How steep is that street?: Mapping 'real' pedestrian catchments by adding elevation to street networks

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Abstract

Objective: This paper develops a way of incorporating steepness into 'ped-shed' analyses to provide a more realistic view of urban walkability. The methodology is tested on the street network in Milton, north Glasgow, but presented such that it could be applied more widely.
Method: Elevation data is added to existing and proposed street networks in Milton which enables a calculation of average walking speed per segment to be made taking into account steepness. The networks are then run through ArcGIS's Network Analysis extension, using time (adjusted for uphill and downhill slope) as impedance.
Results: 'Real' walkable 10-minute roundtrip catchments around neighbourhood centres are compared with 2D catchments, for existing and proposed street networks. As expected, the 'real' 'ped-shed' is smaller than the 2D 'ped-shed' for both networks, although the walkability of the more connected, proposed street network is less affected by steepness, most likely as a result of greater choice in route selection.
Discussion: This research builds on existing established practice in walkability analysis, incorporating the often-overlooked steepness variable as a key statistical element of the walking experience. It also prompts a discussion on other factors which may affect walkability and could be included in a more sophisticated walkability index.

Keywords: 'Ped-shed', Walkability, Urban Road Networks, Catchment, Slope

Introduction

Walkability is a widely used concept connecting many divergent fields, including transportation planning, sustainability, sociology, health and urban design (Talen & Koschinsky, 2013). It is defined broadly as the level to which walking in a given area is deemed to be both practical and present, often relating to a number of factors such as air quality, safety, crime, mixed-use neighbourhoods, sidewalks/ pathways, transit and, arguably most importantly, urban density (Spacey, 2016).

A key principle of contemporary urban design theory is that everyone living in an urban area should be able to access routine shops and services within easy walking distance. In fact, walkability is both a motivation and consequence of a more holistic approach to city design.

There is a widespread environmental and sustainability goal of reducing car-centric urbanism by creating walkable pedestrian environments, related to the degree to which neighbourhoods are compacted (Frey, 1999). The geometry of street networks can have a big influence on whether shops and services are likely to cluster in an area. More interconnected networks and more central streets can support more shops and services (Mehaffy, et al., 2010; Porta et al., 2012). These networks are inherently more walkable (more connections mean shorter blocks), and this walkability can in turn reinforce the economic diversity and vibrancy of an area making it more attractive to retailers, not to mention improving environmental and human health conditions as a result.

In a 1999 Urban Task Force (UTF) report titled 'Towards an Urban Renaissance', the question of how four million projected new homes in the UK over the coming twenty-five years might be accommodated was addressed. Part of this report sought to illustrate the distance a typical person is prepared to walk in order to reach local facilities. It found that most people are prepared to walk five minutes to get to their neighbourhood shop, school or bus stop (UTF, 1999). The hierarchical network of urban districts and distinct neighbourhoods advocated by this UTF report and other work also call for 'pyramids of intensity'; that is, density being higher towards the centre of each neighbourhood and district within the hierarchy. These conceptual 'rings' around nodes have become important tools in concept planning in urban design.

It's easy to draw conceptual pedestrian catchments around clusters of shops and services on masterplans, but these are commonly Euclidian 'as the crow flies' catchment distances and as such not representative of reality.

Figure 1 illustrates such basic practice whereby conceptual circles are drawn around locations based solely on Euclidian distance with this then translated into time with few (if any) additional constraints considered.

Humans are generally confined to a network of streets and paths to complete a journey. For an urban designer, therefore, it is much more valuable to map actual walking routes. Mapping actual walking routes should provide a far more informative means to determine how the layout of streets might be altered to increase pedestrian walkable catchments. When trying to determine required residential density to support certain types of shops and services, then, actual walkable catchments are invaluable.

Such mapping is a considerable improvement on conceptual circles and is more recently being used in city and transportation design, sometimes with sophisticated extensions including accounting for the presence of traffic lights and the number of street crossings.

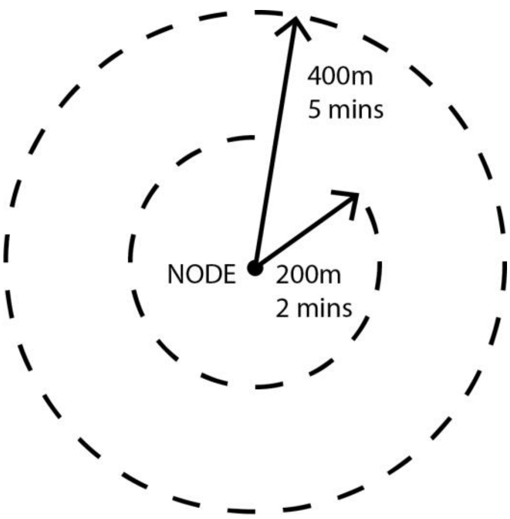

Figure 1. *Walkable catchment areas are commonly represented as conceptual circles around a node.*

For two potential neighbourhood nodes in Milton, north Glasgow, this paper compares conceptual circular catchment areas to actual walking distances along the street and path network. In turn, a comparison to actual walking distances along a new proposed street network is made, with shorter blocks and more intersections. Milton is at the limits of Glasgow's boundary, around 2.5 miles north of the city centre, and was built between 1940 and 1960 as part of the city's slum clearance program. Its street network is characterised by oversized blocks and long roads, sometimes broken up by pedestrian paths (UK Housing, 2016).

