knowledge for navigating through space (e.g. Here's High Definition Map product for automated driving) or for monetising location-aware services. However, the same LIDAR plots can also be used to measure sidewalk continuity, obstructions, wheelchair accessibility, etc. (Ai and Tsai, 2016) – all features which are useful for a more precise understanding of pedestrian and wheelchair accessibility.

Generally, the embarked sensing capabilities in vehicles will increasingly contribute to a better understanding of the overall quality of road and road-adjacent networks. This, in turn, will help better inform actual travel speeds for those travelling on or next to roads. The same video and LIDAR scans can inventory roadside trip attractors such as shops, restaurants and other commercial and non-commercial establishments if vehicle manufacturers chose to activate these functions and put in place data-light protocols to transmit this information from the vehicle. In the end, however, much of this data will rest with vehicle manufacturers or service providers (including public transport services using video and LIDAR

sensing) and how insights from this data collection might be shared to improve the understanding of accessibility remains an open question.

Figure 6. **Road footprint and centre-line extraction using Delaunay triangulation of GPS-derived Beijing taxi tracks**
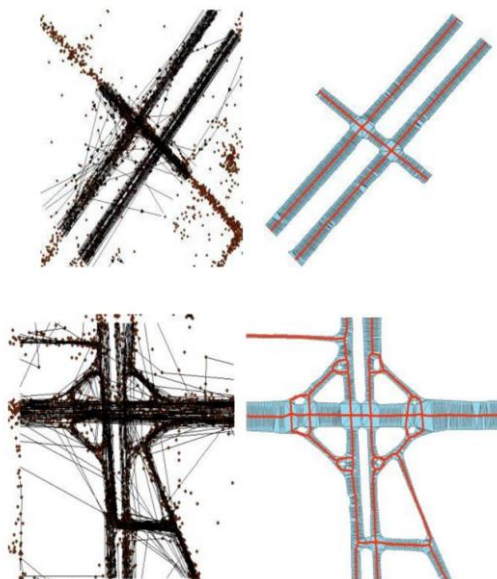
Source: Ai and Yang (2016).

Availability and quality of transport service and measuring outcomes

Data on road networks help to understand how these contribute to accessibility, but for many transport services – formal and informal bus and minibus services, rail-based public transport, bicycle and car-sharing – understanding actual accessibility requires additional information. This information relates to the availability of the service, both scheduled and actual service delivery, and the routes serviced. For some emerging modes – like for free-floating ride services and on-demand transport in dense urban areas – information on delivered outcomes may be a helpful and perhaps more meaningful metric to track than service delivery.

Public transport operators have historically produced internal operational schedules and public-facing service schedules – the latter typically in paper form. Many operators now provide on-line and mobile access to schedule information sometimes on their own web platforms and sometimes through API calls. Opening up schedule data more broadly and in a common shared format is a relatively recent phenomenon and one that only became possible through creation and increasing adoption of public transport data sharing standards. These include the Transit Communication Interface Protocols (TCIP – historic standard used in North America), the Service Interface for Real-Time Information (SIRI – a historic standard deployed mainly in Europe) and the General Transit Feed Specification (GTFS – a broadly disseminated global standard for public transport information). GTFS merges operator and schedule information, fare rules and classes, and geo-localised route and stop information in a simple flat file format that is easy to integrate into accessibility analyses.

GTFS-static describes scheduled information that can help derive the theoretical level of accessibility offered by public transport - but in many cities, especially those with poor public transport services or high levels of congestion, scheduled public transport services may not accurately reflect actual performance. GTFS-realtime is an alternative protocol that, as its name suggests, allows actual public transport service to

be described and can serve as the basis for understanding how the system delivers different levels of accessibility in response to actual travel conditions.

Another important development linked with the rapid rise of station-based or free-floating bicycle-sharing services around the world has been the development of the General Bikeshare Feed Specification (GBFS). This data sharing standard is inspired by GTFS but has less global uptake at present (Spring 2017), especially outside of North America. It has a flexible syntax that covers both station-based systems and increasingly popular free-floating smart bike systems. This data is helpful for understanding the accessibility benefits conferred from mixing various modes with travel on shared bicycles, especially for trips that include a first- and last-mile element that can be handled by a bicycle-sharing service.

Many public transport operators still do not provide digital information about their services in GTFS (or another standard) format. There are many reasons for this. Some may not be aware or have the technical capacity to do so, especially for smaller transport operators outside of North America and Europe. Others may view schedule information as proprietary and wish to control the channels through which it is disseminated in order to maximise their revenue. And in many parts of the world, a significant share of public transport is informal based on small, sometimes single-vehicle operators providing unscheduled services. The lack of available standardised data on public transport services in these contexts complicates accessibility analysis, especially in areas where public transport use is high either for the overall population or for specific income and demographic groups.

In the case of informal transport networks, the combination of the GTFS and location-logging devices and apps has helped to capture entire networks that previously could not be easily incorporated into accessibility calculations. Built by volunteers logging data on routes, stops and travel times, informal minibus networks have been codified and distributed in open format in cities as diverse as Nairobi, Cairo, Cape Town, Dhaka, Kigali, Manila and Mexico City (see Figure 7). These schedules and routes can then be incorporated into OSM and thus become part of the global data pool on public transport services.

Figure 7. **Crowd-sourced mapping of Cape Town's Minibus Taxi Network**
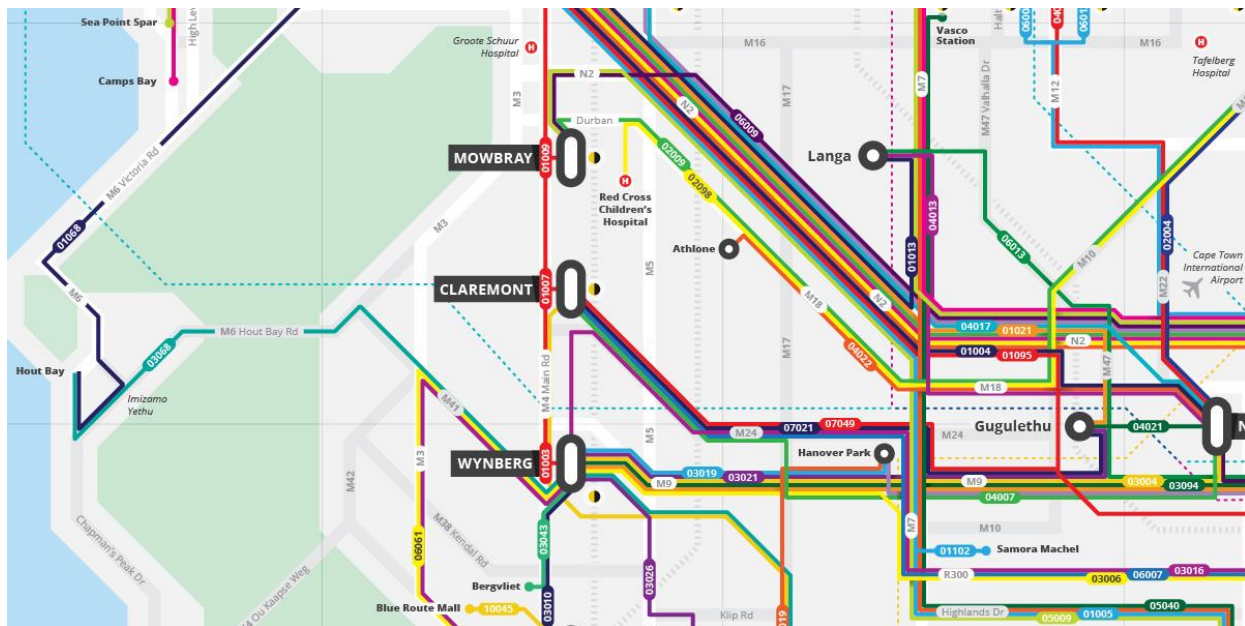
Source: Whereismytransport (2017).

Standardised data formats for public transport services can also serve as the basis for interactive accessibility analyses. Tools built for evaluating the accessibility and other impacts of changing service schedules or routes, for instance, can help decision-makers understand the impact of service changes on delivered outcomes. Tools, such as those offered by Remix (Figure 8), build on GTFS-transcribed service specifications to understand how to optimise public transport service delivery.

Figure 8. **GTFS-enabled interactive accessibility analysis of public transport service delivery**
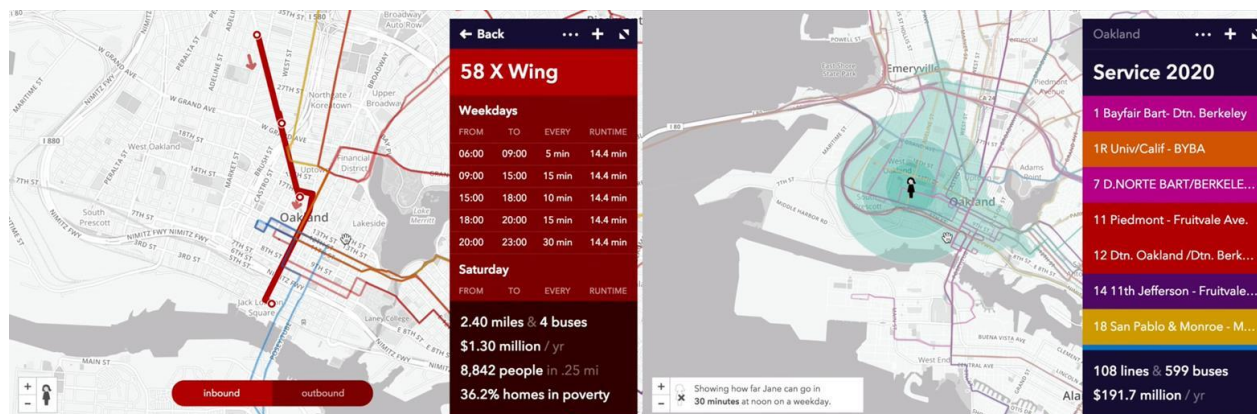
Source: Remix (2017).

Figure 9. **Average waiting times for Uber pick-ups across the Los Angeles basin in 2016**
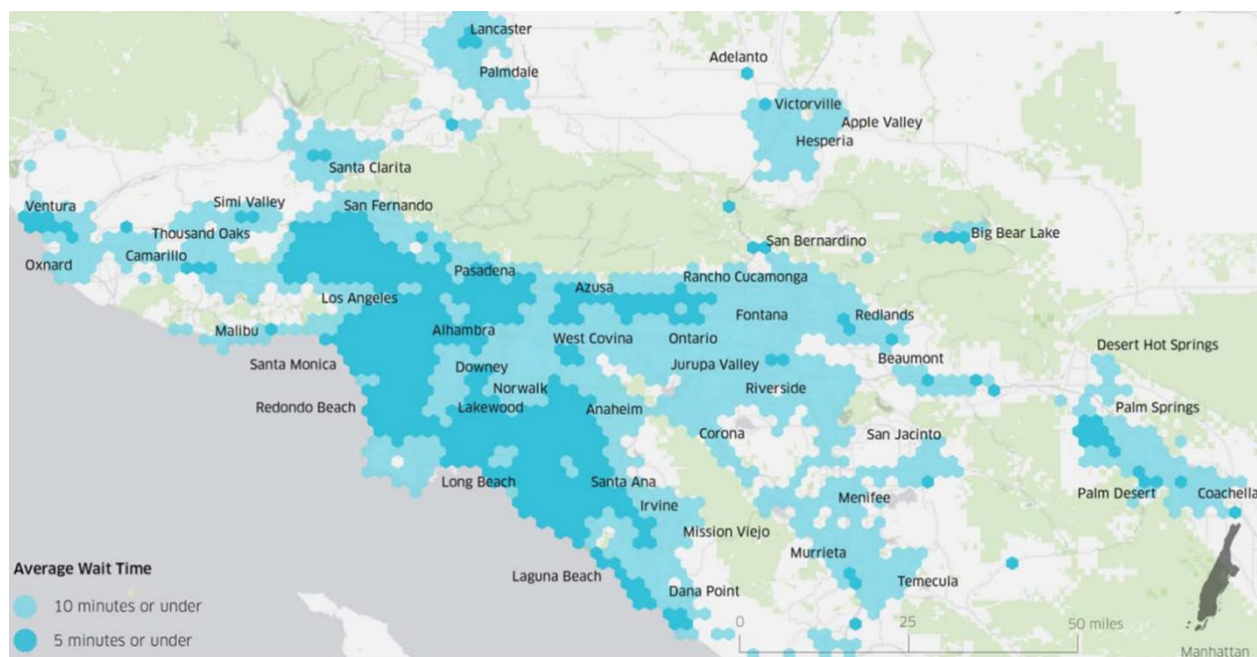
Source: Salzberg (2016).

Not all transport services operate on schedules – notably taxis and ride services. In these cases, accessibility profiles will depend on the availability of rides that serves as a rough proxy for service frequency and latency. This parameter is in turn dependent on the density of vehicles in different parts of the city at any given time. Because ride services keep extensive data logs relative to individual trips, this

information can be used to build latency profiles describing the gap between the time a ride was requested and the time the passenger was picked up. This can then be added to the vehicular travel time for more accurate accessibility calculations. Figure 9 shows average waiting times for Uber pick-ups across the Los Angeles basin in 2016. This average hides how waiting times also evolve at different times of the day – more detailed indices describing average waiting times per hour and on different days could enable more dynamic and relevant accessibility profiles – at least for the services that collect and provide this data.

Understanding where people are going and how they travel

As noted at the beginning of this section, accessibility calculations rely on information regarding transport networks and information regarding where people are travelling to and from. The latter is particularly important since destinations help to understand what people want to access. Household travel surveys extract data on origins and destinations by asking people where their trips began, where they stopped along the way and where each trip ended. These surveys also ask people to describe how and for what purpose they travelled. These rich data allows planners to better understand disaggregate travel behaviour and account for it in land use and transport planning. It also helps to understand what it is that people are trying to access at different parts of the day. In order to carry out useful accessibility analyses, it is necessary to have data on where people live, work, shop and travel to. While these data exists in many urban areas, they are missing or outdated in many instances. Here too recent changes in the availability of origin, destination and travel mode data can improve accessibility calculations.

As discussed in Chapter 3, population density can serve as a proxy for access to opportunities. Many regions in the world lack spatially distributed population data, and globally comparable data at a fine enough scale for urban accessibility calculations has been lacking until recently. Part of the challenge has been to take census-based population data and distribute it realistically across urban regions. The availability of globally consistent remote sensing data has helped in that fine-scaled urban boundaries can be extracted from spectral and hyperspectral satellite data. Extraction methodologies differ in details but most rely on the comparison over time of the same place, looking for areas where vegetative cover goes unchanged throughout the seasons. This indicates impervious areas that are likely candidates for built structures. The accuracy of this approach requires several adjustments across regions – most notably in the tropics – but generally delivers good results in outlining two-dimensional urban footprints. These footprints serve as a weighting factor when distributing population across urban territories. A good example of this approach that also uses the presence and location of various amenities like schools, hospitals and government buildings as additional weighting factors is the WorldPop initiative used in our global cities accessibility analysis in Chapter 4 (see also Box 4).

More recently, analysis of backscatter effects generated by radar signals hitting built structures when deriving digital elevation data using synthetic aperture radar produces very detailed building footprints (see Figure 10) that enable more accurate population distribution. Moreover, data on building height, which can also be derived from these signals, enable population distribution accounting for overall floor area and not just building footprints. This improves accessibility analysis in areas with a mix of short and tall buildings.

As noted previously, volunteered geographic information combined with certain new LIDAR and video scanning capabilities can improve the richness and accuracy of the distribution of travel-generating amenities such as food stores, schools and hospitals. These also help to understand what people may want to access.

Remote sensing scans and volunteered geographic information all serve as proxies for understanding where people might want to go and where they might travel from. They do not reveal actual travel choices or behaviours. The rise of ubiquitous mobile computing and communications generates very rich datasets that reveal actual travel behaviour and, with some analysis, can help to infer origins and destinations. Mobile devices consist of many sensors and other technologies that provide varying degrees of location accuracy

and tracking capabilities – both of which are limited by battery life. While the potential for highly accurate and continuous tracking exists, the reality is that prioritising this function in mobile devices would lead to unacceptably short battery life. Extracting useable location and longitudinal tracking data from mobile devices must thus balance accuracy, duration and energy use. Recent developments here also have opened up possibilities for both generating and using location fixes from mobile devices in accessibility work.

