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USING REALISTIC TRAVEL-TIME THRESHOLDS IN ACCESSIBILITY MEASURES OF BICYCLE ROUTE NETWORKS

Improving space syntax based bikeability analyses by taking speed variations along routes into account

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ABSTRACT

Bikeability of street networks is an issue where space syntax based methods have shown to be useful. The methods include topological analyses calculating the measure choice/betweenness taking angular change into account, in GIS-based analyses of accessibility to particular destinations, and in combining these two in measuring origin-destination betweenness (OD-betweenness). In all these analyses, metric distance along bicycle routes has been the distance-threshold applied. Even though this is a more realistic modelling than applying only Euclidian distance, the approach of metric threshold is still a simplification in the sense of assuming equal speed on the entire network. As known from research, as well as personal experiences, there is great variation in bicycling speeds; uphill and in crowded mixed-use areas, bicycling can be as slow as walking, whereas downhill a bicycle can be as fast as a car. In order to grasp speed variation along routes, a GIS-based model has been developed for estimating speeds depending on horizontal and vertical geometry of the route. In order to distinguish the speeds in the two directions at any point of the route network, the GIS-model is bi-directional. By so-called Markov-modelling based on empirical data found by GPS-tracking of bicycling in Trondheim, Norway, and Gothenburg, Sweden, a statistical model for estimating speeds along routes at a very detailed level has been developed. This paper explains this new speed model more in detail and shows how it can be applied for improving methods for analysing bicycle route networks. The proposed model uses travel-time rather than distance as threshold measure in accessibility analyses. The first stage of the analysis consists in applying the Markov speed model to estimate speeds in both directions at every point of the network. By this, the model approximate travel time for every segment in the network. Based on these times, and taking also impedances at junctions into account, network analyses based on realistic travel-time thresholds can be conducted. This paper presents this new model used in the case of the bicycle route network in Trondheim, Norway, and describes how the model can be developed for more advanced travel-time-based network analyses.

KEYWORDS


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1. INTRODUCTION

For reasons ranging from public health to liveable cities and carbon emission reductions, to increase the modal share of bicycling in daily commuting at the expense of driving private cars has become an aim of numerous actors dealing with regional planning, transportation planning and urban design. Peoples’ travel mode choice is a complex phenomenon relying on social, economic, technical and geographical issues that are intertwined in intricate ways. Despite this complexity, there are some overall patterns. Zahavi (1974, 1979) pointed out that travel mode is determined by households’ choices within their particular budgets of travel-time and travel-costs. When cost differences between modes of daily travel are low compared to peoples’ income, which is the case at least in the Nordic countries, travel mode relies very much on time and convenience of travel. Marchetti (1994) stated that travel-time is the key issue and has been constant throughout the history of human, typically about one hour a day. Therefore, in order to change modes of travel in sustainable directions, conditions influencing time and convenience of the different travel modes must be understood and included in urban planning.

For comparing bicycling to other modes of transport in planning, for instance in the case of examining costs and benefits of alternative investments, there is need for models estimating travel time of bicycling similarly to the models applied for motorised transport. Such models for bicycling are hard to find, likely because information on bicycle speeds is seldom available, and because it is complex to model due to the dependency on multiple factors. Instead, studies of accessibility or travel distance on bicycle are usually based on distance thresholds, typically about 3 - 5 km, based on the fact that the modal share of bicycling rapidly decreases when distance pass 3-5 km (Scheiner, 2010). Explicitly stated or not, the use of fixed distance thresholds in accessibility analyses means assuming the same speed at all routes. In cases where speed is constant or when speed variation is evenly distributed in the entire network, this concept of measuring distance as proxy for time may work fine. However, when speeds vary a lot, which is often the case for bicycling, the measure of distance alone is less useful, and even possibly misleading. On bicycle, the speed may range from slower than walking when you must walk with the bike in a crowd of pedestrians, to the speed of a car down a steep hill. Due to this speed variation for bicycling, methods that grasp speed differences along routes will be much more realistic and likely provide more useful results than current methods measuring solely distance.