To add further complication, there is an additional constraint for humans and one that is less widely incorporated into analysis, on top of being constrained to a path network. When planning in 2D, it is surprisingly easy to abstract from the fact that land is three-dimensional. What classic 'pedestrian shed' (commonly referred to as 'ped-shed') analysis, defined here as a means to summarise the basic building blocks of walkable neighbourhoods, fails to incorporate is the impact of changing elevation on route selection and walkable catchments. If walkable catchments are expressed in time, it seems reasonable that the steepness of streets could considerably impact upon which places are deemed reachable within specified time limits. 'Ped-sheds' are regularly defined as the area covered by a 5-minute walk (typically 400 metres) and may be drawn as perfect circles but in practice 'ped-sheds' have asymmetrical shapes as they cover the actual distance walked, not the linear (Euclidian) distance (pedshed.net, 2016).

To provide evidence for this assumption, a comparison is undertaken of the performance of both networks when the elevation of the streets is accounted for. This also considers whether the impact of topography is mitigated by a more densely interconnected street network.

Interestingly, past work in this domain has had a tendency to simplify walkability and calculate this based merely on time as a function of distance without considering ground topography. Research by Newman and Kenworthy (2006) focusses on walking times independently of slope whereas Babb et al. (2011) appreciate that different people have different walkability thresholds by separating adults from children but also do not adjust calculations to reflect ground conditions, topography is mentioned in this work but it is deemed 'optional'. Similarly, Giles-Corti et al. (2011) conduct a walkability study with regards to the potential to walk to school and make use of street connectivity and traffic exposure only, no mention is given to topography or elevation and this typifies work to date in the field.

Data

The key input to any walkability analysis is data on streets and paths (location, directionality, length etc). Geographical Information Systems (GIS) software reads this vector data as a series of connected, georeferenced polylines. These polylines are read in a two-dimensional space, as if the landscape is perfectly flat at all times. Walkability and 'ped-shed' analyses to date focus almost exclusively on this premise.

For the purpose of this research, this network data is a combination of Ordnance Survey's Integrated Transport Network (ITN) layer and the related ITN Urban Paths layer. These datasets were cleaned and combined in the GIS environment (using ESRI's ArcGIS software), using local knowledge of the study area to add and delete pedestrian paths where appropriate thus creating a contemporary network as illustrated in Figure 2.

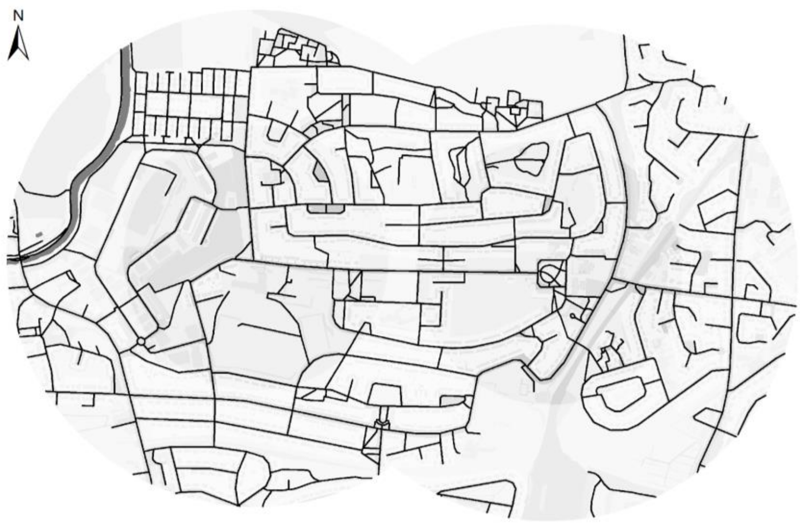

Figure 2. The combined existing street and path network in a subsection of Milton, Glasgow. Data adapted from OS ITN and Urban Paths layers, 2017.

For the proposed network, the two layers shown in Figure 2 were taken as the base, then edited with the changes according to a concept plan for the study area.

The second key input for any walkability analysis which takes into account topography is that of elevation. A Digital Elevation Model (DEM) provides the third (Z) dimension to supplement 2D (XY) data in GIS. The DEM for this analysis was sourced from Ordnance Survey's Terrain 5 DTM layer (Figure 3). This is a faster input to the GIS environment.