Figure 10. **Spectral vs. radar backscatter remote sensing of urban footprint (Langfang, China)**
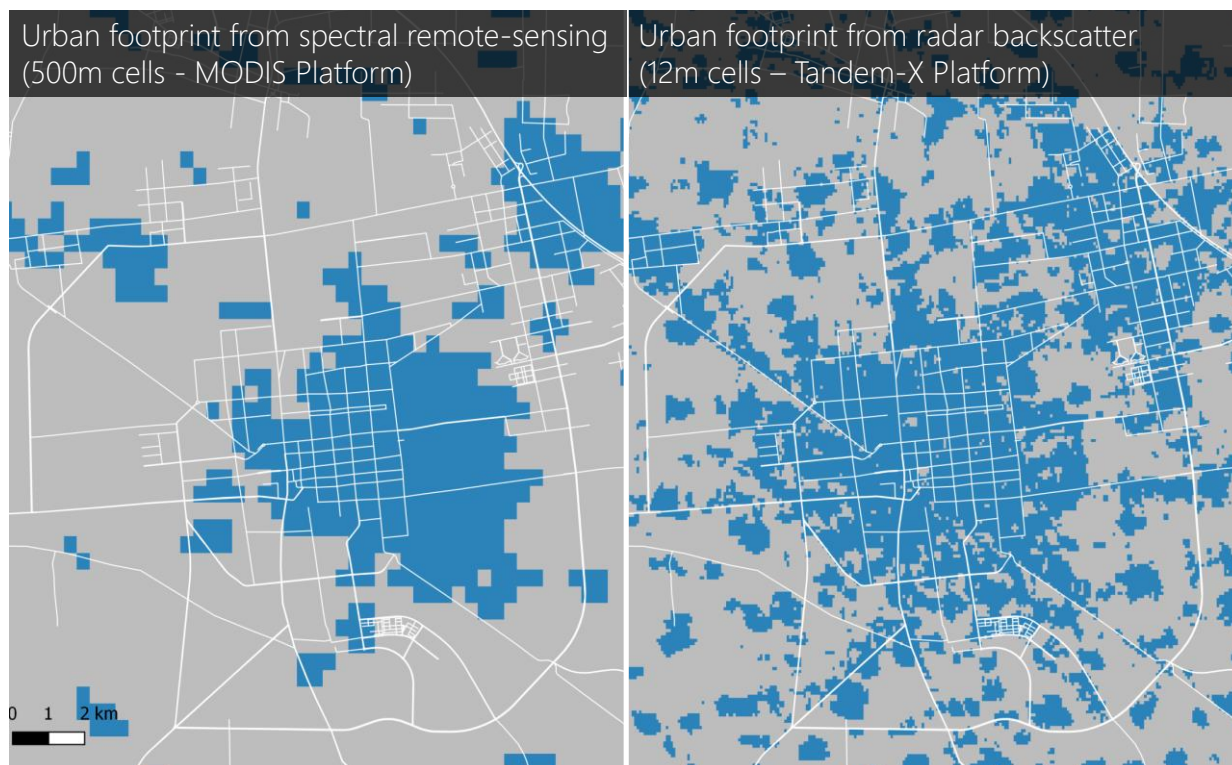
Source: Based on data from U-TEP (2016); Schneider (2009); and OpenStreetMap (2017).

Signals derived from cellular phones and smart phones represent the bulk of this location-relevant data. The way in which these devices connect to mobile communications networks and the protocols they use to handle constant connections across multiple cell phone tower service areas provide data that, when triangulated using signal strength and cell tower coordinates, result in detailed location fixes. The accuracy of the location data thus generated depends on the density of cell phone towers and the resulting size of the service area but can deliver rough location fixes (10-25 metres in dense cell tower networks). Perhaps more importantly, this data can indicate the staying behaviour of phones (and presumably of their owners). Long periods of night-time immobility reveal where people are likely to sleep (and thus potentially reveal their home location) and similar patterns of day-time immobility reveal potential work places. Where cell phones have high and evenly distributed penetration rates within the population, these location fixes and the tracked movement between these can represents a proxy for origin-destination travel behaviour. Cellular signal-based data alone can give rise to under-reporting or over-reporting of certain types of trips. For instance, many inter-cell trips may not be detected by cellular phone data and this might lead to an under-reporting of shorter trips – especially walking and cycling trips (Smith, 2015).

Box 4. **Worldpop: Global weighted and gridded population data**

The global human population is growing by over 80 million a year, and is projected to reach the 10 billion mark within 50 years. The vast majority of this growth is expected to be concentrated in low-income countries, and primarily in urban areas. High resolution, contemporary data on human population distributions and their compositions are a prerequisite for the accurate measurement of the impacts of population growth, for monitoring changes, for assessing accessibility and for planning interventions. Whilst high-income countries often have extensive mapping resources and expertise at their disposal to create such databases, across the low income regions of the world, relevant data are either lacking or are of poor quality. The scarcity of mapping resources, lack of reliable validation data and difficulty in obtaining high resolution contemporary census statistics remain major obstacles to settlement and population mapping across the low-income regions of the World. Initiated in 2014, the Worldpop project fills this gap by leveraging open data resources.

The WorldPop project reallocates contemporary aggregated spatial population count data from a range of open geospatial datasets using a flexible regression tree framework. Statistical assessments suggest that the resulting maps are consistently more accurate than existing population map products, as well as the simple gridding of census data. Moreover, the 100m spatial resolution represents a finer mapping detail than has been available at national extents, and the integration with household survey, microdata, satellite and other data sources enables the production of more than simple population count estimates - age structures, births, poverty and urban growth are all mapped, with further variables under production.

The approaches used in WorldPop dataset production are designed with full open access and operational application in mind, using transparent, documented and shareable methods to produce easily updatable maps with accompanying metadata. Given the speed with which population growth and urbanisation are occurring across much of the low-income world, and the impacts these are having on the economies, environments and health of nations, such features are a necessity for both research and operational applications.

Figure 11. **Hanoi, Vietnam, population density by administrative unit and by Worldpop grid**
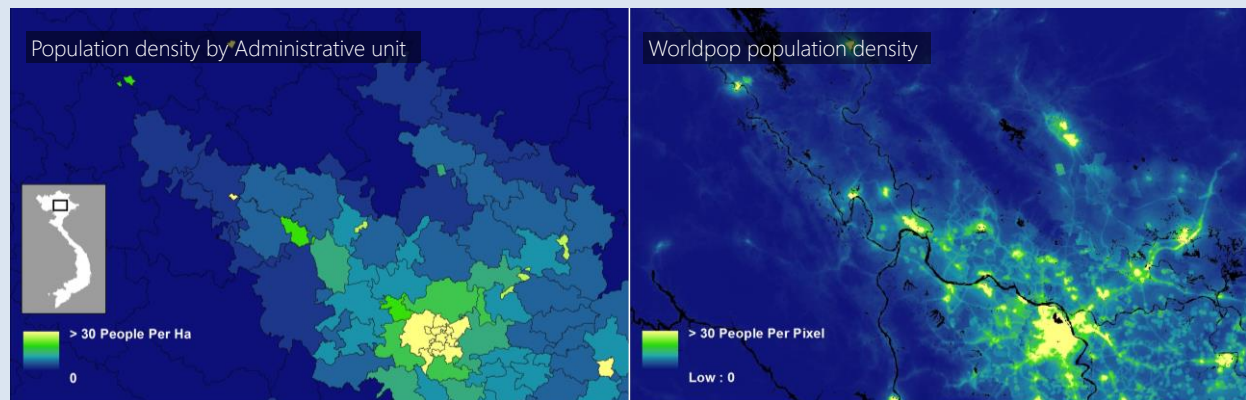
Source: Text and figure adapted from Worldpop (2017).

Greater location accuracy – necessary for more easily tracking actual travel behaviour and associating or "snapping" it to specific transport infrastructure and services - can be derived from global navigation satellite system (GNSS – including, for example, the US Global Positioning System [GPS]) sensors and signals. These have the advantage of providing greater accuracy but have a low initial latency, perform poorly in built-up areas with interrupted lines of sight to satellites and require a significant amount of power. For these reasons, GNSS-alone location-tracking is not a good option for collecting revealed travel behaviour data from people using handheld devices, though it can be helpful in tracking GNSS-equipped vehicles. This is an important distinction to keep in mind when evaluating accessibility derived from GNSS data.

Figure 12. **On-street parking availability in Amsterdam**
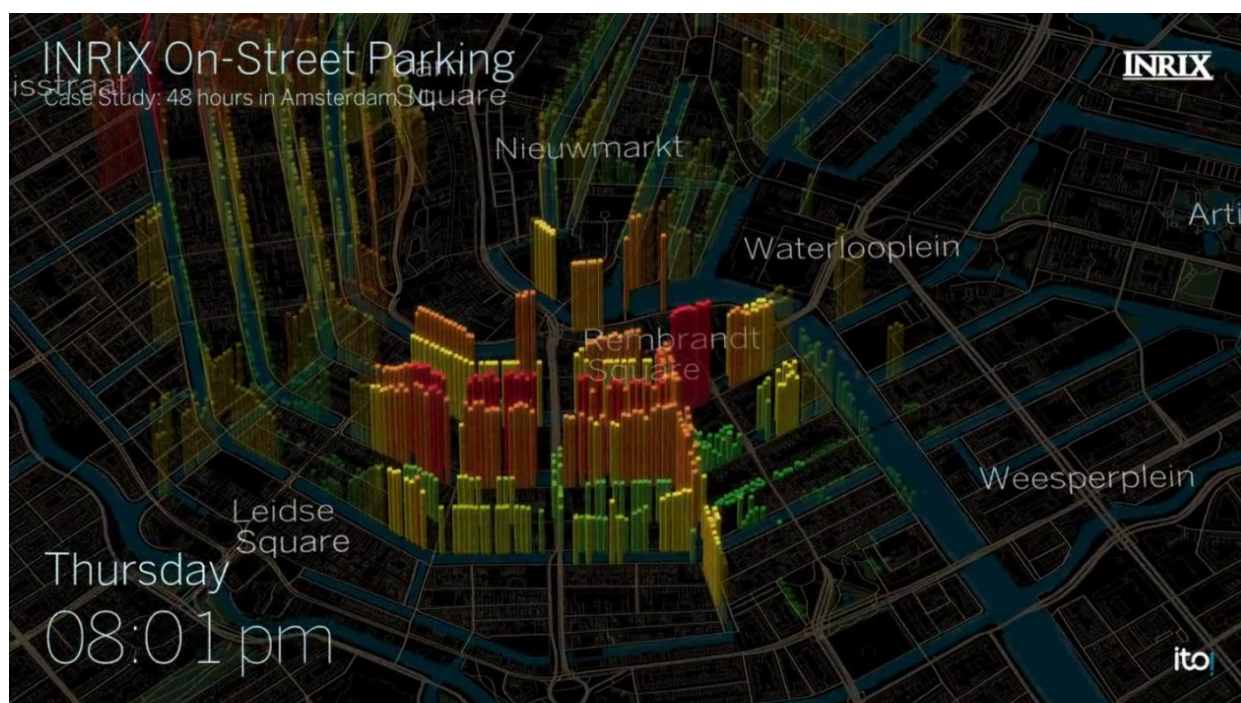
Source: Ito World (2015).

Handheld mobile devices provide other possibilities for accurately representing location and trajectories. These include registering the strength of wireless communication signals to Wi-Fi routers and fixed Bluetooth devices. Because smartphones regularly assess what devices are within its range and communicate this back to central databases tracking Wi-Fi/Bluetooth station names and locations, very accurate location data can be derived from triangulating signals to the web of known station locations. This location and tracking accuracy extends inside of buildings as well as underground where those locations include Wi-Fi or other connected technologies. Combining all of the location-fixing capabilities of smartphones and other connected devices has led to the rise of a suite of companies providing hybrid and highly accurate location-based services (LBS). This data allows collection of low latency and energy efficient location and trajectory data, which can improve the accuracy of non-household travel survey-derived data on origins and destinations. This data can also help to reveal patterns in daily, weekly or monthly mobility that may not be easily captured through survey-based methodologies.

Beyond revealing simply where people are travelling, LBS and other sensor-derived data can reveal important ancillary information that can improve accessibility analysis. For instance, in many urban areas, searching for parking represents a significant amount of time. Accessibility analysis that fails to account for total travel time including parking search time may misrepresent the level of accessibility conferred by cars and delivery vehicles – at least at certain times of the day and in certain parts of the urban area. Capabilities now exist to track parking occupancy, capacity, vehicle dwell time and vehicle trajectories and thus can help improve accessibility analyses by showing where travel times are likely to be higher due to parking search (see Figure 12).

One risk in using strictly observed behaviour of devices (and not people) is that the representativeness of this data may be poorly correlated with reality. If cell phones or connected vehicles have higher penetration rates amongst certain population or income groups, accessibility analysis built on the basis of that data may only reveal those groups' accessibility profiles. This failure has important equity implications since policy

derived from looking at the accessibility profiles of the mid- to upper-income households, for instance, may not address poor accessibility and lack of opportunities for lower income households. Bias-correction is an important part of any policy-oriented data collection exercise and this is especially true for the spatial data necessary for mobility and accessibility analysis. Just as there are methodologies for bias-adjusting traditional household travel survey data, new techniques are also available to correct bias in travel data generated from mobile handheld devices (see Box 5). Authorities using novel data sources should understand sources of bias inherent in that data and document how they have been accounted for in order to increase the relevance accessibility analysis.

Box 5. **Adjusting for population and income bias in location-based service data**

Streetlight data is a mobility analytics company that helps decision-makers and other clients understand how and why people move on the basis of mobile and other connected device data. As such, they must control for bias in their sample to ensure that the insights derived from the data are accurate and relevant. They, like other companies in this area, must address how representative their data is. To do so, they apply two tests. The first to determine sample share or the percentage of a given region's population who use the devices that create the location records in the sample. The other to test if the device users in the data set represent the income distribution of people living in that region.

The first test consists of determining home locations within census blocks. This is done by assigning a probability that devices are affiliated with a particular census block based on how many night-time hours they spend there. The next step is to sum up all the devices in the sample that are probably affiliated with each census block. This is then compared to the official census-based population estimate for each census block. For instance 20 devices in a block with a population of 100 people would represent a 20% sample size. To preserve anonymity, these are aggregated up to census tracts that contain multiple census blocks. This sample size is then compared across census blocks and tracks to see if it is consistent (and thus representative) or if sample size varies across geographies (and may indicate bias).

The second test for income bias is one that is also relevant for other forms of travel data. For mobile device data, Streetlight uses the same aggregated "device home block locations" - or "night-time locations" used for sample share analysis. These are aggregated up into census block groups (between census blocks and census tracks) since income data in the American Community Survey (ACS) is reported by census block group. Streetlight then determines the average income distribution of each block group in order to determine if the mobile device sample share is different across higher-income and lower-income block groups. This finding is then used to determine the income representativity of the sample and ensure that analysis based on the sample adequately reflects the behaviour of all income groups.

Source: Adapted from Schewel (2017).

Data derived from mobile and other sensor-enabled devices can also help infer travel modes. This may be due to the nature of the data itself – for instance public transport travel card data can serve as the basis for representing travel by public transport (Nassir et al., 2015). Sensor-based data from accelerometers and gyroscopes and location fixes from GNSS or LBS services can also help determine specific travel modes and thus capture the behaviour, travel routing and travel speeds of modes that are typically hard to otherwise adequately monitor – especially pedestrians and cyclists (Hemminki et al., 2013). There are many algorithmic approaches to sensor-based activity detection but some of the most robust employ classification mechanisms that provide higher certainty for the detection of walking (and to a certain extent cycling) as compared to other modes (Ellis et al., 2014; Pham and Thuy, 2016). This is important since many other survey methods find it challenging to accurately capturing large-scale data on walking and cycling. Activity detection as a service is also a potential source of this type of inferred mode choice data – for instance, Google offers an activity recognition API for developers on the Android platform. The accuracy of activity detection for mobile devices is increasing as algorithmic skill improves and as computational power increases in both smart phones and dedicated activity tracking devices (ITF, 2014; Shafique and Hato, 2015; 2016) but robust longitudinal activity detection is still constrained by battery life – a challenge that is being approached by improved battery technology and improved, low-energy detection and transmission methods (Bhattacharya and Lane, 2016).

When combined with other data sources relating to the location of transport networks, real-time public transport service and traffic speeds, automatic mode classification opens the door to near-real-time urban mobility scanning. This, in turn, opens mid-term perspectives for urban-scale real-time accessibility monitoring.

Figure 13. **Crowd-sourced bicycle data for accessibility calculations: Bike Citizens ride data in Berlin**

Source: Bike Citizens (2017).

As noted above, the paucity of detailed data on cycling and walking detracts from the accuracy of estimates of accessibility delivered by these modes (See discussion in Chapter 5 for more on measuring accessibility by bicycle). In addition to automatic activity and mode-recognition methodologies, a growing volume of crowd sourced data for these modes can improve accessibility calculations. These include data derived from dedicated smartphone applications like Strava and Bike Citizens. The former has launched an urban mobility data product, Strava Metro, which displays detailed route and speed profiles for cyclists and runners. Because the Strava platform is oriented mainly towards sport cyclists and runners, there is a risk that this data may not be representative of everyday, utilitarian cycling or of pedestrian activity where route selection and behaviour among the two groups are similar. Bike Citizens is a utilitarian cycling-specific navigation app that helps cyclists map routes according to slope, the presence of bicycle facilities, the revealed preference of other cyclists for specific routes and traffic density (see Figure 13). Applications such as these track where cyclists travel, how fast they go and help reveal trajectories that may for any number of reasons deviate from more direct routes. Incorporating this data into accessibility calculations improves the relevance of these for active modes.