Over the past decade, space syntax based methods have shown to be useful for analysing bikeability of street networks (McCahill and Garrick, 2008). Methodological developments within this field that can contribute to planning for bicycling consist in street network analyses calculating choice/ betweenness taking angular change into account (Turner, 2001; Hillier and Iida, 2005), and in software combining space syntax methods with GIS-based analyses of accessibility (Stähle et al., 2005; Nourian et al. 2015). The space syntax measure segment angular choice within metric distance along routes is useful for grasping bicycle flow potentials of routes in the network (Raford et al., 2007; Manum and Nordström, 2013; Law et al., 2014). For studying bicycle flows in detail, origin-destination betweenness measures (OD-betweenness) are promising (Manum and Nordström, 2017). In all these analyses, metric distance along bicycle routes has been the distance-threshold applied. Even though this is a more realistic modelling than applying only Euclidian distance, the approach of metric threshold is still a simplification in assuming equal speed on all parts of the bicycle route network.

Aiming at improving modelling of bicycling, recent research has developed methods for grasping speed variations. Cooper (2018) derives metrics that, in addition to other factors, incorporate speed variation due to slope by the principle of weighting the distance in accordance with slope. Arnesen et al. (2017) and Manum et al. (2018), applying so-called Markov-modelling, have developed a model that based on horizontal and vertical geometry estimate speed along route in very realistic details. Leaning on this work, this paper presents an approach to time- rather than distance-based analyses of accessibility on bicycle. The proposed model includes the temporal cost of travelling in different directions depending on the topography, the curvature of the route and the crossing of junctions. As the new approach is based on a more realistic modelling of bicycling speeds than the common practice of measuring catchment areas simply by distance, it should provide more realistic catchment areas by bicycle, this to the benefit of land use planning aiming at supporting bicycling or exploiting the potentials of bicycling.

An essential element in improving conditions for bicycling involves planning and building bicycle-routes, either by replacing poor routes (worse and slower than average) with better ones, or by adding
new routes (better and faster than average). In this search to improve poor or mediocre conditions, bicycle planning today lacks adequate tools for assessing the likely effects of alternative improvements, since prevailing approaches based on average speed/distance are unable to capture precisely that deviation. A new model, grasping speed difference at a detailed level, should have potential for becoming highly useful in estimating likely effects of proposals for route improvements which is a condition for wise choices in planning for bicycling.

This paper presents a study of these issues in the case of Trondheim, Norway, comparing analyses by the realistic travel-time based model with analyses by the conventional distance-based accessibility measures. Following a review of recently developed bicycle speed estimation models, we describe the proposed modelling approach and the methods applied. Next, the paper presents results of the analyses, advancing a reflection on how the model can be applied in accessibility analyses and suggests improvements and refinements of the model.

2. BACKGROUND

The framework for bicycle route network analyses presented in this paper is based on several studies conducted over recent years. One is a bicycle speed model developed in the case of Gothenburg, based on space syntax network analyses developed over ten years, taking route context as well as the kinds and quality of routes into account (Manum and Voisin, 2010; Manum and Nordström, 2013, 2015). A second is a so-called Markov-model estimating bicycling speed variation along routes at a very detailed level, and a third is bicycle network analyses distinguishing the delays at junctions and the two directions of a route, which are pre-conditions for realistic bicycle speed modelling at network level. This section describes this theoretical background in some more detail and concludes with a brief introduction to the analyses carried out.

2.1 The model for estimating speed variation along routes

There are different approaches for handling the effect of speed variation along route. One possibility is to set speed as a simple function of slope (Miljødirektoratet (2002), Parkin and Rotheram, 2010). Another is to define a metric based on ‘perceived’ rather than actual distance travelled, which can be based on applying a function of slope as a multiplier of distance, among other factors including levels of motorized traffic (Cooper, 2018; Cooper and Chan, 2018). An approach that more in detail captures real speed variation along routes is based on statistical models grasping speed dependence between contiguous road segments (Arnesen, Malmin and Dahl, 2017). Such a model for estimating bicycling speeds at a very detailed level has been developed in the case of Gothenburg, Sweden (Manum et al., 2017; 2018). Based on so-called Markov-dependence, this model estimates continuous speed profiles along entire routes, and not only average speed levels on road segments seen independently. The model was estimated using GPS-tracking of bicycling in combination with GIS-based data of bicycle route networks and context of routes. The covariates included in the model are route geometry, intersection impedances, type of bicycle-route, kind of surface, and density of entrances to buildings along route. The latter is a proxy for slower bicycling due to vibrant urban context.