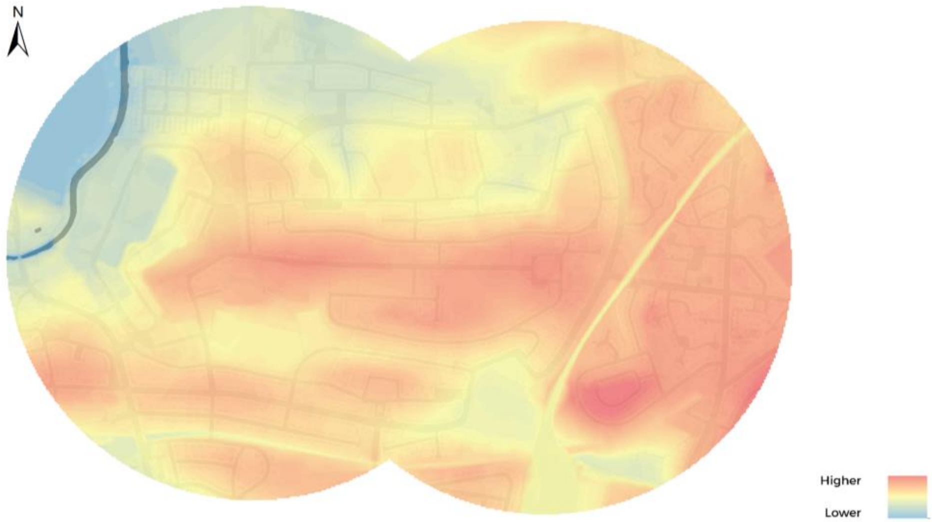

Figure 3. *Digital Terrain Model showing elevations for a subset of Milton, Glasgow. Data sourced from OS Terrain 5 (2016).*

To provide context, Ordnance Survey's Topography layer was also used. This offers a useful backdrop of information, including buildings and water bodies. For this analysis, each category of topographic information in this vector layer was assigned a grayscale colour.

Data were also required on the whereabouts of the neighbourhood nodes in order to calculate catchment areas around them. A 'Neighbourhood node' is a term used to describe clusters of everyday shops and services serving between 5,000 and 10,000 people depending on residential density (UTF, 1999). Since these are potential rather than existing nodes, a vector layer was created containing two geo-referenced points for this purpose, both within the Milton area of Glasgow.

Methodology

Analysing walkable catchments across a 2D network is relatively straightforward. To analyse walkable catchments taking elevation into account is more complex and requires a clear methodological framework with several steps. The following sub-sections evidence this framework.

Logic

The logic of adding elevation information into walkability analysis starts from the premise that more effort is required to walk uphill or down steep slopes, this is deemed common sense even if it is under researched in the field to date. Using 2D distance misses something of the reality of the pedestrian (or cyclist) experience, and walkability could be considerably misstated, particularly over hilly and irregular terrains.

This 'effort' operates as an impedance to pedestrian travel over the network, the same way that speed limits and traffic lights act as an impedance to vehicular travel over a road network.

Effort is related to speed. Tobler's hiking function is an equation which calculates anisotropic distance based on time – that is, average walking speed taking into account the slope of the terrain (anisotropic because the time-distance is not the same in both directions) (see Figure 4 for a graphical illustration). The equation for Tobler's hiking function was originally estimated from empirical data and is used widely in analyses modelling slope as a contributor to route selection (Tolber, 1993). The equation is as follows:

$$W = 6e^{-3.5|S+0.05|}$$

where W is walking speed in kilometres per hour (km/ph) and S is the slope (the differential of elevation difference and distance). Where the slope is 0°, W is calculated at circa 5km/ph. It is an exponential, not linear function. The graph shown in Figure 4 indicates that a maximum walking speed of 6km/ph is achieved when ground slope is marginally below -3°.