Calculating travel times

Many of the examples given in the previous sections improve the precision of travel time calculations across networks for different modes and at different times of day. These can be aggregated into segment-specific speed on the basis of data collected from probe vehicles (cars, trucks, trams, buses and bicycles) or logged by devices (e.g. smartphone apps). More accurate and richer speed data helps account for differences amongst various groups of people or commercial operators and thus improves the relevance of accessibility

analyses. This also helps understand how access changes depending on the use of theoretical or observed speeds and how it changes over the course of the day as traffic increases or decreases (see Figure 14).

Figure 14. **Comparison of number of jobs accessed within 30 minutes in Boston:
Posted speeds vs. crowd-sourced observed speeds**
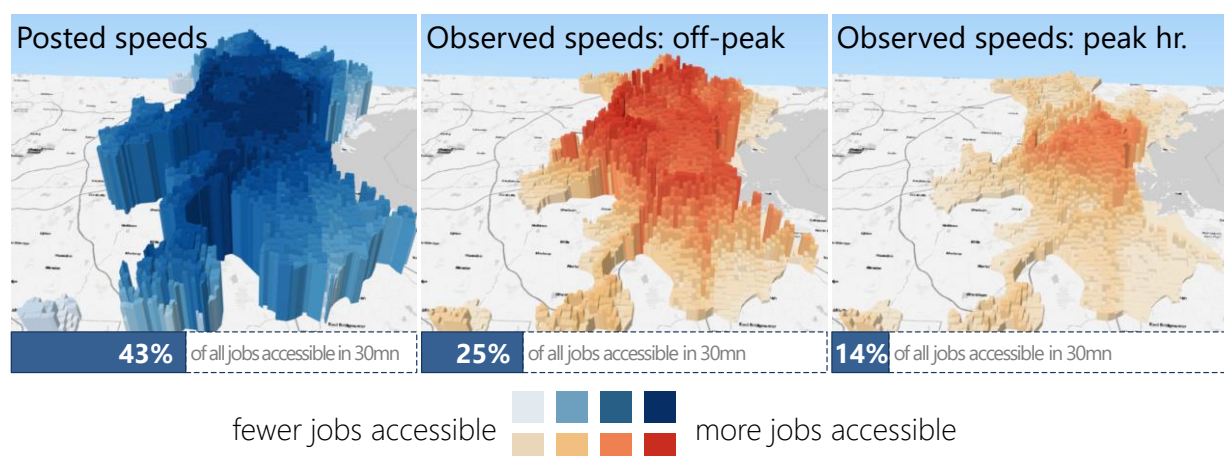
Sources: INRIX, Map tiles by Stamen Design, under CC BY 3.0.

Understanding why people travel

Inferring travel purpose from non-household travel survey data is challenging and yet disaggregating accessibility profiles by travel purpose can be helpful for understanding the variation in travel destinations and how accessibility varies according to why people are travelling. Linking trip trajectories to the location of different amenities can help reveal travel purposes, albeit imperfectly. Chaining identified travellers to specific transactions (by linking home location, travel card identity and financial transaction data from payment terminals) can reveal a lot about why people are travelling but are highly privacy invasive and in many contexts illegal without express permission granted by individuals. Nonetheless, in certain closed systems – for example where public transport cards are also used for payments for services in and around public transport stops – rich data can be extracted. This is the case in Japan, for example with the Passmo and Suica travel cards. This data is proprietary and it is uncertain if operators can be sufficiently incentivised to provide this data for accessibility analysis in a way that preserves the commercial value of the data and protects the privacy of clients.

There may be some value in extracting trip purpose from volunteered social media data to infer travel purposes associated with volunteered geographic information (Grant-Muller et al., 2015). Social media data is comprised of multiple facets including presence/location, sharing, conversations, group affiliation, reputation, identity and relationships (Kietzmann et al., 2011). Relating the geospatial element with many of the other attributes can provide rich (yet sometimes uneven) data on activities (Chen et al., 2016; Sánchez et al., 2016). Social media "check-ins" relating to specific activities like eating at restaurants – e.g. in conjunction with crowd-sourced rating apps - are relatively straightforward cases of activity inference. Other more challenging inferences may be derived from mining shared social media postings for key words (e.g. "just landed", "shopping", "Doctor's") (Abbasi et al., 2015). Some trip purpose data can also be inferred from geo-tagged photographs shared on social media platforms (Chaniotakis et al., 2015).

Gauging the subjective travel experience

Not all travel experiences "feel" the same. For instance, a straight-line pedestrian connection through an unlit neighbourhood may feel less safe than a longer walk on a busy street. In these cases, accessibility profiles that do not account for subjective factors that could alter route selection and travel times may not accurately represent actual levels of accessibility – especially across groups of people for whom subjective travel experiences matter most. One way to account for this is to cross several ancillary data sources with network data – for instance, making routing decisions in accessibility modelling conditional on the presence of street lighting, or a certain number of ground-level shops and commerce. As the availability of the data increases in open platforms, so too will the accuracy of accessibility calculations, especially for walking.

Volunteered geographic information can also help understand transport "stress", "happiness" and the overall "feel" of different trajectories and mode choices. Transport mode choices have an incidence on perceived well-being (Duarte et al., 2010; Lathia et al., 2017; Martin et al., 2014; St-Louis et al., 2014) and this, in turn, has an incidence on how people experience travel. New methods of collecting this type of subjective data (e.g. via smartphone apps or extracted from social media feeds) can enrich accessibility analysis since these types of inputs improve the understanding of how people view travel options available to them. This then increases our ability to differentiate the quality of accessibility according to subjective preferences.

4. Comparing accessibility in cities: A global perspective

Why benchmark accessibility across cities?

Looking at different urban areas across the world, it is intuitively obvious that significant differences in accessibility exist. Road congestion problems are known to be more important in large cities of the developing world, while transit systems development is extremely uneven across cities. Yet intuition can easily be misleading as cities have densities, scales and transport network structures that are hard to fathom with simple observations. As is well known, accurate and meaningful comparisons require uniform and comparable metrics.

By learning from each other, cities could significantly improve how they design their transport networks. There are many ways of doing so, but a strong prerequisite is to set up an adequate benchmarking framework with a comprehensive set of comparable performance indicators. This allows designing better urban policies based on evidence rather than subjective judgement. Benchmarking frameworks and databases focusing on the performance of cities already exists and recognise that mobility and more specifically accessibility is one of the fundamental issues. The European Commission has for instance created the urban audit, a set of indicators that has grown substantially over the past years and now has over 100 indicators in the database covering a large number of European cities (EC, 2016).

This chapter explores the challenges and possibilities of an urban accessibility metrics that can easily be used at a global scale. It argues that existing attempts are not fully satisfying, but the increasing availability of standardised data makes it possible to move toward meaningful and comparable measurements of urban accessibility. After reviewing and discussing existing approaches, the chapter presents the ITF Urban Framework, a tool to compute accessibility metrics at the global scale. As any work of this magnitude, it leaves room for improvement and must be considered as a first step in developing a more comprehensive architecture capturing accessibility globally.

Toward a global urban accessibility: The ITF Urban Access Framework

Global measurements of urban accessibility: A review of the existing indicators

Numerous accessibility studies have been produced in a case-studies format, focusing on a single city or comparisons across a very small set. For instance CEREMA (2015) listed 21 accessibility studies conducted in France in the last decades, excluding academic works. Most of them were conducted using slightly different methodologies, data and software so they can hardly be compared. Although most of these studies were certainly enriching for local policy making, their limited spatial scope and poor comparability prohibits any large-scale benchmarking.

When it comes to comparative studies of accessibility in cities beyond the case study format, the objectives of accessibility measures are usually more modest and often based on the concept of proximity. This has been largely due to limited availability of data and computing power. As a recent example of applied research, the European Commission measured accessibility to public transport in European cities (Poelman and Dijkstra, 2015). The study calculates the share of the population living within walking distance of public transport facilities and assesses the frequency at those stops and stations. This metric allows for comparison of the population share covered by the public transport network and the quality of service, as measured through frequency. The advantage of such proximity-based metrics is the relative ease of computation, moderate data requirements and the clarity for policy messaging. However, the policy implications might be limited as the distribution of actually valued destinations, and hence the constraints to reach them are not sufficiently taken into account (Peralta, 2015).

The arrival of new standardised sources and tools for computation and measurement of geo-referenced data make it possible to go beyond accessibility metrics that are limited to single case studies and infrastructure-based measures. Innovative research by the Accessibility Observatory located at the University of Minnesota estimated in a series of reports the potential accessibility to jobs in more than 40 US metropolitan areas by car, public transport and walking for 1990, 2000 and 2010 (Owen and Levinson, 2014; 2015; Levinson, 2013). Combining disaggregated census population data, job locations and detailed information of the urban transport network, timetables and travel speeds, this research estimates the number of jobs an average city dweller can reach in ten-minute time bands up to one hour. Valuing job locations with shorter travel times more than with longer ones, this location-based metric adds an element of attraction decay with distance.

In a similar vein, the World Bank calculates average accessibility to jobs by different modes of transport for a number of cities in Latin America, Africa and Asia. The metric computes the average accessibility to jobs by mode within an assumed maximum commuting threshold of one hour. Working on a case-by-case basis this approach uses detailed and locally specific data, taking into account travel and land use patterns allowing the assessment of different accessibility scenarios, comparison between modes and different points in time (Peralta and Mehndiratta, 2015). The drawback of this approach is that it remains case-study based and dependent on locally available data, notably job locations, which are difficult to obtain or unavailable on a broader scale.

The requirements for global accessibility metrics

Taking stock of the merits and drawbacks of existing research, ITF (2017) has proposed a metric that aims to balance policy-relevance with data availability. It follows three principles:

- **Conceptual simplicity**: While the state of the art in accessibility research has been moving towards more complex models of accessibility (Geurs et al., 2012), a conceptually simple approach allows overcoming the challenge of extensive data and computing requirements. Contour-based metrics calculating the number of opportunities within a time threshold are best suited to bridge data availability, theoretical complexity and comparison between cities and regions.

- **Global data availability or global reach:** As the main interest of global metrics is to compare, situate and benchmark cities across the world, data need to be standardised across countries and widely available. As a consequence, only globally standardised datasets are used for this analysis.

- **Multi-modality:** This approach considers accessibility for private car and public transport to account for modal differences of accessibility in cities.

Based on these principles, our global indexes are defined as the average number of inhabitants that can be reached within a 30-minute threshold by private car or public transport. In other words, our metric is the number of inhabitants leaving inside the 30-minute isochrones of each territorial units of a city. Regarding the framework discussed in Chapter 2, this implies:

- **Generalised costs are restricted to travel time**. Generalised costs are indeed composite indexes summarising components by weighting them by perceived values. These values (of time, reliability or other) are largely subjective and might vary significantly from region to region.

- **The impedance function is restricted to a stepwise function.** Again impedance functions should be assessed on a case-by-case basis, and it is thus more appropriate to keep them in a simple form for a global analysis.

In this case, the spatial distribution of the population in cities is used as a proxy for opportunities. While population does not represent actual opportunities, there is some empirical evidence that population density correlates with opportunities such as jobs and services, particularly in city centres. For instance, Kaufman

et al. (2017) showed that the distribution of services, offices and commercial spaces within US cities is highly correlated to population. Such a proxy is very useful in the case of a global study; detailed analysis of specific cities should however rely on the actual location of opportunities.

The methodology used in this report

Technical details matter when dealing with worldwide data. The methodological choices made in the current study can be grouped in three parts.

First, the definition of the cities considered and their extents must be defined. The aim was to account for the 1 692 cities listed by the United Nations (2014). After merging cities belonging to the same urban agglomeration (for instance Pretoria and Johannesburg), 1 557 entries remain. A point of attention was to carefully define the urban area associated to each of these cities. Indeed accessibility is usually higher in city centres compared to suburbs so that a larger urban area usually implies lower accessibility. As definitions of cities vary greatly from country to country, objective comparative analyses cannot generally be obtained using administrative definitions of urban areas. Thus this study defines the urban boundary for each selected city based on the Global Built-up Reference Layer (Pesaresi and Carneiro Freire Sergio, 2014), complemented by the space-based land remote sensing data LANDSAT for the year 2010. The population distribution of each city was gathered from various sources and projected on a 1 km by 1 km grid.

Second assessing travel time speeds in an accurate and comparable manner is challenging. For road transport, they have been estimated using the open street map network. It has been completed by observed data from INRIX and TomTom so that the actual speed, including congestion, was assessed. For public transport, schedule data, provided by local authorities in the General Transit Feed Specification (GTFS) format, was used.

Table 1. **Data sources available for accessibility benchmarking at a global level**

Name	Description	Source
Urban built-up areas	BUREF - Global Built-up Reference Layer (BUREF2010) a spatial raster dataset containing an estimation of the distribution and density of built-up areas	European Commission, Joint Research Centre, http://publications.jrc.ec.europa.eu/repository/handle/JRC90459
Road networks	OpenStreetMap (OSM) road network	https://www.openstreetmap.org/
Congestion estimation	Large sample of speed observations on Congestion Index on over 150 cities (Only morning peak speeds were used in this study)	INRIX, 2016 ; TomTom, 2016, https://www.tomtom.com/en_gb/trafficindex/
Public transport schedules	Schedules in General Transit Feeds (GTFS) format for 23 cities	TransitFeeds, https://transitfeeds.com/

Third, the actual computation process is performed in a three-step approach presented in Figure 15. The travel times for each mode are assessed between each pair of units of the grid, so that a complete origin-destination (OD) matrix is computed. Then, for each cell, the number of inhabitants within a 30-minute range is assessed. At this stage, the two accessibility metrics, for road and public transport, are known for each unit of the grid taken as origin. To summarise the metrics in two single values for each city of our sample, the accessibilities at the unit level (as origin) are finally aggregated using a mean weighted by the population.

Figure 15. **Methodology for ITF accessibility indicator in three steps**
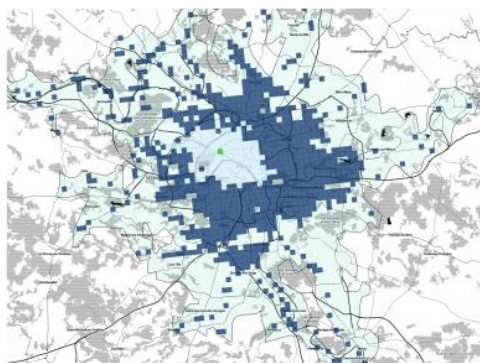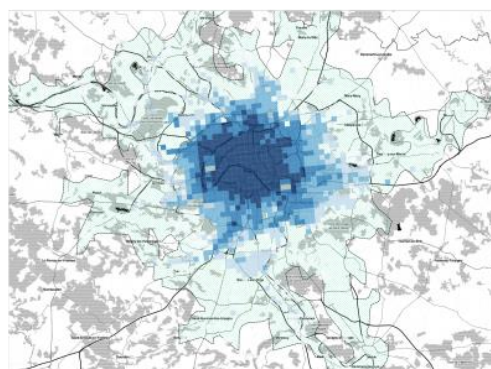
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0.

The main results

Road accessibility: Why is road accessibility higher in developing cities?

The results of this analysis for cities between 3 and 5 million inhabitants are presented in Figures 16 and 17. They notably show that road accessibility is higher in developing cities. In Africa, Asia and Middle East, an average inhabitant can reach 30% of the city population in a 30-minute car ride. This percentage falls to 15% for cities in Northern America, Europe and OECD Pacific. This result is counterintuitive as the road network is higher and congestion less intense in developed cities. On average travel speed in African cities is 11 km/h when it is 21 km/h in North America. Half of this difference comes from higher free flow speeds, i.e. by the higher availability of fast roads, and half from lower road congestion.

How can this result be explained? An accessibility index combines two aspects: the efficiency of the transport system, (i.e. the average speed to reach a destination), and the density of opportunities (i.e. the average distance to reach a destination). In other words in a dense city, even if travel speeds are low, average distances to travel are lower (Figure 16). The work undertaken here allows quantitative clarification of how those two opposite effects interact. First, the road accessibility index is more sensitive to speed than to population density. We estimated that its elasticity with respect to (w.r.t.) the average speed is 1.6 against 0.7 for elasticity w.r.t density. But, in relative terms, population density varies more across regions than speed. For instance the ratio between Northern American cities and African cities ranges between 1:8 for density, but only 1:2 for speed. As a result the accessibility index has an average value of 13% in North America against 31% in Africa.