The basics of the Markov model is introduced briefly in the following, however for detailed explanations see Arnesen et. al. (2017) or Manum et al. (2018). For a predefined route of n points i = 1, ..., n, assume h_i and v_i to be the horizontal and vertical curvature, respectively. As an intermediate speed estimation let

\[ r_i = \beta_0 \exp\{\beta_1 v_i I(v_i \geq 0) + (\beta_2 v_i + \beta_3 v_i^2)I(v_i < 0)\}, \]  

(1)

Where \( r_i \) in this framework has the interpretation as the speed a bicyclist will converge to under constant slope and zero horizontal curvature. The parameters \( \beta_0, \beta_1, \beta_2, \beta_3 \) are all parameters estimated from data, and \( I(\cdot) \) is the indicator function. A Markov dependence are introduced by assuming that a second intermediate speed estimation \( v_i \) in point \( i \) is dependent on the end speed estimation \( y_{i-1} \) in point \( i - 1 \), by the relations

\[ v_i = y_{i-1} \alpha_i + (1 - \alpha_i) r_i, \]  

(2)

\[ \alpha_i = \exp\{-\omega ||w_{i-1}||\}, \]  

(3)
where $0 < \alpha_i < 1$ act as a weight, where we assume $\omega > 0$, such that as $||w_i||$ increases, the dependency of the previous speed decreases. To obtain the final end speed estimate of point $i$, there is dependence introduced between speed and horizontal curvature ahead by

$$y_i = v_i \exp\{\beta_4 H_i\} + \epsilon_i, \text{ where } \epsilon_i \sim N(0, \sigma^2), \text{ and}$$

$$H_i = h_i + \sum_{j : D(i, j) \leq \eta} \frac{h_j}{D(i, j)}.$$  

where $D(i, j) = ||w_i|| + ||w_{i+1}|| + \cdots + ||w_j||$, is the total horizontal distance from point $i$ to point $j$, assuming $j > i$, and where $\epsilon$ is assumed to be i.i.d. zero-mean Gaussian noise. Through Equation (4) and (5) adjustment to the modelled speed is introduced by assuming that turns less than $\eta$ meters ahead influence the speed of the bicyclist. The model is run by assuming $\eta = 50$, and $\omega$, $\beta_4$ and $\sigma^2$ is estimated from data.

Comparing different models for bicycle-speed estimations in the case of a sample of bicycle routes in the city of Gothenburg, Sweden, the new model including the Markov-based speed estimation, proved to be very promising in describing speed variations along route at a realistic and detailed level. Fig. 1 shows the results of comparing different model in the case of one direction of a particular route. The new model (green line in fig. 1) resulted in more detailed and realistic speed estimations than the previous models.

![Figure 1: The new Markov-based speed model compared to previous models in the case of a particular route in Gothenburg.](image-url)
2.2 Handling the impact of junctions on bicycling speeds

In a network of routes, junctions make average speeds significantly slower than for similar routes without junctions. This also counts for bicycling. Therefore, aiming at a realistic travel-time based model for estimating accessibility on bicycle, delay at junctions, or junction impedances, must be taken into account. However, as already mentioned, current software does not allow for Markov-dependence through junctions in cases of several possible routes. In addition, making the issue even more demanding, junction impedance alone is a complex issue (Rouphail et.al, 2000), Dalton (2015), based on space syntax theory, has suggested to grasp the issue of cyclists’ aim of keeping momentum versus the impedance at junctions by a kind of weighted topological distance. In the study presented in this paper, and as elaborated in section 3.2, delay at junctions is handled by distinguishing between three levels of impedances.