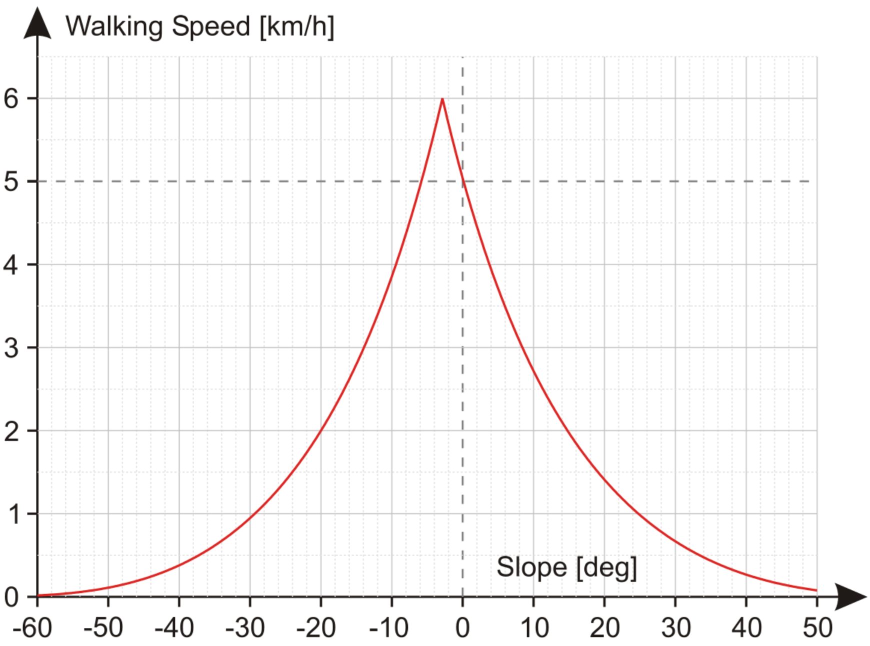

Figure 4. *Tobler's hiking function models anisotropic distance based on time. Going up is slow progress, but so is going down when paths are steep.*

The methodology/framework used in this research is as follows:

1. Add elevation data to the street network.
2. Calculate, according to Tobler's function, the speed at which each segment of the network can be traversed.
3. Using the equation *Time = Distance / Speed*, calculate from the speed (metres per minute) the time in minutes taken to traverse each segment going uphill, and going downhill.
4. Sum the uphill time and downhill time together to get the time taken to traverse the segment in both directions (hence the 'round-trip').
5. For 2D distance, ignore Tobler's function and use the equation *Time = Distance / Speed* to calculate the time in minutes taken to traverse each flat segment, using a base speed of 5km/ph. Multiply this time by 2 to obtain the round-trip time.
6. For each neighbourhood node, use the Network Analyst extension function in ArcGIS to calculate isochrones depicting walkable catchments along the network for 5- and 10-minute round-

trips. Network Analyst’s Service Area function uses the Dijkstra Shortest Path algorithm, which solves the single-source shortest-path problem.

The 400m / 5 minute conceptual catchments frequently used in urban and transport design and planning equates to a flat walking speed of 4.8km/ph. Five and ten minute round-trips calculated with this method roughly correspond to conceptual 200m and 400m catchments.

Limitations

ArcGIS’ Network Analyst runs a shortest-path algorithm over the street network when calculating the catchment area for a point. Although it is possible to calculate uphill and downhill slope, and therefore walking speed, for each segment along the network, Network Analyst does not automatically know which value to use when standing at the start point – it does not know in relation to this point whether a segment goes uphill or downhill. With advanced programming knowledge, it would be possible to inform Network Analyst which slope (speed) to use.

The round-trip time is therefore a compromise. It is an improvement over 2D analysis, but with two key limitations: first, it overstates the walkable catchment in comparison to a one-way directional catchment towards the neighbourhood node, since a steep uphill journey to the node can be compensated for by an easy downhill journey back home; second, the algorithm is minimising the round-trip time but limited to traversing each segment both ways. This implies that the same route must be chosen to and from the node. This may or may not be realistic. If slopes (or the perception of slopes) are minimal, a pedestrian may well choose to go back the way they came. If slopes are more extreme (and who knows where the cut off is!), a pedestrian might choose a different route in either direction to minimise uphill travel. This second option would not just invalidate the round-trip assumption, but might also invalidate the assumption that a pedestrian seeks to minimise journey time. People may trade off time against slope when making journey decisions. This could understate the walkable catchment if either the to- or from-journey, in reality, deviates onto a less steep path.

The round-trip compromise is more meaningful than the next-best alternative, though, which is to calculate catchment based on absolute positive slope, which just produces a 'worst case' catchment ignoring direction.

The other limitation comes from using speed as a proxy for effort in adding impedance to the networks. There may be a cut-off point for walking uphill, which may put off even the fittest of pedestrians. In calculating effort, it's not only 'speed' which matters. Energy expenditure or perceived effort may be just as, if not more, important.

This consideration leads to several ideas for extensions of the analysis, discussed further later in the paper.

Technical steps

First, it is necessary to combine the street network (XY) with elevation data (Z) to determine the slope of each segment in the network. ArcGIS calculates minimum, maximum and average slope of each segment when adding surface information from the DEM model to a paths network.

Segments on the graph are pieces of line between two intersections. In a sparse network, intersections can be quite widely spaced, and so elevation differences along that piece of line can vary considerably. Figure 5 shows possible elevations of a street between two points. Street (A) has a constant slope along the whole segment, so its elevation is well-described by minimum, maximum and average slope. Street (B) follows are much more irregular trajectory, culminating at a higher elevation than its start point, but via several peaks and troughs. Taking an average slope of this whole segment would not describe its trajectory well. Clearly, in order for these figures to be meaningful, segments must be reasonably short: it is not possible to rely on long segments similar to (A) to accurately describe slope, but the shorter the distance between two points is, the closer it resembles (A), even when the overall trajectory of the street is irregular, like (B).