Figure 16. **Why road accessibility is higher in developing cities: Speed vs. density effects**
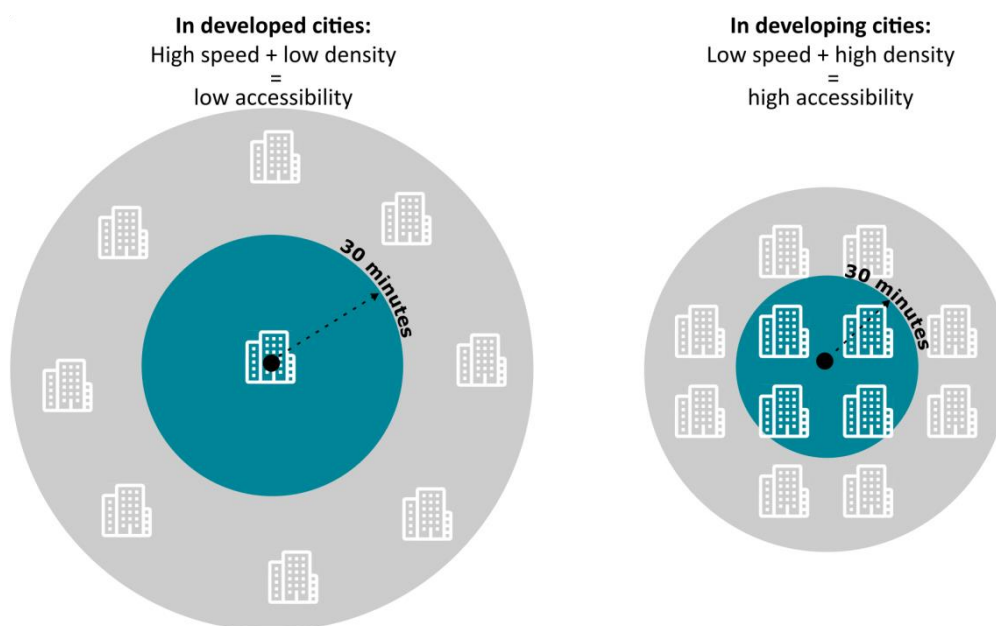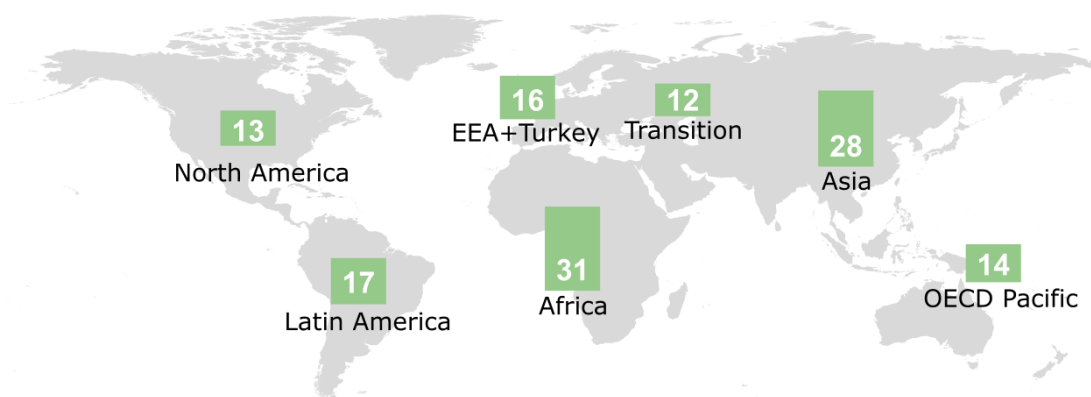

Figure 17. **Road accessibility by regions (in % of the city accessible)**

Source: Adapted from ITF (2017).

Accessibility by public transport: Public transport coverage is extremely uneven among cities

Vast coverage by public transport is a prerequisite for good general accessibility. Public transport coverage measures the number of residents in a city who live within walking distance from public transport stops. Public transport coverage has already been extensively computed for world cities (see for instance ITDP, 2016) although the work presented here is by far the most exhaustive estimation currently available. Based on the available data on public transport stops, public transport coverage is calculated for 1 014 cities. The proximity to stops is evaluated for bus and for mass transit (defined here as railway and tramway, underground and bus rapid transit). The walking distance threshold is 1 km, which is equivalent to approximately a 12- to 15-minute walk. Public transport coverage is calculated as the percentage of residents of a city living within that threshold from at least one public transport stop.

On average, around 53% of the residents of the considered cities live close to a public transport stop, with 28% of all the residents covered by mass transit. The contrast between regions is sharper than in the road accessibility case. Cities from Europe and transition economies have by far the best coverage, with an average of 85% and 80% of the population respectively and relatively high shares of mass transit: 51% for Europe and 47% for transition countries. OECD Pacific, North America and Asia have lower public transport coverage rates (less than 50% or even 20% in smaller cities) but fairly large shares of mass transit (up to 20% in OCED Pacific large cities). The rest of the world regions tend to have a significantly lower coverage with bus prevailing over mass transit modes.

Accessibility by public transport: Networks from large European cities offer higher accessibility

For now, computing the accessibility index for public transport has only been possible for 23 cities due to limited data availability on public transport services. Nevertheless these initial results, presented in Figure 19, give the first insights that will need to be confirmed by a more global analysis.

Accessibility by public transport varies greatly by city, with European cities generally offering higher accessibility than developing cities. As an average across all units as origin, around 12% of the 10 million inhabitants of Paris urban area can be reached in 30 minutes by public transport compared to less than 4% of Cairo's 17 million inhabitants. Although Cairo is nearly twice as dense as Paris, its public transport system is only half as fast, but the much less extensive coverage leads to a lower accessibility. Here, the speed of the public transport network needs to be understood as the average speed over all trips, assuming that the geographical distribution of trip ends is similar to that of density; it is not the average commercial speed of the lines composing the network.

As presented in Figure 19, accessibility and coverage results lead to very different insights. For instance, in Washington, all of the population is covered by public transport but only 2% of the inhabitants can be reached in a 30-minute ride. Although the supply of public transport stops is very high, the services offered are characterised by low frequencies and speeds.

As in the case of roads, public transport accessibility is driven by population density and speed. Those two variables explain 80% of the variability between cities. Accessibility is much more sensitive to speed than density: the elasticities are 2.9 and 1, respectively. Because public transport tends to connect dense areas, a small increase in speed has a great effect on the number of inhabitants that can be reached in 30 minutes. This highlights the interest of mass transit as a lever for enhancing accessibility, especially when co-ordinated with land use.

The accessibility gap in favour of European cities relates to an unequal distribution of public transport speeds. The average public transport speed for cities ranges from 5 to 15 km. Most of the cities with no or little mass transit achieve a speed of between 5 and 8 km/hour, one notable exception being the transport network of Nairobi which, with nearly no rail transport, offers a speed of 8.8 km/h thanks to a large and rather efficient informal transport system. The so-called *matatus* are mini-coaches operating on a network

of 2 000 stops with a peak frequency of nearly 30 buses per hour. The average speed can go up to 15 km/h for cities with significant mass transit provision.

Figure 18. **Public transport coverage by regions and size**
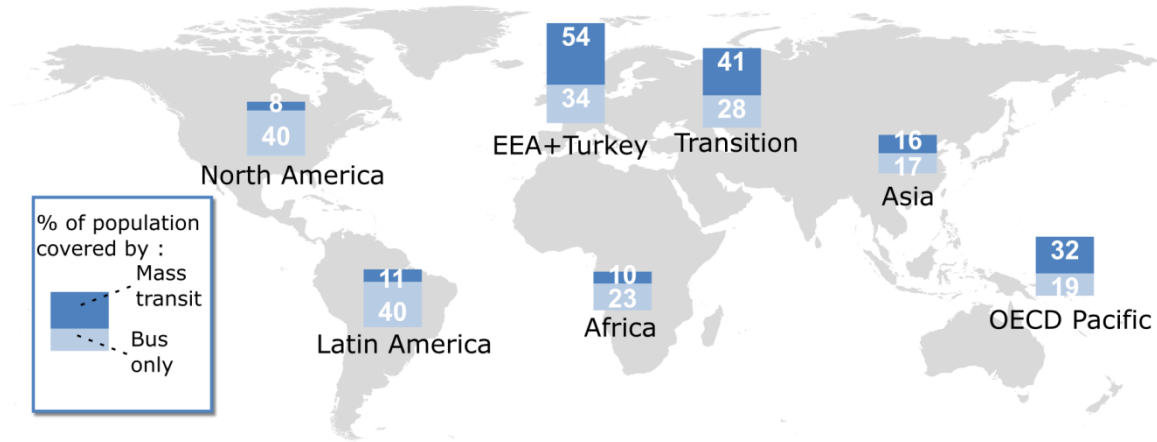
Source: Adapted from ITF (2017).

Figure 19. **Public transport accessibility and coverage for 23 cities**

Source: Adapted from ITF (2017).

Using the ITF Urban Accessibility Framework for policy guidance: Two examples

ITF urban accessibility framework is a first attempt to understand and learn from the difference in accessibility between cities worldwide. There is still much room for improvement. More data is needed to improve the estimation of road speed and to compute public transport accessibility in more cities. Integrating a better representation of opportunities, by considering the spatial distribution of jobs, services or other type of amenities is also an important subject.

However the framework is already a powerful analytical tool, which can be used to perform quantitative analysis producing valuable evidence to support decision making. This is showcased in the following section where the framework is used to answer policy-relevant questions.

Access to education in cities: How big is the gap between regions?

Developing cities offer good accessibility in general, but it might be lower for some specific commodities, especially public facilities. Indeed the general lack of public investment in the developing world leads to a low supply in schools, hospitals or social services. Taking the example of access to education, Table 2 illustrates this for different regions of the world. For cities with over 1 million inhabitants, the number of education facilities per inhabitant (in this report primary and secondary schools but not universities and kindergartens) in North America is 1 for 1 thousand inhabitants when it is only 0.2 for Africa. Even if cities are more compact in Africa, the resulting density of schools is lower with 1.3 schools per km² compared to 1.9 in North America.

Building on this data and on the ITF framework, it is possible to compute a rough estimation of access to education in different regions. As expected with lower speeds and lower school densities, access to education is lower in developing cities. In a 30-min car ride, an inhabitant of a large northern American city can reach 224 schools when in an African city it is only 54. As such this is not especially low, but access tends to increase very quickly with the travel time threshold. In a 15-min ride, this number drops to four schools in African cities: this means less education choices for inhabitants, especially when specific education needs are required.

From a policy perspective, improving access to education in developing cities can be achieved by two ways: either improving speeds by investing in road or public transport infrastructures, or increasing the density of education facilities. Of course the appropriate solution will be case-specific but accessibility analysis can help to compare options. This is the subject of Chapter 6.

Table 2. **Access to education in cities over 1 million inhabitants**

	Schools/thousand inhabitants	Schools/km²	Schools reachable in a 30-min car ride	Schools reachable in a 15-min car ride
Africa	0.3	1.3	54	4
Latin America	0.3	2.4	117	9
Transition	0.4	3.0	151	12
EEA + Turkey	0.8	1.4	150	12
OECD Pacific	0.9	1.3	210	16
North America	1.1	1.9	224	17

Note: Asia and Middle East where excluded from the analysis because of poor data coverage.
Source: ITF computations based on OpenStreetMap data.

Looking forward: What are the consequences of urban sprawling in developing cities on accessibility?

Despite their slow transport networks, cities from the developing world offer reasonable accessibility by car and public transport because of a high population density. While this result describes the current situation, policy decisions have to take into account that real world situations are not static. In particular what would happen if cities in Asia, Latin America and Africa became less dense as they became richer? The following section shows that the Urban Access Framework, together with ITF Urban Passenger Model, can give insights on this subject (for a presentation of the Urban Passenger Model see ITF, 2017: Chapter 5, Annex 2).

If no stringent land control policies are put in place, urban density will globally decrease by 5% by 2050. Indeed a statistical analysis of the ITF city database shows that the two main drivers of urban area are population and GDP per capita. Urban area increases at a slower pace than population, thus bigger cities tend to be denser. However, richer cities tend to be more sprawled out. Overall the effect of GDP per capita more than compensates that of population, leading to a decrease in density as cities get richer. The density decrease is observed for all regions of the world, although to different degrees: it is particularly sharp in Asia, where the GDP per capita will be a significant driver of urban expansion.

Yet maintaining accessibility levels with these levels of urban sprawling would require road investments that are not financially or environmentally sustainable. By analysing historical trends, it is clear that the level of investment in infrastructure is strongly constrained by GDP. ITF, using its Urban Transport Model, has produced baseline projections of urban road investments. If no radical policy change occurs they are likely to double or triple in many rapidly growing cities of the developing world. However the infrastructure needs to maintain accessibility would be even higher. The situation is particularly dramatic for Asian cities. The drop in density is sharp, -19% between 2010 and 2050. Although the trunk road length is projected to grow by 137%, maintaining road accessibility constant would require multiplying the trunk road network by six. To a lower extent, similar trends are observed in transition economies and Latin America. This shows that road investments alone are not a sustainable option to guarantee an adequate level of accessibility in the rapidly growing cities. Global accessibility is thus expected to deteriorate between 2010 and 2050 in most cities of the developing world, unless significant changes in the evolution of modal shares intervene, which could require that strict policy packages are put in place. This also emphasises the crucial importance of stringent land-use policies in maintaining accessibility to opportunities in the developing countries.

Table 3. **Projected changes in some city characteristics between 2015 and 2050**

	Density (%)	Trunk road needs (%)	Trunk road forecasts (%)
Africa	-8	158	180
Asia	-19	295	137
EEA + Turkey	-7	39	46
Latin America	-8	92	49
Middle East	-2	98	99
North America	-1	36	39
OECD Pacific	-8	24	11
Transition	-15	120	57

Source: Adapted from ITF (2017).

5. Challenges related to measuring bike accessibility

The differences between cycling and motorised modes' accessibility

Characterising accessibility with non-motorised modes - and cycling more specifically - is a subject that has received little attention relative to motorised accessibility. Only a few academic studies have expressly addressed this topic (Iacono et al., 2010; Vale et al., 2016) though it is a source of interest for municipal governments in many cities and the object of policy in high-cycling countries like Denmark and the Netherlands. Part of the interest for understanding and designing more bicycle accessible networks stems from the inherent transport advantages cycling can deliver for short-distance trips (e.g. convenience, reliability, cost) but, equally important are the health benefits that cycling confers to people – especially those that have sedentary or low levels of physical activity (ITF, 2015).

One of the principal reasons for the scarceness of studies on the topic of cycling accessibility is that, until recently, data availability for cycling trips and preferences has been scarce. As noted in Chapter 3, new data sources, including GPS tracks, sensor-based roadside counts, crowd-sourced/volunteered data and activity-detection data have enabled new possibilities. Additionally, new crowd-sourced data on routes and preferences are expanding upon insights from studies that previously had been limited and spatially focused (Ehrgott et al., 2012; Stinson and Bhat, 2003).

More fundamentally, cycling has often been overlooked in transport planning since its characteristics are poorly aligned with traditional transport planning methodologies, especially in four-step travel demand modelling for traffic forecasting. One reason for that is cycling's small modal share in many cities, especially when transport planning focuses on distance travelled. Furthermore, in many models, a significant share of cycling trips take place within a single traffic analysis zone and so these trips are not captured in traditional analysis.

Moreover, route assignment methods in four-step models are not adapted to the specificities of cycling as a transport mode (Paez and Cómbita, 2017). Typically, route assignment is done through the shortest (or quickest) path, which is dependent on the availability of a road or public transport network. Mode choice for cycling however is inherently different from motorised modes. Movement is achieved through physical effort, a fact that makes road and terrain characteristics much more significant. The traveller is exposed to traffic and roadside risks with little inherent safety-improving protective devices or structures. Overall perception of risk by cyclists is thus an important factor in route choice.

Another factor to consider is that, while cycling plays an important role in urban mobility in many countries, it often serves primarily low income and disenfranchised travellers outside of northern Europe and some emerging economies. This is changing as more and more cities seek to increase cycling to improve transport and health outcomes. Recent efforts to preserve or increase cycling outside of countries or regions where it is popular – especially in parts of Europe, North America and certain parts of Asia (e.g. Chinese Taipei) and South America (e.g. Colombia) has raised awareness of the importance of adapted methodologies that account for the specificity of cycling.

Finally, because of the combined aspects of physical exertion and subjective risk perception, the population at large displays broad heterogeneity as concerns willingness to cycle and level of comfort doing so in different contexts and conditions. These differences can be summarised according to the following four categories (Geller, 2007):

- Strong and fearless cyclists: Unafraid to ride in heavy and mixed traffic – often young and male, typically a very small minority.

- Enthused and confident cyclists: Willing to ride in traffic but prefer calmer conditions and slower speeds.

- Interested but concerned: Those who are willing and interested in riding but whose subjective perception of risk keeps them from doing so – especially on roads with mixed traffic. Represents a large share of the population.

- Those that for practical or other reasons are not at all interested in riding a bicycle for everyday transportation.

A further differentiation comes with age and changes in the physical and cognitive abilities of cyclists – children may only feel comfortable in certain contexts, gaining confidence with age whereas older riders may lose confidence in contexts where they once were comfortable. Certain national standards, such as those in place in the Netherlands and Denmark, explicitly or implicitly account for the heterogeneity of the potential cycling population in the design of their bicycle facilities in order to achieve high levels of bicycle accessibility across a wide range of abilities and risk perception (CROW, 2007).