2.3 Tools for handling bi-directional speeds

For studying how bicycle speed variations along a route relate to urban form and to route network properties, there is a need for GIS tools handling different speeds in each direction of any route. For this purpose, available tools include ArcGIS Network Analyst and sDNA+, which produce almost identical results in terms of calculating catchment areas. The latter of these allows for arbitrary functions of distance, elevation change, link direction, angular change and user defined data to be used and combined as a distance metric (Cooper, 2018). sDNA+ supports the approach presented in this paper, developing a method for bicycle network analyses based on time rather than distance as threshold of the analyses, by including the Markov-based speed model results in the network analysis. Currently, the software does not provide options for real Markov-based speed dependence across junctions.

2.4 Trondheim and Sluppen, the case for examining the proposed method

Trondheim is a historical city characterised by the river Nidelva going north into the fjord and city centre located within a meandering curve of the river. From this location, the terrain slowly rises towards South. Towards the East, and even steeper towards West, there are hills about 100 m above sea level before reaching 300 m to 500 m above sea level at some further distance. About 3 km south of the city centre, the area of Sluppen is currently being planned for urban development. For testing the proposed model, the entire bicycle route network of Trondheim is taken into account. As sustainable mobility is a major issue in the urban development project at Sluppen, this area is chosen for examining the contribution of the proposed method of travel-time thresholds on the catchment-areas for daily commuting by bicycle.

3. METHODOLOGY

This section describes the proposed approach in detail, including the various stages of the method, and how the results are assessed in this paper. In its current version, the method consists of three analysis steps, after modelling the bicycle route network in GIS. The first step is to calculate speeds in both directions of all segments, based on a simplification using three categories of junction impedances. This provides detailed speed profiles along routes, similar to the green line in fig.1. The second step is to convert these speeds into travel times for every segment in the network. Based on this, the third step consists in using travel-times along routes as threshold in catchment analyses of the network. For shedding light on the applicability of this new travel-time based method for bicycle route network analyses, the results are compared with results based on metric distance thresholds along routes. The software used in this methodology are a combination of sDNA+, ArcGIS and QGIS.

3.1 Establishing a detailed GIS-model of the bicycle route network

Bi-directional network analyses in SDNA+ taking slope into account depend on street network modelled as segments in the format of 3-D polylines. The Markov-model calculates speeds based on route geometry at a very detailed level, and the route network must be modelled in GIS with appropriate precision regarding both horizontal and vertical geometry. The background data for doing this in the case of Trondheim has been two previous GIS-models. The first was a space syntax axial line map that includes all routes in Trondheim available for bicycle but including neither altitude nor real horizontal curvatures of the routes. The second was the street network GIS-model from the local authorities of Trondheim, describing the street-network geometry by centrelines in 3-dimensions, but not clearly identifying bicycle routes. By combing these two GIS-models, and checking against ortho-photos, a
new GIS-model of the entire bicycle route network in Trondheim was developed. The network, in total 1700 km, includes paths not necessarily recognised formally as bicycle routes in maps or by local authorities, and does not include streets used exclusively by cars.

3.2 Modelling junction impedances

As available tools do not handle real Markov-modelling of speed through junctions, the current method handles junction impedances in a simplified way and calculates speeds that are converted to time before running time-based network analysis using SDNA+. More in detail, we have chosen to model junction impedance taking a pragmatic approach, distinguishing three levels of impedance through junctions. This is done by a combination of speed reduction, explicit time additions, and a heuristic for routes that in practice have continuous speed despite the presence of junctions. Listed in order from high to low impedance, the three categories of junctions are (1) signal crossings and also some roundabouts without signals, (2) the normal or average junctions (without signal), and (3) junctions with neglectable impedance.