As such, before adding elevation information to the street network, vertices were added to paths at 2 metre intervals (although given that the DEM is a 5m grid, 2m may be regarded as overzealous), and split at the new vertices to create separate segments. All of these small segments then resemble (A), and the average slope information added is, as a consequence, meaningful.

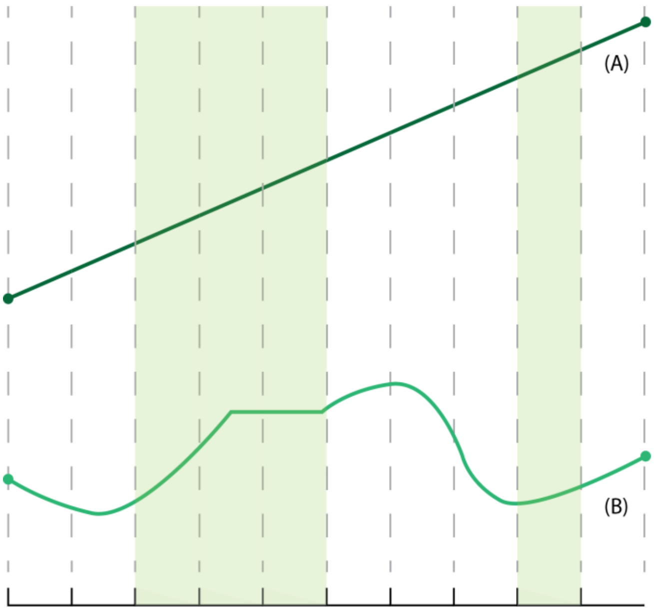

Figure 5. *The shorter segments of street are, the better an average slope measure approximates the true slope of that segment.*

At this stage, a street network in which every segment (maximum length 2 metres) has a new absolute average slope attribute (in percent) is present. The attribute table can then be exported to a spreadsheet for further manipulation.

In the spreadsheet environment (using Microsoft Excel in this research), further attributes were added to the dataset for each individual segment:

- Uphill slope in radians (radians are required by the tan function) *[Tan^{-1} (Slope in percent / 100)*(π / 180)].*
- Downhill slope in radians, equal to uphill slope in radians multiplied by -1.
- Uphill speed in km/ph, calculated according to Tobler's hiking function, where $S = \tan$ *(uphill slope in radians).*
- Downhill speed in km/ph, where S = tan *(downhill slope in radians).*
- Uphill time in minutes, calculated by converting uphill speed in

km/ph to metres per hour (metres/ph), and using *Uphill time = (length of segment / speed) * 60*, where length of segment is in metres, speed is in metres/ph, and the resulting uphill time is in minutes.

- The equivalent for downhill speed.
- The sum of uphill and downhill time in minutes, *3D roundtrip = uphill time + downhill time.*
- Time taken to traverse segment without elevation at a constant speed of 5km/ph (5,000 metres/ph), where *Time at flat speed = (length of segment / 5000) * 60.*
- The sum of to- and from- journeys in minutes, 2D *roundtrip = 2 * Time at flat speed.*

With these calculations complete, the table was then re-joined onto the street network in the GIS. Figure 6 and Figure 7 show the calculated uphill and downhill speeds for each segment of the existing network in Milton, Glasgow.