Another way to characterise the heterogeneity of cyclists (and potential cyclists) is to account specifically for the subjective physical and cognitive stress they experience in different contexts (Mekuria et al., 2012)(see Box 7). This, and other types of rider typologies, can help inform relevant cycling accessibility analyses across a range of current and potential cycling populations. This is especially important when looking to design cycling networks and guide infrastructure investments in order to provide high quality accessibility for groups of people that want to, but do not yet, use the bicycle as an everyday transport mode.

How to measure cycling accessibility?

Accessibility analysis generally uses one of two approaches as noted in Chapter 2 of this report. The first is to account for an "impedance" factor that increases with distance or time. The second is to assign a "cost" that reflects the distance to services and opportunities and can also include other cost-factors that have an impact on route choice and travel time.

The choice of impedance function determines how many locations are considered near each origin. The use of a threshold or stepwise function allows easy communication of results (e.g. 300 restaurants within 30 minutes) but creates a significant issue. Getting to a location that is just above the threshold would require minimal additional effort but is not included in the results. A progressive S-curve function can solve this problem. This type of function can also help account for the fact that due to the physical effort required for cycling, nearer destinations (and flatter routes) are disproportionately more attractive than further destinations (or uphill destinations). The S-curve gives higher importance for nearby locations and minimal difference for locations further away.

When using a cost-based approach, consideration should be given to the unique features of cycling outlined above. This "cost" can be a direct time or value cost, or a generalised cost that includes a combination of both of the former in addition to other relevant attributes (see Table 4). This approach makes sense for cycling accessibility analysis since many additional factors have a direct incidence on route choice.

Table 4. **Mode and route choice for cycling: Factors affecting generalised bike travel cost**

Study	Factors	
Ehrgott et al., 2012	Road gradient	Parked cars
	Traffic volume	Percentage of heavy load vehicles
	Traffic speed	Cycling facilities
	Lane width	Pavement conditions
Iacono et al., 2010	Off street cycling facilities	
Broach et al., 2012	Number of turns	Bike paths (+)
	Road gradient* (--)	Bike lanes
	Traffic volume (--)	
Hood et al., 2011	Road gradient** (--)	Bike routes (+)
	Bike paths (+)	Turns (-)
	Bike lanes (++)	Cycling against traffic (-)
	Bridge cycling facilities (+)	
Stinson and Bhat, 2003	Bike lanes (++)	Bridge cycling facilities (+)
	Bike paths (+)	Number of crossings (-)
	Traffic volume (--)	Number of turns (-)
	Pavement conditions (-)	Road gradient*** (-)

Notes:
*Used as the upslope percentage of the road   **Used as the rise in meters
***Categorised in different situations (mountainous, hilly)   +(+) (Strong) positive effect
-(-) (Strong) negative effect

Methodological approaches for measuring bike accessibility

A few methodological approaches to measuring cycling accessibility have been developed. These account for many of the cycling-specific factors described above. Some approaches explicitly account for factors in a generalised cost approach – this is the case for the accessibility analysis of cycling in Minneapolis (Iacono, et. al, 2010) described in Box 6. Another approach seeks to account for traffic stress levels in evaluating cycling accessibility as described in Box 7 (Mekuria et al., 2012). Hybrid approaches that seek to assess the overall "bikeability" or attraction of different networks and zones for cycling travel have also been proposed (Winters et al., 2013)(see Figure 20). One of the best-known approaches combines several cycling-relevant factors into an overall network and zone-based bike rating. This rating can then be used for routing decisions in accessibility analysis (Winters et al., 2016).

In the analysis that follows, we base the choice of factors that affect cyclists' route choice on studies found in the literature; those considered most important and with reliable data available were used. These factors affect the distance travelled by increasing or decreasing it accordingly and creating a metric that represents perceived or equivalent distance.

Road gradient is considered one of the most important factors in bike mobility. Understandably so since taking a route with a steep slope is physically taxing and leads to decreased speeds. The importance of slope for cycling, however, may progressively diminish as more and more cyclists use electric bicycles – and the importance of slope for elderly cyclists may disproportionately decrease as this group accounts for a greater-than-average share of electric bicycle purchases (ITF, 2015).

Figure 20. **"Bikeability" map for Vancouver and its components**
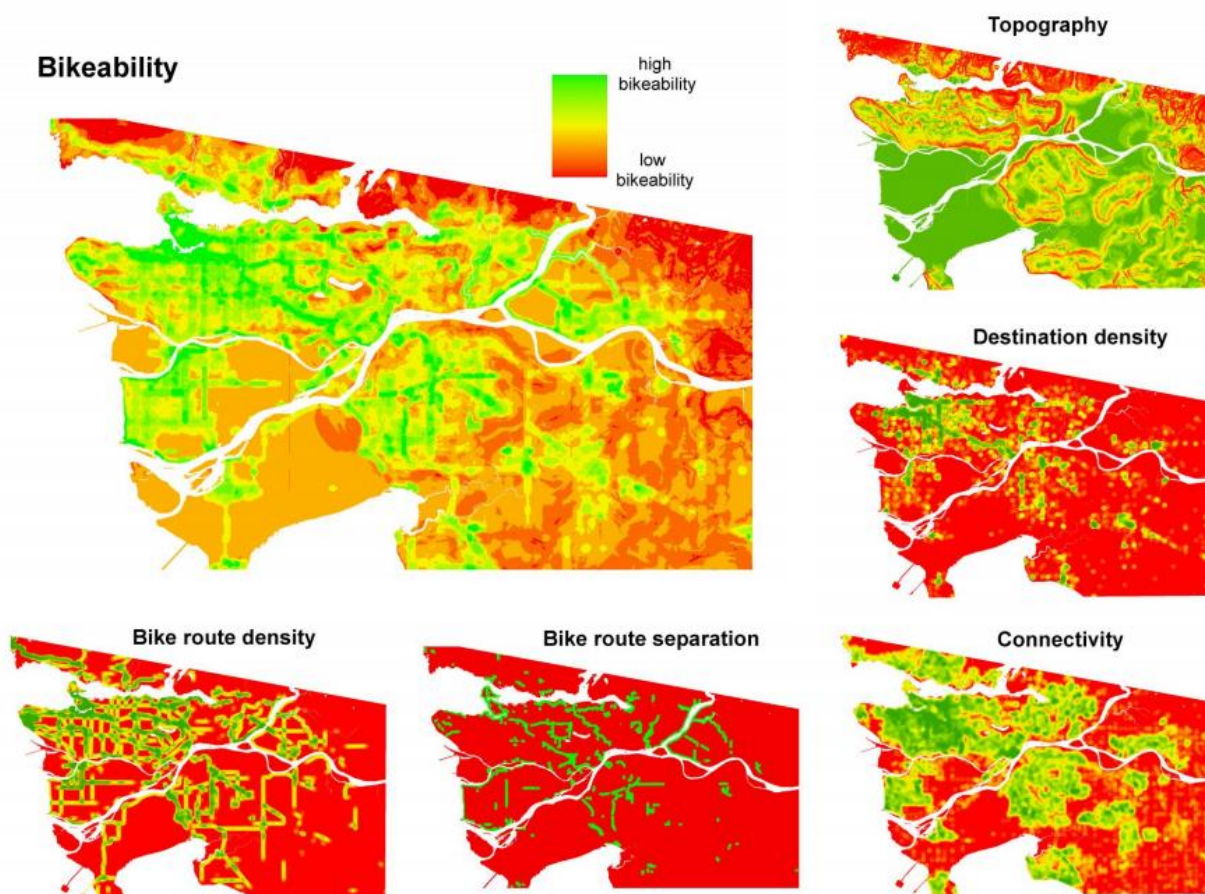
Source: Winter et al. (2012).

In the analysis that follows, road gradient effect is calculated by assigning equivalent distance based on the road gradient percentage. The effect of road gradient can either be linear or stepwise. When linear, the road gradient is multiplied by a specific number, resulting in the equivalent distance (Hood and Charlton, 2011). The stepwise approach estimate clusters the road gradient in groups, assigning a different weight to each cluster (Broach et al., 2012). Both cases have distinct advantages, so in the analysis that follows, we use a hybrid option. Road gradient is multiplied by the distance, but with different weights for each percentage of additional upslope. For example, a road of 100 metres with 2% upslope would have an equivalent distance of 120 metres, while the same road with a 5% upslope would have an equivalent distance of 350 metres. The opposite, having a downslope, despite requiring less physical effort was not considered to have a decreasing effect. Going down roads (with a negative slope) requires increased attention due to increased speed. Using such a formula, road gradient is included in the perceived distance metric.

Similarly, the characteristics and typology of the road is very relevant for cycling. A large share of current and potential cyclists state they prefer to use separated bicycle facilities or cycle lanes, even if this implies higher travel distances. The relative safety of those routes, combined with the absence of car traffic is a major factor for bike route choice. Also, for the same reasons, when using the regular road network, routes with less traffic are viewed favourably. Therefore roads with high traffic increase perceived distance, whereas bicycle tracks and bike lanes decrease perceived distance in our analysis.

The other important element of the methodology was the impedance function used to estimate the attraction of each opportunity based on its distance. We employ a S-curve to better represent the "near" and "far" ranges and the attraction decay between them.

Box 6. **Bike accessibility measurement in Minneapolis**

Iacono et al. (2010) examined non-motorised mode accessibility (walking and cycling) in Minneapolis, Minnesota (US). They identified and sought to address four main issues:

1. lack of reliable non-motorised travel behaviour data for a variety of trip purposes

2. lack of high-resolution land-use data

3. inadequate zonal structure and travel networks

4. arbitrary impedance functions used for walking and bicycling activity.

In their analysis, the authors state the importance of detailed travel networks, which include pedestrian and bicycle paths and lanes. To cover the benefits that these facilities bring to the traveller, lower "travel cost" per distance unit is assigned to them. Additionally, the spatial distribution of non-motorised trips is rather limited and therefore a decreased spatial focus is required. Regarding the impedance function, more complex functions are considered necessary, with the negative exponential function as the authors' choice, since it declines more gradually than the power function. They provide an example for bicycle accessibility to shopping locations, as seen in Figure 21. The importance of a central bike path (shown with green in the figure) is evident. Increased bike accessibility around this corridor comes in contrast with the main highways, which "separate" areas by not allowing cyclists to cross them.

Figure 21. **Bike access to shopping**
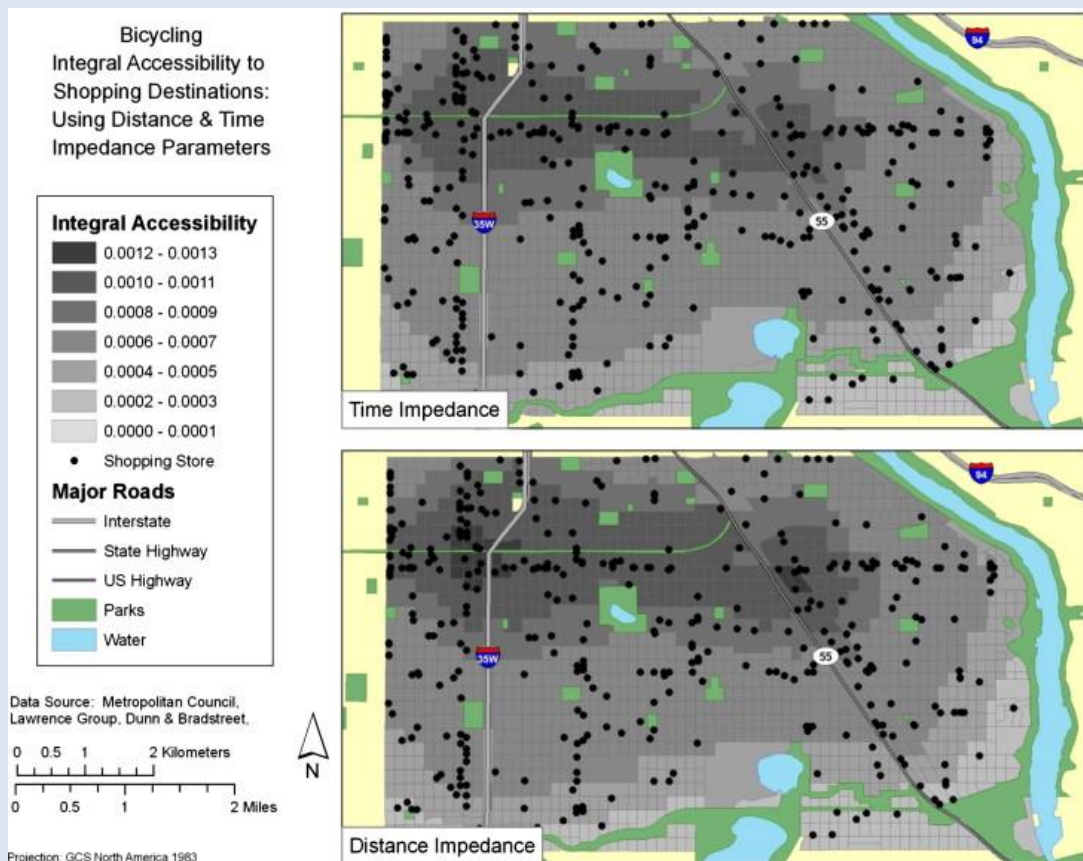
Source: Iacono, Krizek and El-Geneidy (2010).

Box 7. **Low-stress bicycling and network connectivity: San Jose Case Study**

Mekuria et al. (2012) take into account physical and cognitive stress experienced by people riding bicycles in order to assess subjective cycling network connectivity and accessibility in the city of San Jose, California. They classified city streets according to four levels of traffic stress roughly based on those used for Dutch bicycle infrastructure planning:

- LTS1: A stress level that most children can tolerate

- LTS2: A level of traffic stress tolerated by the mainstream adult population

- LTS3: The traffic stress level acceptable to enthusiastic and confident cyclists

- LTS4: Traffic stress levels tolerable only to the most fearless and strong cyclists.

Their focus on connectivity according to traffic stress level allows them to map how interventions to improve low-stress connectivity can encourage increased cycling – especially amongst intermittent and non-cyclists.

Using San Jose as a case study, they determined the extent of total road distance by traffic stress level; LTS 1: 64% of total; LTS 2: 3% of total; LTS 3: 8% of total; LTS 420% of total; Freeways (Bicycles Prohibited): 4% of total. Despite much of the road network being classified as LTS1 and LTS2, these road networks were largely disconnected due to barrier effects of LTS3 and LTS4 roads. Only 0.7% of all trips of less than 4 miles could be connected at LTS1 levels and only 4.7% of all trips of less than 6 miles could be connected at LTS2 levels.

The study looked at the potential impact of a set of improvements that focused on junction approaches and crossings, connecting cycle paths and two longer dedicated cycling facilities. The study found that these changes, spread over 16 corridors, could improve the fraction of trips of 6 miles or less connected at LTS2 from 4.7% to 12.7% and overall node-to-node connectivity by 480%.

Figure 22. **Low-stress cycling connectivity in San Jose, California, before and after infrastructure improvements**
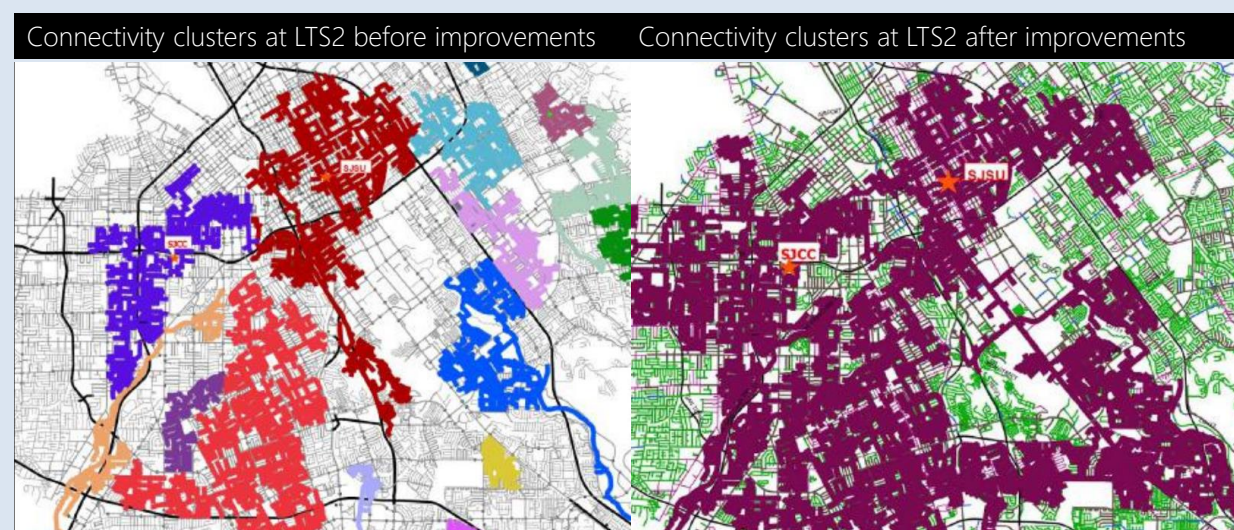
Source: Adapted from Mekuria, Furth and Nixon (2012).