The slowest category (1), the signal junctions, are modelled by adding 10 seconds to the bicycling time of all segments linked to the junction, implying 20 second in added travel time as junction impedance for any route through the signal junction. According to de Groot / CROW (2007), 20 second is a typical value of time delay at junctions for bicycle routes of moderate standard. The time is based on total time delay by a full stop on red light multiplied by the probability of this stop. In the GIS-file of the bicycle-route network described in previous section, many junctions happen to be more complicated than segments from junction to junction simply connected at one point being the junction. For achieving a simple and still realistic modelling of signal junctions and roundabouts, in the cases where the GIS-file includes separate route-segments within the junction, these junctions are modelled by a circle covering the small segments within the junction (see fig. 2). This circle counts as “the junction” and the 10 second impedances are given to all the segments crossing this circle, not to the segments within the circle.

In the second category (2), normal non-signal junctions along bicycle routes, bicyclist in Trondheim usually just slightly reduce speed and only sometimes stop completely. To capture this impedance, a speed somewhat slower than average is set as in- and out-speeds for the segments into (and out of) the junction. In this study, this speed was set to 4 m/s, leaning on video recordings of bicyclists during an afternoon in Trondheim, and measuring time and distance through a common junction. In the Markov model, the out-speed of 4 m/s is obtained by manipulating in a sharp turn at the end of the link. That is a horizontal curvature is iteratively adjusted so that the output speed becomes 4 m/s at most. This was the same approach used in Manum et. al. (2018) for junctions although the effect of a junction was estimated.

Figure 2 (left): The circle marks the junction in the case of small route segments within the junction.

Figure 3 (right): Modelling of “direct routes”, meaning routes that despite the presence of junction have neglectable impedance at junctions. Red lines show longer segments on top of local shorter segments. The marks across the red lines show ends/starts of the longer segments.
The fastest category of junctions (3) have in practice neglectable impedance. An example of this is junctions with minor streets with little traffic, most typically T-junctions with a minor street in uphill-direction of a main route. In such cases, the low impedance is modelled by placing additional and merged longer segments on top of the junction-to-junction-segments. In doing so, the GIS network model captures local connectivity as well as long distance speed continuity (fig.3).

3.3 Calculating speeds and times along segments

After completing the GIS-model and setting the in- and out-speeds of segments, the speeds in both directions along all individual routes were estimated using the Markov-model. In this study, aiming to test the applicability of the method for realistic travel-time based accessibility analyses, the variables determining the speeds in the Markov-model are horizontal and vertical geometry together with the simplified model of junction impedances. From the average speed in each direction of every segment, the time in each direction of every segment was calculated. For segments connected to a signal junction, the 10 second signal-junction-impedance described in previous section was added. These bicycling times in direction A-B and B-A of every segment are two attributes of the segments in the GIS-model of the bicycle route network. The variables to be included in the network analyses by sDNA+, in this case travel-time, must be assigned to the network segments, and cannot be assigned to junctions.

3.4 Calculating network catchment areas

In the proceeding analyses, we use sDNA+ in the case of Trondheim, testing the methods by examining accessibility on bicycle to (and from) the Sluppen area. We calculate catchment areas to- and from Sluppen by time thresholds using the new realistic travel-time based model. Based on the knowledge that the modal share of bicycling for daily commuting strongly decreases for journeys longer than 3-5 km (Scheiner, 2010) and that typical average speed is in the range 14-20 km/h (Jensen et al., 2010; Parkin and Rotheram, 2010), having in mind that Trondheim is a city with significant hills, a travel-time threshold of 15 minutes in one direction is a reasonable value for calculating the catchment. As bicycling speeds vary a lot depending on slope, the distance of travel within a certain time will in Trondheim often significantly differ in the two directions of a route. Therefore, the expected result of time based catchment area calculation based on Markov-model, is that the to- and from- catchment areas will be very different in the steepest directions.

One way of comparing the time-based model with the fixed distance model, is to simply examine the geometry of the catchment areas of the two models with the same origin. In this study, the origin for the measures is a central point in the urban development area Sluppen. For comparisons by maps to illustrate differences between the models, the thresholds of the two model should be tuned for the threshold areas to be comparable. If setting a time threshold, as suggested in previous paragraph, the scaling can be done by tuning the fixed distance threshold so that the catchment areas of the two models are equal measured by area. Alternatively, which is the option chosen here, the distance threshold can be calculated on the basis of the average speed of the travel-time based model.