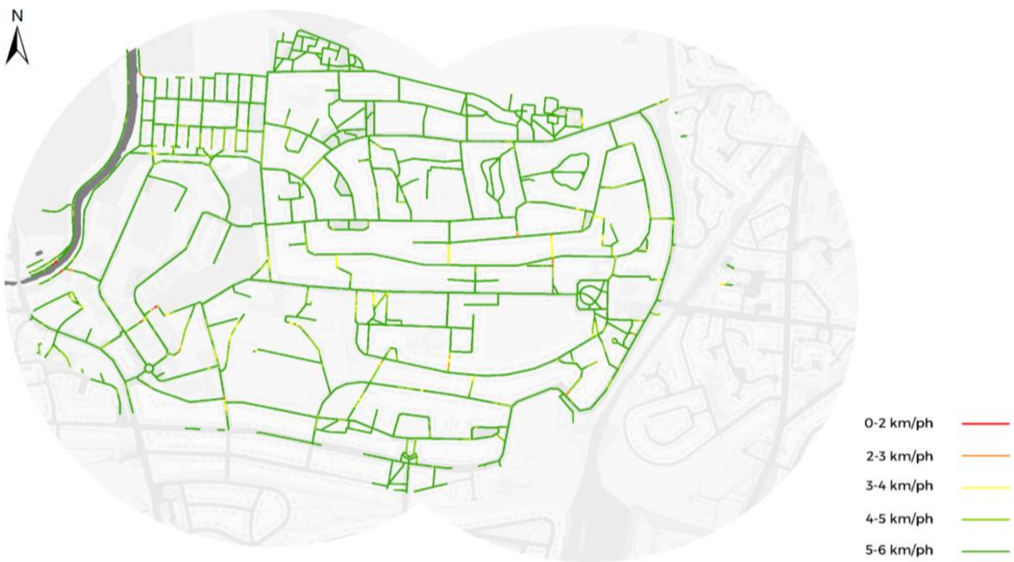

Figure 6. *Downhill speeds on street segments in existing street network. Since going downhill (at least at small inclines), is easier than going uphill, most segments can be traversed at 5-6km/ph downhill.*

Figure 7. *Uphill speeds on street segments in existing street network. Going uphill is hard work; many segments are traversed at 3-4km/ph. Some red segments have stairs.*

Next, ArcGIS's Network Analyst extension was used to create a routable network dataset from this information. When creating the dataset, it is worth flagging two possible impedances based on the table attributes: 3D minutes (which takes into account elevation), and 2D minutes (which does not).

Finally, again using Network Analyst, walkable catchments were calculated ('service areas') for each node ('facility'), using first 2D minutes and then 3D minutes as impedance, with break values at 5- and 10-minute round trips. Catchments extend 30m either side of the street segment.

Analysis of results

Figures 8-14 map the results of the two sets of walkability analysis and are discussed in the forthcoming sections.

If the world was flat: existing versus proposed street network

It can be observed that by decreasing the distance between intersections, the area within both a 5- and 10-minute round-trip increases substantially. As a proportion of the conceptual 400m-minute catchment, 44% around the eastern node and 43% around the western node are covered with the existing network of streets and paths (Figure 8). Following the new street network, 50% (east) and 56% (west) are covered (Figure 9). Decreasing the distance between intersections increases the number of intersections and the likelihood of shorter, more direct routes from A to B.

This highlights the merits of making the transition from conceptual time or distance catchments to actual distances along a street network. For example, firstly, even a highly dense, gridded network will not achieve 100% coverage of the conceptual circle. Second, the structure of the street network clearly impacts the walkability of an area; the conceptual circle indicates the same coverage regardless of the network, which is misleading at best, and could lead to very inefficient decisions being made.

But the world is 'hilly': 'real' walkability of street networks

The study area in general, and in particular where the neighbourhood nodes are, is quite a varied and hilly terrain. Liddesdale Road (indicated, Figure 11) is on a ridge, which means direct paths to and from it will be inevitably sloped.

Following the existing street network (Figure 12), taking topography into account reduces the percentage coverage of the conceptual eastern catchment to just 36%, from 44%, and of the western catchment to 33% from 43%: from an already fairly low base, the reality is around 20% less walkable than the 2D analysis implies (Figure 11).

Following the proposed street network (Figure 13), the difference is less stark. The percentage coverage of the conceptual eastern catchment falls to 46% from 50%; the western from 56% to 53%. This is 5-10% less walkable than the 2D analysis suggests (Figure 14)

This analysis highlights two important points. First, even with this slightly generous measure of the 10-minute round-trip, real walkability is considerably lower than the basic 2D analysis implies. Clearly, it is important for those involved in the built environment to consider topography when conducting walkability analysis and evaluating proposals.

Second, a more interconnected street network can mitigate against the impact of tricky topography by providing more options for pedestrian routes which avoid particularly steep sections. The more interconnect-

ed the street network, then, the closer the simple 2D analysis is to the walkable reality.

Figure 8. *The much denser proposed street network around the western node increases the walkable 10-minute roundtrip catchment by*

26%.

Figure 9. *5- and 10-minute walkable catchments following the existing network, without accounting for topography.*

Figure 10. *5- and 10-minute walkable catchments following the proposed network, without accounting for topography.*