Case study: Biking in Lisbon, Portugal

Built on seven hills, Lisbon has many roads with high slopes. Additionally there are few dedicated bicycle facilities in the city, mainly in relatively flat parts. Access by bicycle was measured to education activities, since this is an activity people often use bicycles to reach. Additionally access to restaurants was measured, since they can be considered as a proxy for social activity. Figures 23 and 24 show the distribution of education locations and restaurants across the city of Lisbon respectively. Locations of education-related

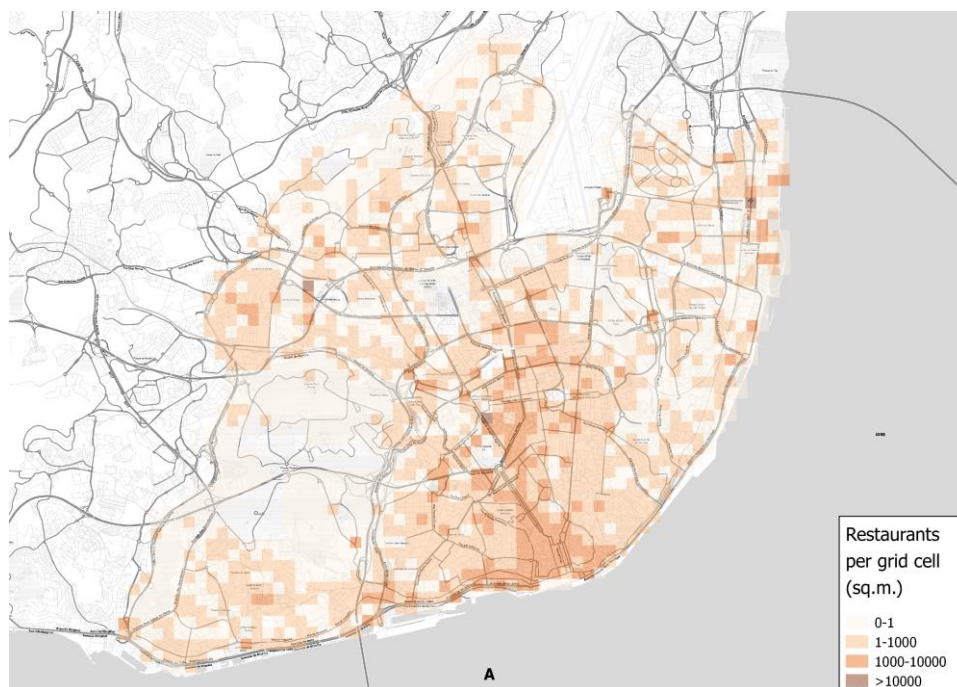destinations are more or less spread out throughout the residential parts of the city, while a large number of restaurants are clustered near the historical centre.

Figure 23. **Distribution of education activities in the city of Lisbon**
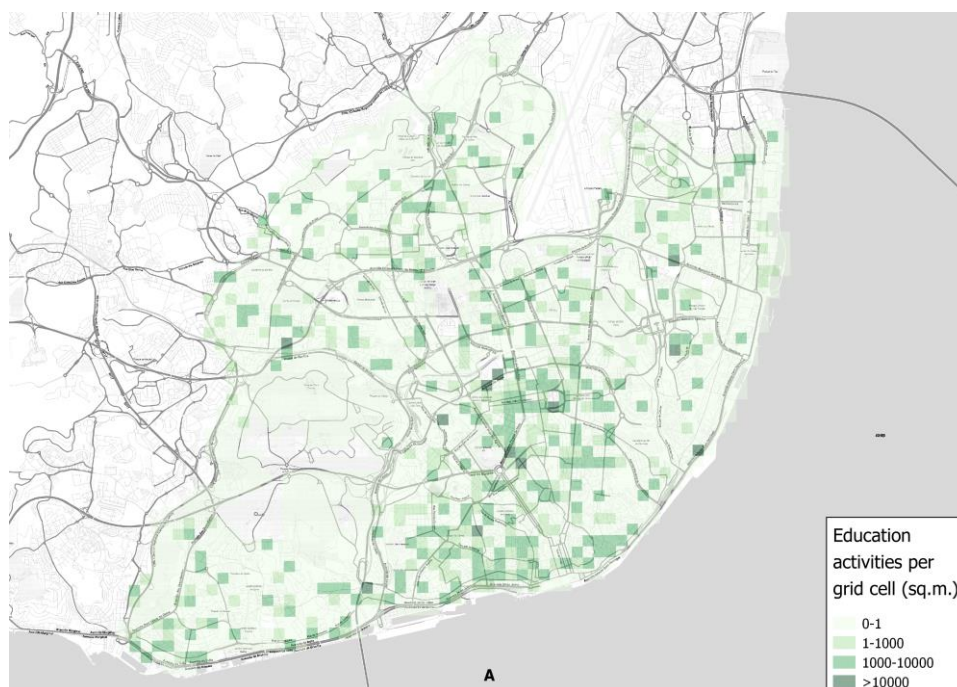
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0.

Figure 24. **Distribution of restaurants in the city of Lisbon**

Source: ITF, Map tiles by Stamen Design, under CC BY 3.0.

Our analysis considers a homogenous bicycle speed of 12 km/hour. This is a very important assumption, which tries to include the fact that cyclists have to slow down and often stop at intersections or when turning and that cyclists display different abilities, preferences and strength – all of which impact speed. Cyclists speed is also dependent on road conditions, such as traffic and road gradient, but the case study attempted to capture their effect through the equivalent distance metric.

Beyond seeking to capture the speed variations, the distance metric also tries to encompass the element of comfort and safety or lack of it, which is associated with bike travel. The following adjustments were made in the road network distance in order to estimate this metric: Travel in bike paths/lanes, in order to simulate the choice preference of bike users, received a length decrease of 40%. This value was estimated by averaging those found in the literature (Broach et al., 2012; Hood and Charlton, 2011). This means that 1 000 metres of actual distance in a bike lane are treated as 600 metres in the analysis. Upslope has been found to be a main element of bike route choice preference and therefore also contributed to the equivalent distance measurement (see Box 8). Road gradient data were computed by using altitude information from the European Digital Elevation Model for Lisbon's road and cycling network. Road traffic also plays an important role in bike mobility and its effect was calculated based on a formula in Box 8. Road traffic calculations were based on a traffic assignment model by Martinez (2010).

Box 8. **Calculating road gradient and traffic volume**

The function used to estimate the effect of road gradient is the following: $m_g = 1 + a * s * 100$

Where: mg = effect of road gradient, s = road gradient,

$a = \{$ 0 for   s ≤ 1%,

0.1 for 1% < s ≤ 2%,

0.2 for 2% < s ≤ 3%,

0.4 for 3% < s ≤ 4%,

0.5 for 4% < s ≤ 5%,

0.6 for 5% < s ≤ 6%,

0.7 for s > 6% $\}$

In Broach et al. (2012) traffic volume and its effect on cyclist route choice is recorded in vehicles per day. In order to estimate it in a per hour average the following assumption was made. Half of the daily volume happens during the four rush hours, and thus can the equivalent vehicles per hour for the effect of different traffic volumes on cyclists be estimated. The following function was used: $m_t = 1 + V$

Where: mt = effect of traffic,

$V = \{$ 0 for   vehicles/hour < 500,

0.2 for 500 < vehicles/hour < 1 000,

0.4 for 1000 < vehicles/hour < 1 500,

0.6 for 1500 < vehicles/hour < 2 500,

1 for 2500 < vehicles/hour < 3 500,

2 for vehicles/hour > 3 500 $\}$

Last but not least, to counter the issue of mobility happening within the same zone, it was decided to use the same very small zones as for other work done by the ITF based on Lisbon data, with a square 200-metre cell grid. A total of 1 969 grids, cover all the populated area of the municipality of Lisbon.

Each grid contains information regarding the type of activities and opportunities available there, measured in number of opportunities or m^2 of activity. In our example, the size of educational activities and restaurants in m^2 in each grid is used.

Figure 25 contains four maps, which show accessibility to education opportunities with the effect of the different adjustments on network distance. All figures include the effect of bike paths/lanes. Figure 25A shows bike accessibility without any other adjustment, using the real length of the roads. Figure 25B shows bike accessibility when considering the road gradient, whereas Figure 25C when including traffic during morning rush hour (8:00-9:00). Finally Figure 25D shows bike accessibility with both road gradient and morning rush hour traffic effects. The four quartiles of Figure 25A are used as a colouring reference for the other maps.

Similarly, for access to restaurants, Figure 26 contains four maps. Figure 26A shows bike accessibility without any other adjustment, using the real length of the roads. Figure 26B shows bike accessibility when considering the road gradient, whereas Figure 26C when including traffic during morning rush hour (8:00-9:00). Finally Figure 26D shows bike accessibility with both road gradient and morning rush hour traffic effects. The four quartiles of Figure 26A are used as colouring reference for the other maps.

Figure 25. **Accessibility to education by bike**
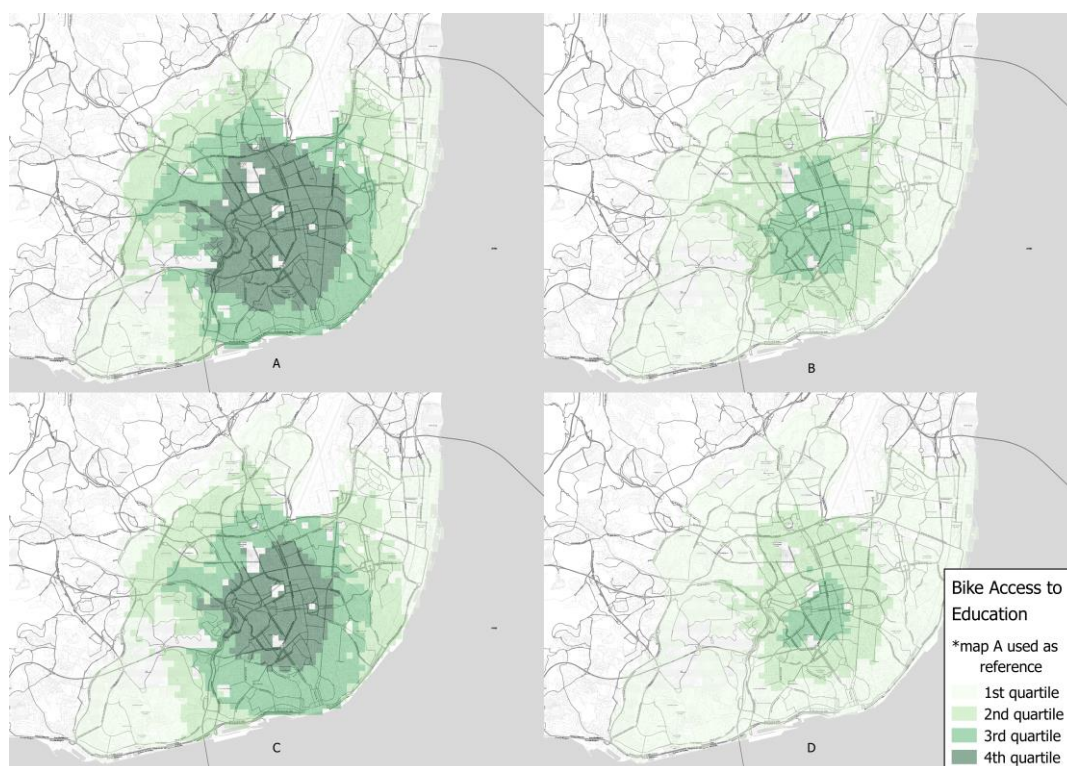
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0.

Figure 26. **Accessibility to restaurants by bike**
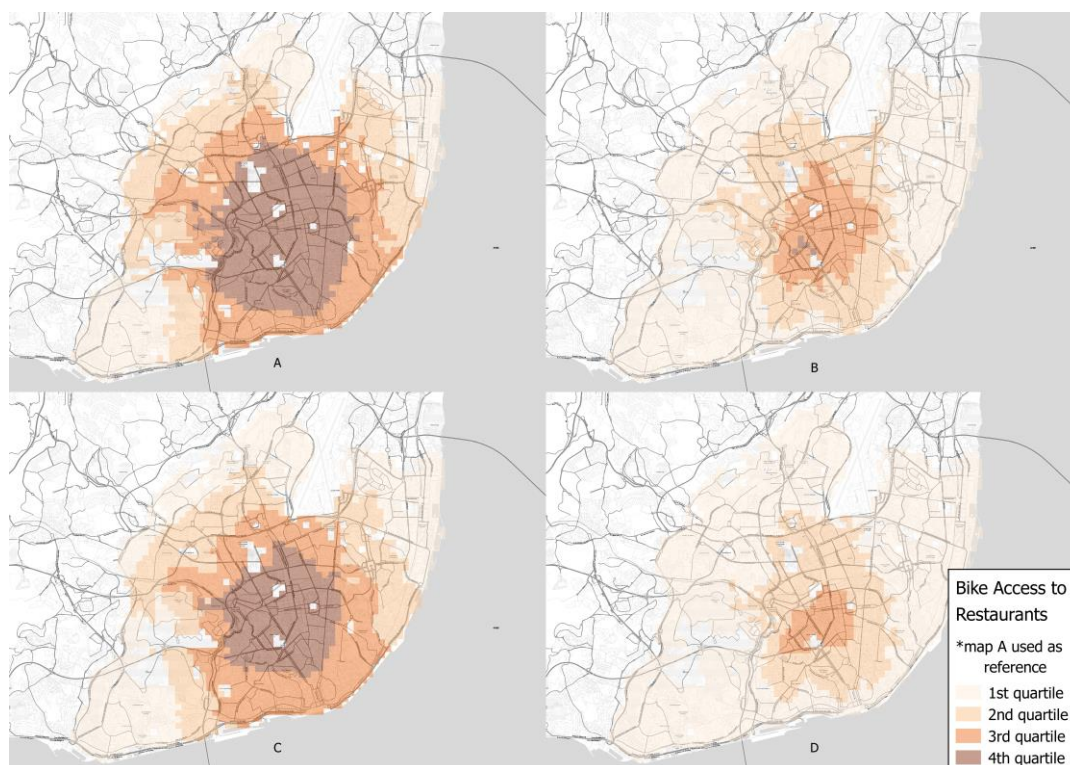
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0.

It seems clear that bike accessibility to education and restaurants is affected significantly by elements like road slope and traffic. By weighting the accessibility of each cell by its population, we estimated a weighted average of accessibility for the entire city. Considering free flow conditions and no slopes, in Lisbon a person on average can reach 61.6% of the total education opportunities by bike. When accounting for slope and morning peak traffic, this drops to 35.2%. Figure 27 shows the relative contribution of slope and traffic to this decrease in accessibility. A similar trend seems clear regarding access to restaurants. Interestingly, despite the differences in spatial distribution of education centres and restaurants, the results are very similar. The only notable difference comes from the effect of slopes, which have a bigger impact in access to restaurants. This is explained from the fact that there are many restaurants in and near the city centre, in areas with many hills and high slope roads.

Figure 27. **Percentage of access reduced by traffic and road gradient**
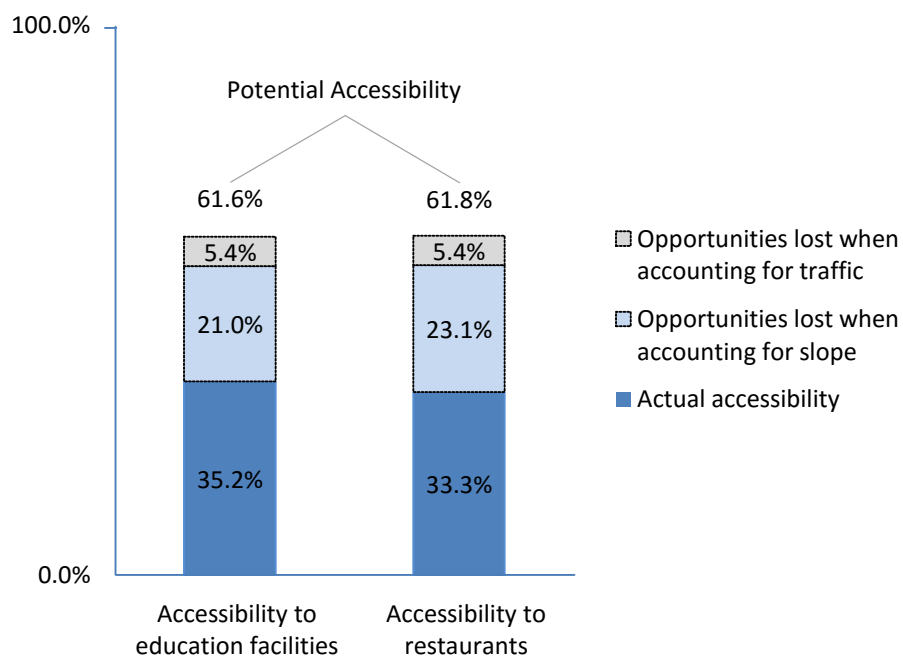
Figure 28 shows a direct comparison between accessibility (from each cell as origin) by bike to education activities and restaurants with all effects (road gradient and traffic) included. The results are clustered in five quintiles of 20%. The distribution of restaurants in the historical centre emerges from this map, as these areas have comparatively better access to restaurants than education.