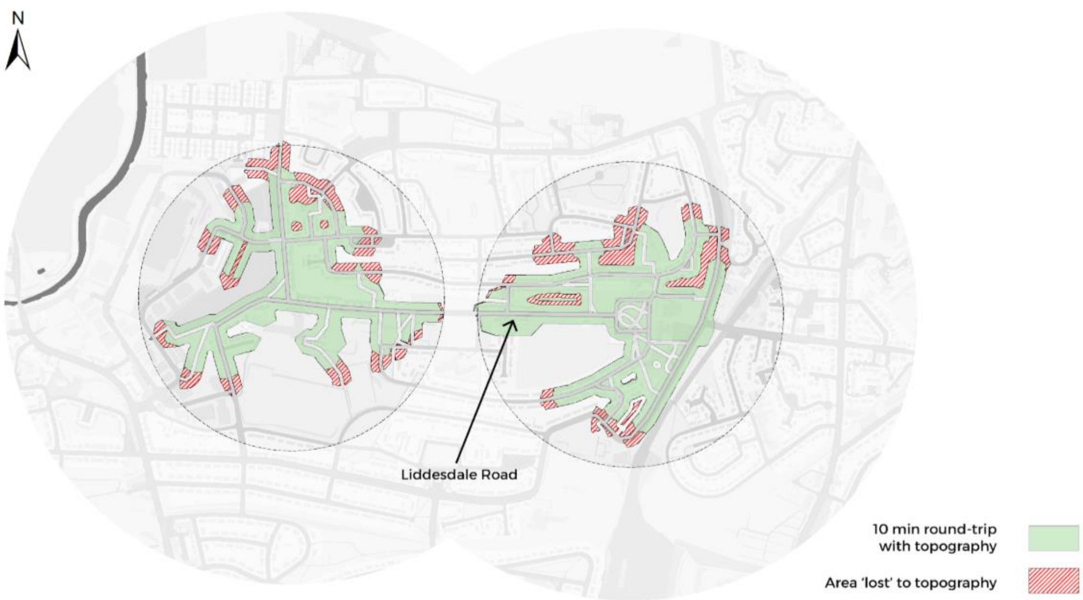

Figure 11. *Difference between walkable catchments following the existing network, with and without accounting for topography. Catchments are around 20% smaller once topography is accounted for.*

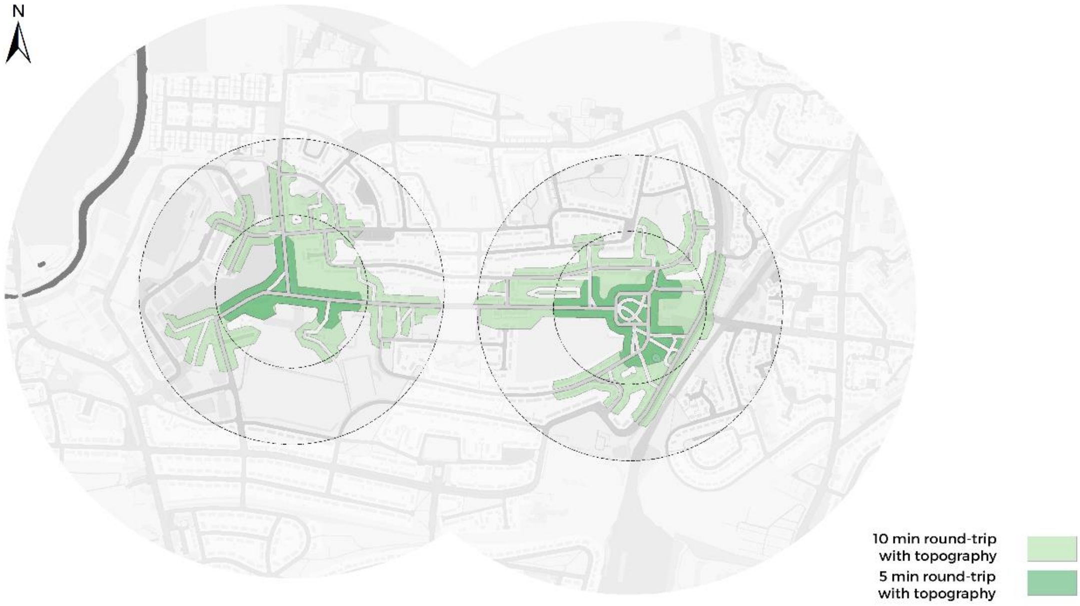

Figure 12. *5- and 10-minute walkable catchments following the existing network, accounting for topography.*

Figure 13. *5- and 10-minute walkable catchments following the proposed network, accounting for topography.*

Figure 14. *Difference between walkable catchments following the proposed network, with and without accounting for topography. Catchments are around 20% smaller once topography is accounted for.*

Improvements and extensions

There are a few technical improvements which would add to the accuracy and usefulness of this analysis. First, as discussed earlier as part of the imitations, a script informing Network Analyst whether a segment is uphill or downhill relative to the start point in a path would allow a truer 5 minute catchment to be calculated, instead of the compromise 10-minute round trip catchment. Second, nodes in this analysis are represented as single points. Realistically, neighbourhood centres (as opposed to bus stops, for example, which are well represented as single points) may be a row of shops along a street, in a line or other formation. It would be useful to incorporate this reality into the model as catchment areas taken from the 'edges' of a line of shops will differ from catchments calculated from centroids. Third, the catchments highlight all land area within a 30m distance of the street centreline. From a master planning perspective, it may be preferable for catchments to highlight all street edges, plots or buildings which are reached along the walkable line. Fourth, from a transport planning perspective, incorporating population/demographic census information into walkability catchments may provide more useful information to work with.