Figure 28. **Access to education (A) and restaurants (B) including all effects**
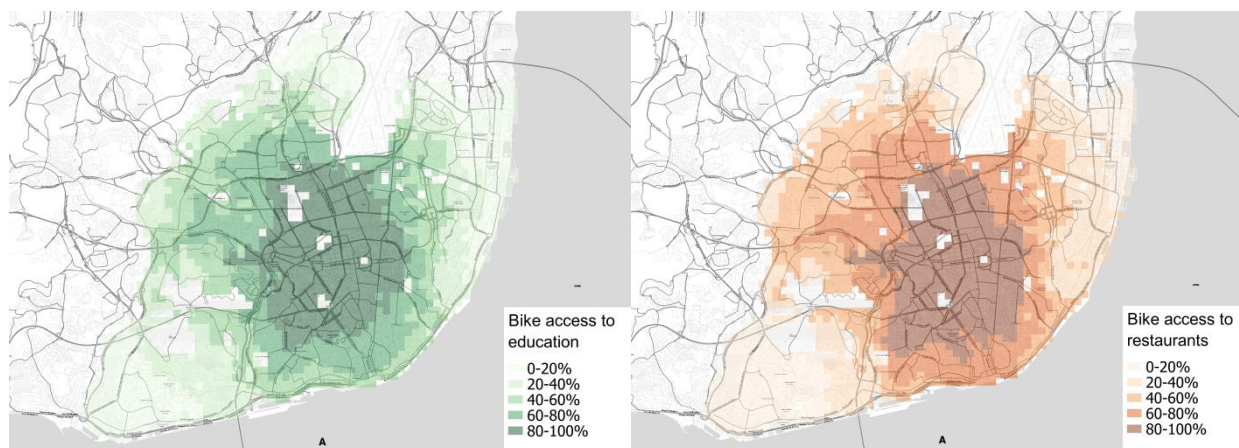
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0.

6. From accessibility levels to inclusion policies in urban areas

Equitable access to opportunity and facilities are key aims of public policy in urban areas. This is most commonly assessed through an analysis of the distribution of an accessibility indicator across the relevant territory. For reasons of affordability to the citizens and of environmental impacts, public transport must ensure equitable access to all citizens.

Chapter 2 showed that different types of definitions and associated indicators can justifiably be used for accessibility. Whatever the definition adopted, the values obtained for each point (or territorial unit) are dependent upon two types of factors:

- the location of that unit in relation to others, and particularly to those of greater mass (of opportunities, population, etc.)
- the impedance of movement between the unit taken as the basis for the calculation and those other units.

Although accessibility is often defined as a function of travel time, we prefer to use the concept of impedance, which covers not only the travel time but also the waiting time and, whenever frequency of service goes below 1 or 2 services per hour, latency, corresponding to an additional time inconvenience due to non-continuous availability of service.

When considering car travel, location is by far the most important factor underlying the different accessibility levels across an urban agglomeration, because travel is possible in virtually all directions and with speeds that do not show great differences in different directions (although they may have strong variations throughout the day). But for the case of public transport with fixed networks and schedules this is not the case because for a significant part of the trips (especially in large agglomerations) there will be the need for transfers, with significant impact on impedance, due to longer travel times (non-direct alignments), plus transfer and waiting times.[1]

So, when dealing with accessibility by public transport, computation of accessibility levels becomes technically more challenging. For example, the distance to the nearest public transport stop is a useful indicator of the minimum conditions required to enjoy acceptable accessibility levels, but the analysis should be deeper whenever more refined data allows. Indeed, as the example developed below in this chapter shows that in spite of quite acceptable (i.e. short) walking distances to the nearest public transport stop across the whole city under analysis, there are wide and unacceptable differences of accessibility levels in its neighbourhoods.

Using each unit as an origin, its accessibility is computed as the weighted sum of the masses of all destinations, the weight for each destination being the corresponding "attraction" factor, according to the S-curve as described in earlier chapters. Once the values of accessibility have been computed and mapped, the relevant policy questions must be addressed, namely: what can be done to improve accessibility levels, especially in areas that currently have the lowest access?

Locations are fixed but masses of opportunities at different locations are subject to policy intervention through land-use planning instruments, and these can be quite effective in reducing problems of poor accessibility to specific types of functions. In general, policies favouring higher density and functional diversity in each neighbourhood will help improve accessibility. This comes in two dimensions: locally, by making a wider range of activities (and associated trips) possible by walking and cycling; and at a distance, by making public transport more viable through the concentration of demand.

We have seen earlier in this report that density and speed of travel were the main factors underlying differences in accessibility across cities in different continents. But we were dealing with aggregate rather than refined data (using population and car-based travel speed as the key indicators).

In this chapter we will focus on a particular city, and how, with increased availability of finer data, it is possible to assess and improve accessibility in areas which are currently poorly served. In many cases, low accessibility is a result of a combination of peripheral location with poor connections; here the idea is to see to what extent improving those connections could improve accessibility and thus contribute to a more inclusive society. So, to some extent, how far could good connections compensate for peripheral location.

Better connections can be achieved by improving the existing network links (through higher speed or frequency) or by the creating new links in that network, e.g. a new bridge or tunnel for the case of infrastructure, or a new bus line in the case of public transport services.

The key concept for this analysis is equivalent direct speed[2] (EDS). The EDS between two units means the quotient of the direct distance (shortest possible, i.e. a straight line in the case of urban areas, independently of the network in operation) by the real minimum impedance between those two units (using the path of least impedance, including transfers if that is required).

Using the S-curve mentioned above we can transform the mass of opportunities available at each destination into mass of opportunities effectively accessible at that destination starting from a particular origin, i.e. considering the willingness of citizens to go there. Thus it becomes clear that the challenge for transport is to "shift" some of the destinations with relevant available mass from the low values of the S-curve to significantly higher values of that curve, by reducing the impedance of that displacement.

Figure 29. **Gains in effective accessible opportunities as a result of reduced impedance**
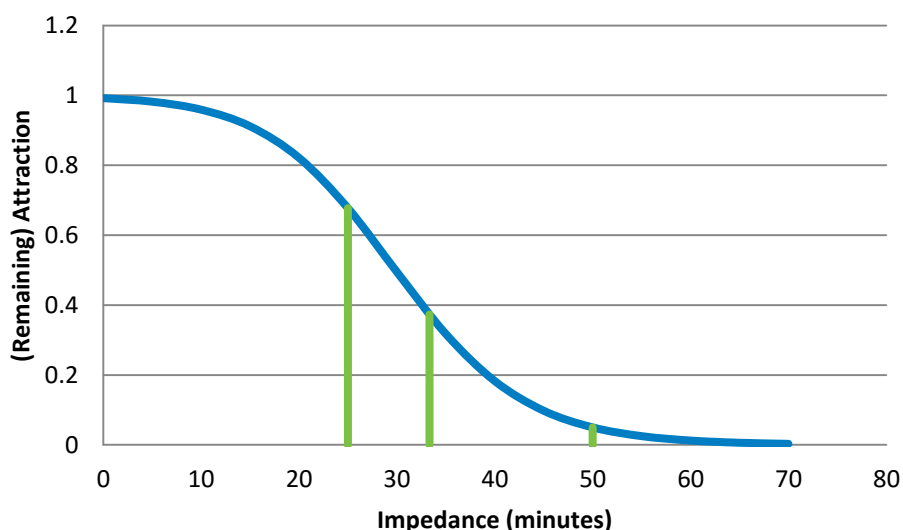
As an example, in the hypothetical (but realistic) case shown in Figure 29 reducing the impedance of travel to a specific destination from 50 minutes to 33.3 minutes (by a 50% increase of the EDS), the attraction coefficient increases 7.5 times as it goes from 0.05 to 0.37. Doubling the EDS reduces the impedance to 25 minutes and increases the attraction by a factor of 13.6 to 0.68.

We will now explore how this approach would be applied to a case with real data in which the policy concern is accessibility by public transport. The case is Lisbon, with the same data as used in other ITF studies (ITF, 2016), namely imposing a 200-metre wide cell grid on the urban space and using the public transport network as in operation in 2010. There is a total of 1 969 cells with resident population in this grid.

Steps and results of the process

This report used a series of steps which are described below. For easier understanding, the procedure in each step is immediately followed by a presentation of the results obtained.

Step 1

Compute the values of accessibility to jobs for all grid cells using the S-curve as presented above. The results obtained (Figure 30) correspond, for each grid cell, to the percentage of the total number of jobs in the city effectively accessible from that cell as origin. This figure presents the values with a large number of classes because of the fine scale of subsequent analysis. The map legend contains for each class its lower and higher limits and the number of cells falling in that class.

Figure 30. **Percentage of jobs accessible from each cell (using public transport and walking)**
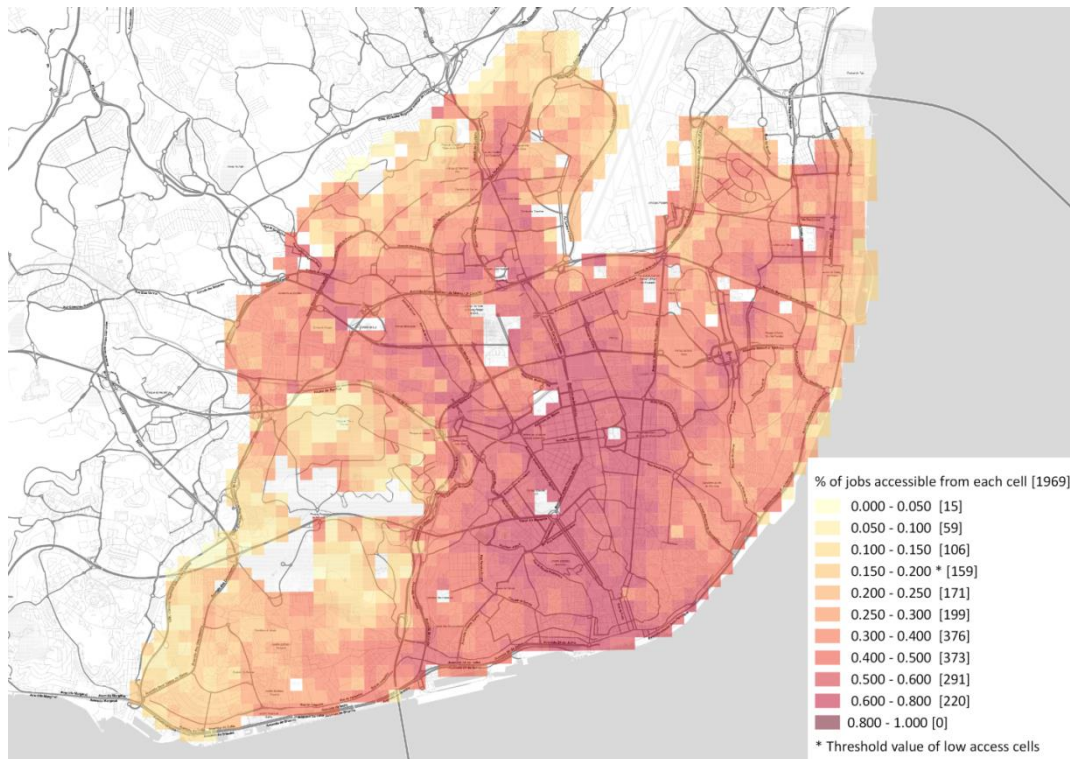
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0

The values obtained have a range between 1% and 76% of the total number of jobs in the city, with a median at 37%. The ratio between the 90th and the 10th percentiles (respectively 60.5% and 15.5%) is 3.9, indicating a situation of considerable inequity.

Step 2

Select an accessibility threshold corresponding to the "minimum acceptable" value in terms of equity. For the sake of this example, we will take one-third of the 90th percentile in the current situation, which means having 60.5% / 3 ~ 20.2 % of the total number of jobs in the city effectively accessible from a given cell. There are 345 cells (17.4% of the total) with unacceptably low accessibility. Globally in these cells we have 5.7% of the residents and 3.5% of the jobs in the city. As expected these are cells with less than average resident population density and much less than average job density.

Step 3

Compute the EDS for all origin-destination (OD) pairs considering only public transport as a means of travel.[3] The range observed goes from 1.1 km/h to 27.48 km/h, with a median of 7.41 km/h. All the cases of less than 2 km/h correspond to situations in which walking (roughly 4 km/h) is not a good choice, either because of barriers or distance, and the public transport solution has long paths and transfers. In fact, these two modal options are so bad that such pairs of cells will only be connected by car or taxi.

Step 4

To increase accessibility levels by public transport improvements, an initial analysis of what could be achieved with relatively simple interventions is useful. For that purpose a benchmark for EDS in any new connections should be defined at such a level that it would be relatively easy to achieve. In this example, the benchmark is a rather moderate ambition percentile of the current EDS values, for instance the 50th percentile, corresponding to 7.41 km/h.

Step 5

Figure 31. **Percentage of jobs accessible from each cell with current public transport supply (A) and with improved supply through higher EDS (B)**
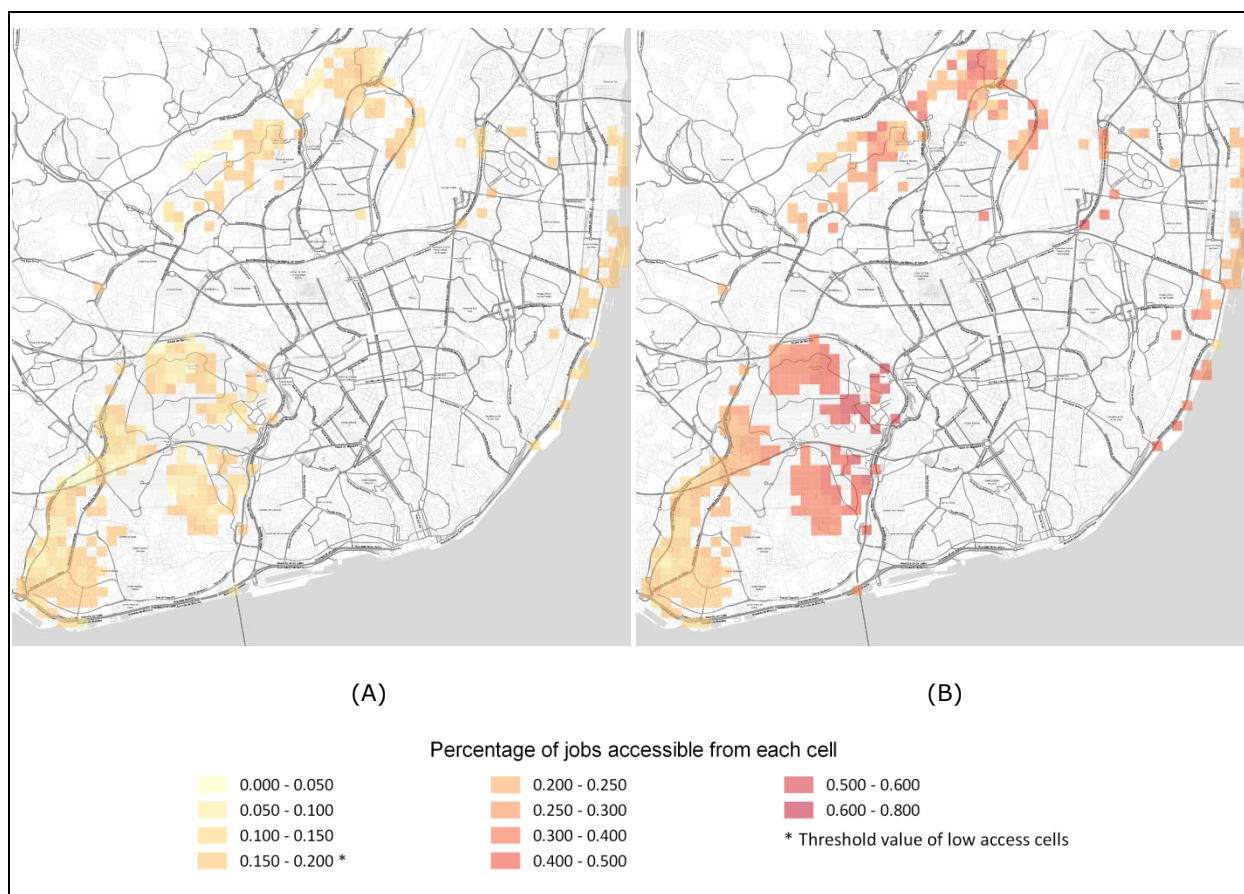
Note: Only cells with current very low access levels are shown.
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0

For each of the cells with values of accessibility below the threshold selected in step 2, calculate the value of "potential accessibility" that would be obtained if its EDS to all destinations[4] would be upgraded to that

benchmark, i.e. by increasing all the sub-par EDS values to the par. The corresponding impedances would be reduced and attraction factors would increase, thus pushing the accessibility value upwards.