Limited mobility and accessibility

While walking on foot is one of the most democratic modes of transport, many people are less able or totally unable to walk. While simple walkability analysis is useful, it is basing analyses on 'average' walkability only. For those less able (through age, physical disability or handicap, e.g. pushing a wheelchair or pram), there may be slope thresholds above which walking becomes very difficult or impossible, or specific surfaces on which walking is difficult, and average base walking speed may be much lower.

For wheelchair users, there will certainly be slope thresholds above which self-propelling is not an option, and above which even battery powered wheelchairs may struggle. Additionally, width and surface of paths will have a big effect on whether a street is deemed passable.

These factors could be incorporated via restrictions and new evaluators in the network dataset. Segments of the network could be marked as passable or impassable with various mobility levels, according to evidence on what the slope thresholds discussed above might be. Differences in average speed could easily be incorporated by re-calibrating the Tobler function for a lower based speed.

Psychological (and other) factors in route selection

Although time is a very significant resource for humans, the idea that the general population optimises routes based purely on time is overly simplistic. What has been calculated in this research is essentially a measure of 'potential' walkability (as evidenced in Nourian & Sariyildiz, 2012). There are a multitude of other factors which might contribute to a decision on routes, or 'actual walkability'. For example:

- Does perception of slope matter more than actual slope? Anecdotal evidence suggests people tend to over-estimate uphill slopes, which might deter somebody from choosing a certain route even if it is time-minimising.

- Is route selection different depending on climatic conditions (and therefore does a 'rainy day' catchment differ from a 'sunny day' catchment in a significant way?) or time of day (does a 'night-time' catchment differ from a 'daytime' catchment?)
- Are people less likely to walk at all if the environment itself is unpleasant (which involves an element of subjectivity)? For example, unsafe, badly maintained, poorly lit etc.
- Will the route selection of some less mobile groups depend, for example, on whether there are benches or other street furniture on which to rest on the way?
- Are high footfall routes likely to deter people given the likely time and congestion implications?

Some of these factors are understandably easier to incorporate into a basic walkability analysis than others, but ideally, then, the 'shortest path' calculation would form only a part of an index contributing to the calculation of walkable catchments.

Bikeability

If urban designers want to encourage other active transport modes, such as cycling, a 'bike-shed' variant of the 'ped-shed' incorporating elevation would be valuable. The impedance over the network would not be calculated according to Tobler's hiking function, but a similar anisotropic function to account for the fact that free-wheeling downhill requires considerably less energy than pedaling uphill. There may also be earlier slope cut-offs for cyclists and to- and from- route selection may differ substantially depending on slopes or perceived slopes. Iseki and Tingstrom (2013) propose a methodology for this form of bike-planning analysis which could be explored to extend this research to other forms of active travel.

Conclusion

Through this analysis, the importance of moving beyond the conceptual catchment to a more human interpretation of walkability has been emphasised. The reality of how far people can travel in 5 or 10 minutes is also clearly related to the geometry of the street network, which has been demonstrated by comparing the existing street network in Milton, Glasgow, to a denser new street network. The more intersections there are, and the shorter the blocks, the more places along the network become accessible. This much is widely acknowledged by urban design practitioners, and these so called 'ped-sheds' are often calculated and compared to the conceptual catchments as in this research.

The impact of topography, however, has been explored far less. Humans walk in 3D, not 2D, environments, and the slopes of paths and streets clearly affect walkability. A sparser network seems to compound the impact of topography; a more densely connected network seems to mitigate it. A wider adoption of this 'real' 'ped-shed' should serve to improve design or repair of street networks where topography is a concern, and contribute to more people-focussed environments.

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Data sources

OS MasterMap Topography Layer [GML geospatial data], Coverage: Milton, Glasgow, Updated December 2016. Using: EDINA Digimap Ordnance Survey Service, Downloaded: February 2017. <http://edina.ac.uk/digimap>

OS MasterMap Integrated Transport Network [GML geospatial data], Coverage: Milton, Glasgow, Updated December 2016. Using: EDINA Digimap Ordnance Survey Service, Downloaded: February 2017. <http://edina.ac.uk/digimap>

OS MasterMap Integrated Transport Network Urban Paths Theme [GML geospatial data], Coverage: Milton, Glasgow, Updated July 2016. Using: EDINA Digimap Ordnance Survey Service, Downloaded: February 2017. <http://edina.ac.uk/digimap>

OS Terrain 5 DTM [GML geospatial data], Coverage: Milton, Glasgow, Updated October 2016. Using: EDINA Digimap Ordnance Survey Service, Downloaded: February 2017. <http://edina.ac.uk/digimap>