Figures 31, 32 and 33 show, only for those units with current accessibility below the acceptable threshold, their accessibility levels before and after the upgrade (Figure 31), the multiplicative accessibility increase factors obtained through this hypothetical transport improvement (Figure 32), and the ratios between the "potential accessibility" thus values obtained and the "minimum acceptable" value (Figure 33).

Even at the small scale of Figure 31 two relevant pieces of information are visible:

- Significant improvements are visible in many of the cells currently characterised by sub-standard accessibility to jobs.

- Some cells remain in rather low accessibility levels, which means that interventions on the land-use side would also be required in those cases.

Figure 32 provides an additional insight of the accessibility benefits brought by the assumed increase of EDS. In this case we have used four categories. The most relevant information coming out of this figure is that significant groups of adjacent cells would experience an increase in the number of jobs effectively accessible with a multiplier of at least 2 (174 cells, i.e. 50% of those 345) or even at least 3 (81 cells, i.e. 23% of those 345).

Figure 32. **Multiplier of number of jobs accessible from each currently under-served cell**

Multiplier of no. of jobs accessible [346]
1.0 - 1.3 [73]
1.3 - 2.0 [98]
2.0 - 3.0 [93]
3.0 - 15.0 [81]
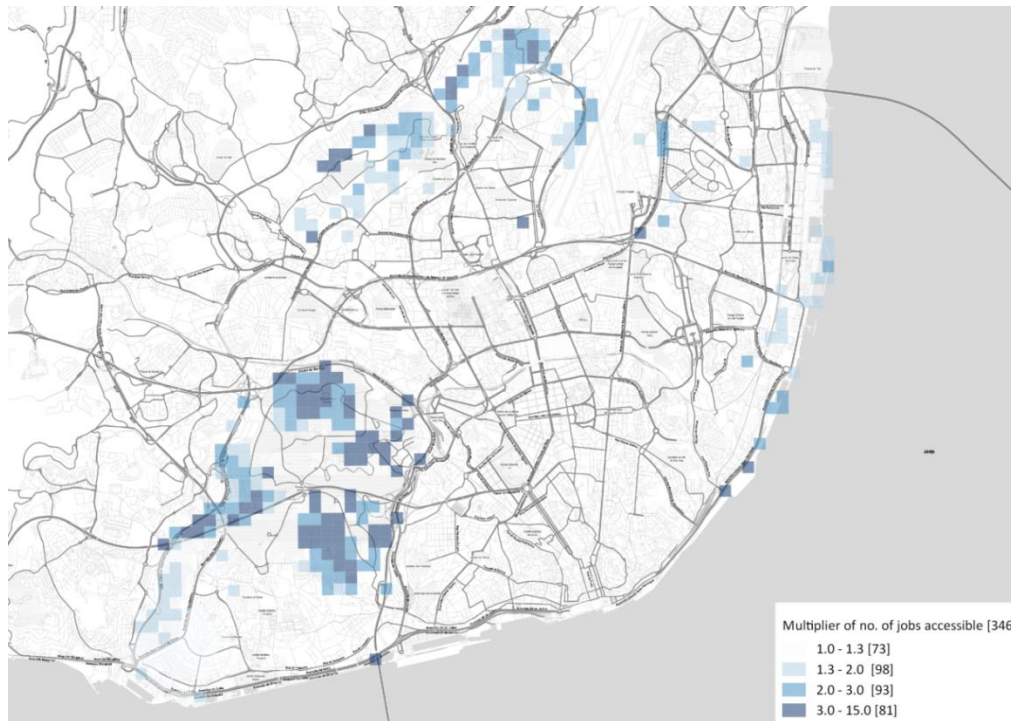
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0

Because the speed improvements were concentrated in the low accessibility cells, there is very little impact on the high accessibility cells and the 90th percentile (P90) of accessibility hardly changes (60.8% of jobs accessible after upgrade vs. 60.5% accessible with the current supply). This small increase is due to the fact that the speed improvements were done assuming symmetry of the public transport connections and

so a few more jobs located in the low accessibility areas become accessible to the residents in the high-accessibility areas.

Consequently, the threshold of "acceptable accessibility" at P90/3 (as defined in step 2) of this method) also has a slight increase from 20.2% to 20.3%. But the interesting aggregate result of these improvements is that the number of cells below this threshold goes down from 345 to 90 (see Figure 33). In these cells there would be 1.7% of the total residents and 2.1% of the jobs.

Figure 33. **Ratio between number of accessible jobs from each cell and the minimum acceptable in equity terms**
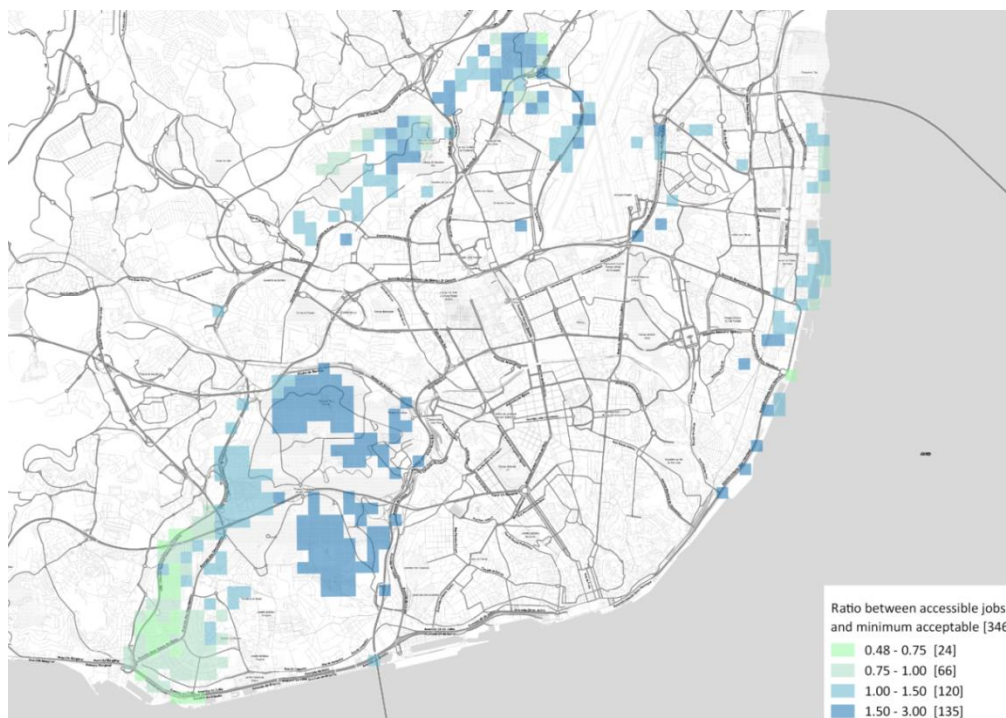
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0

Step 6

The results of this analysis strongly suggest a preliminary division between the cases of cells that could have their unacceptable accessibility level addressed by transport interventions (those with "potential accessibility" above the "minimum acceptable" accessibility level) and those for which an intervention on the land-use side would be required, accompanied or not by a transport intervention (those below that "minimum acceptable"), on the southwest boundary of the city (Figure 33, lower left).

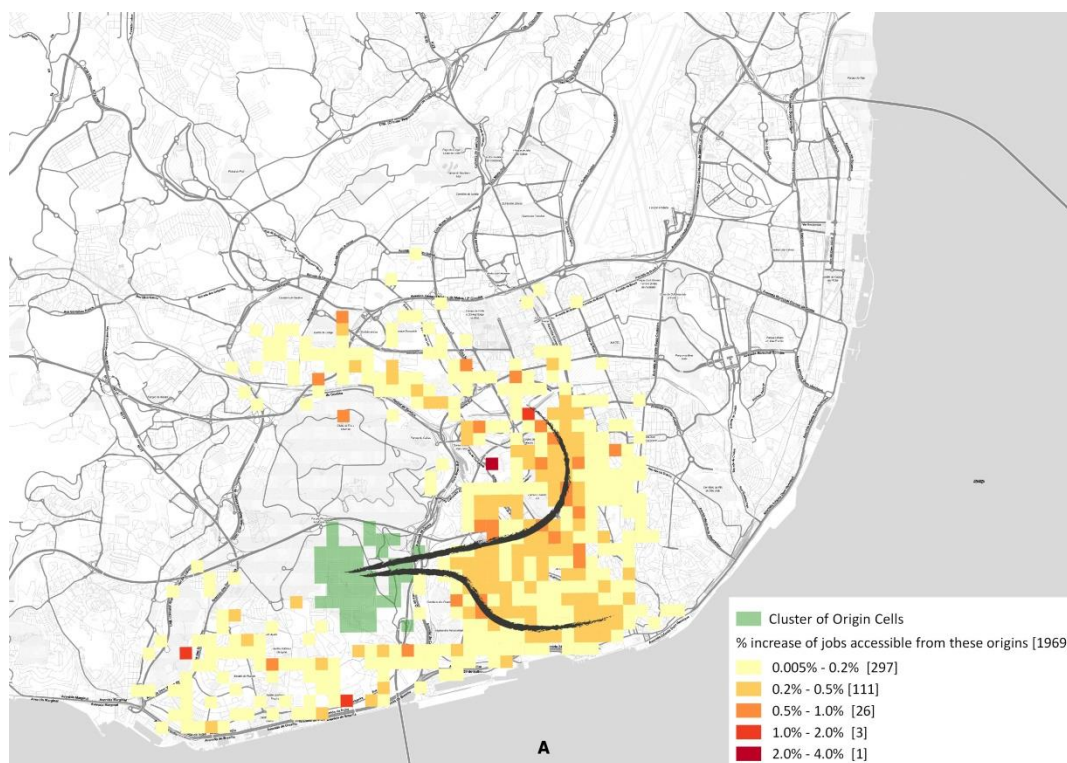### Step 7

For those cells whose situation seems capable of significant improvement via a transport intervention a more detailed analysis would follow, with, for each cell as origin:

   a. Select a group of neighbour cells (a cluster) as origins and make a scan of destinations and computation of the overall accessibility increase of those origins provided by an improved EDS to each destination.

 b. a selection of the destinations that would be targets for better connections (new lines, improved frequencies, etc.), possibly by ranking the corresponding increases computed in step 7.a (see Figure 34).

 c. the kind (and cost) of actions that might be required to achieve the improvements of EDS to at least the benchmark selected in step 4.

Using the cluster of cells defined as origins, Figure 34 clearly highlights in which directions similar scale improvements of EDS would provide a stronger impact of the number of accessible jobs from there. Since these gains of accessible jobs are *per cell*, it seems quite feasible to organise two new bus lines that would go from the cluster of origin cells towards east and then split one towards north and the other towards south-east, with which a significant part of the potential accessibility gains would be obtained. Of course, these need not be two new lines, they could be extensions or adaptations of existing lines, but that requires a much finer analysis beyond the scope of this text.

Figure 34. **Percentage increase of number of accessible jobs in connection with reduced impedance to each destination (from a select group of origins)**

Source: ITF, Map tiles by Stamen Design, under CC BY 3.0.

Step 8

Bringing together the results of step 7 for multiple cells as origins will almost inevitably suggest some interventions of common interest to several cells in linking them to the areas of higher concentration of jobs. This concentration of "clients" on the same services will help increase the expectations of demand for those new or improved services.

Step 9

It may happen that the densities of demand along these (new or improved) lines necessary to remedy the situations on unacceptably low accessibility will be too low for the launch of those improvements, as indeed they may be in some of the existing services.

Step 10

The potential of demand-responsive services (Taxi-Buses) as part of the shared mobility solutions to simultaneously offer great improvements in the equity of accessibility, and do it at a much lower cost, has been shown in earlier work by ITF (2016).

In that case, for ease of communication, the attraction decay was modelled using a step function (any destination within 30 minutes with a weight of 1, and above it counting with a weight of 0). Using the same solutions of shared mobility as in that report, but adopting the S-curve of this chapter for the attraction decay function, the resulting accessibility map is as shown in Figure 35.

In this case, the maximum is 83% of the jobs in the city and the minimum is 29%, with the ratio between the 90th and the 10th percentiles equal to 1.71. And using the same threshold as above for acceptable accessibility (one-third of the 90th percentile), no cells are found in that situation.

Figure 35. **Percentage of jobs accessible from each cell under shared mobility solution (Taxi-Bus)**
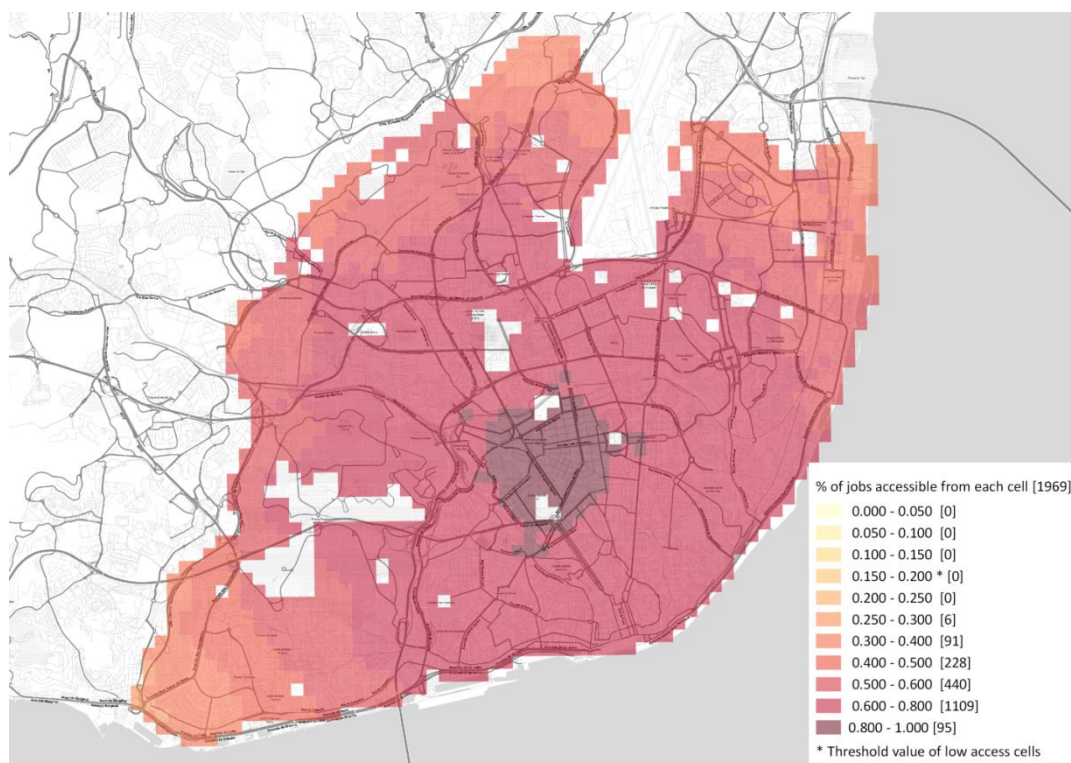
Source: ITF, Map tiles by Stamen Design, under CC BY 3.0.

This exercise is suggested here with a number of parameters (for the S-curve and for the thresholds), but it can easily be adjusted to other values of those parameters with a better fit to the mobility profiles and to the political preferences of a given city. The idea is really to see what the apparent margin for improvement of equity of accessibilities is in a study area if a concentrated effort of improvement of the worst connections is made.

Naturally, similar exercises should be done considering access not only to jobs but also to essential public services (education, health), and to shopping and leisure facilities. In most cities, the areas suffering from poor accessibility in one function/activity will probably have a large overlap with those identified for other functions, and the allocation of priorities for the transport improvements could also consider for how many of these functions each such improvement would bring the beneficiary city areas into the acceptable accessibility range.

For the cases requiring interventions on the land-use side, however the efforts would have to be additional, with investments in each of the functions for which the accessibility was lacking. Naturally this leads to more functionally diverse and pleasant urban environments, but the additional costs may lead to a greater delay in addressing the problems.

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Notes

[1] Although important for citizens, for reasons of data availability, this analysis will neither consider aspects related to physical effort and inconvenience in transfers, nor the reduced reliability of the trip when formed by two or three links instead of just one (direct connections).

[2] The term "speed" is used here in a somewhat informal way since we are not dealing purely with travel time but with impedance, including that travel time plus waiting and transfer times. But the essential concept of "speed" is still valid, in that it corresponds to the quotient of a distance by a time to span it.

[3] Of course, for real trips, walking is the natural option for relatively short distances and it must be considered when computing the accessibility values, but in this exercise the purpose is to improve the connections by public transport. And because the benchmark speed is obtained by calculating a percentile, the speed of the connections made by walking should not be considered in step 3.

[4] Also considering the utilisation of walking for the cases in which it provides the lowest impedance.

Linking People and Places
New ways of understanding spatial access in cities

This report examines how different people and groups experience accessibility in cities. It reviews the latest research findings, methodologies and data sources on urban accessibility and discusses how better data and computing power can enhance accessibility analysis and mapping. The findings provide policy makers with guidance on how to make it easier for citizens to physically reach services and opportunities that matter to them, and to help build more equitable and sustainable and economically viable cities.

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