4. RESULTS

This section presents the results of the speed estimations based on the proposed methods, and of the realistic travel-time based network analyses, and compares these to a traditional constant speed or travel distance analysis.

4.1 Speeds along segments

Figures 4, 5 and 6 illustrate the speeds of route segments as calculated by the Markov-model. Figure 4 shows the average of the speeds in both directions for every segment, whereas figures 5 and 6 show the average in the fastest and the slowest direction, respectively. As expected, since delay of uphill is known to be more than the gain downhill (Parkin and Rotheram, 2010), the average of speeds in both directions is highest for horizontal routes, particularly those with few junctions, for instance the main North-South route and the route along the seaside (fig. 4). Since uphill and downhill speeds still tend to balance each other, the average of the speeds in both directions varies far less across the network than the maximum and the minimum do (fig. 4 compared to figures 5 and 6). In the city centre, where the junctions are most frequent, we see that the average speed is lower even though the terrain is flat. The routes with lowest average speeds are the steep and very curved ones.
Looking at average speeds in slowest direction for every segment (fig. 6), we see how the model as expected grasps speed reduction due to slope at a very detail level, and steep uphill being the slowest. We again see that very curved segments are slow. Not surprising, the segments with highest average speed in the fastest direction (fig. 5), which of course is downhill, are in general the same as the segments with the lowest average speeds in the opposite direction (fig. 6), which is uphill at the same place. The fastest of all, are downhill routes with few junctions.

Figure 4: The bicycle route network in central Trondheim. Segments coloured by average of speeds in both direction. (km/h)
Figure 5 (top): Segments coloured by average speed in fastest direction. (km/h)

Figure 6 (bottom): Segments coloured by average speed in slowest direction. (km/h)
4.2 Catchment areas

Based on a 15 minute time-threshold, as described in section 3.4, and the average speed of the entire network time-model being 15.4 km/h, the distance-threshold applied in the constant speed analysis to be compared with the time-based analyses is set to 3.85 km.

Fig. 7 shows catchment areas within 15 minutes to and 15 minutes from Sluppen. For comparison, the figure also shows the catchment area of 3.85 km distance along route. In general, the map illustrates how the Markov-model grasps speed variation due to slope. Towards the city centre, the only direction which is not uphill from Sluppen, is the only direction where travel from Sluppen reaches farthest, slightly farther than the distance threshold and the 15 min. to Sluppen threshold. At the hills West and East of Sluppen, the to- and from- catchment areas are significantly different; the from-direction reaching shortest, in accordance with the altitude differences and the river being a barrier.

Towards South-East, we see that to- and from- as well as the distance-threshold provide identical borders of catchment areas. The explanation is simply that the entire network in this direction is within all three thresholds.

Regarding population, 67 050 people today live within the 15-minutes-to-area, whereas 50 050 live within the 15-minutes-from-area, and 51 100 within the fixed distance threshold, illustrating how the different measures models provide different information essential to planning of transportation.

Figure 7: Catchment areas to and from Sluppen.

**Dark blue**: Catchment areas for bicycling to Sluppen, 15 minutes to Sluppen.
**Light blue**: Catchment areas for bicycling from Sluppen, 15 minutes from Sluppen.
**Red**: Catchment area within 3.85 km (catchment area based on average speed as constant speed).
**Black line**: Sluppen, an area under planning for urban development.
5. Discussion

5.1 The Markov-speed-model

Before describing options for improving the model for network analyses presented in this paper, it should be pointed out that the Markov-model itself is under development. In its current version, the Markov-model for estimating speeds along routes is itself estimated from somewhat biased empirical bicycling speed data, partly from Trondheim and partly from Gothenburg (Manum et al., 2018). In practice, this may imply that the current version of the Markov-speed-model underestimates the disadvantage of uphill bicycling. Due to this uncertainty, the purpose of the analyses presented in this paper is not to evaluate bicycle routes in Trondheim or elsewhere. The purpose is to test the Markov-model in network analyses and plan for further development of the methods. Before applying the Markov-model in extensive studies at network level, the Markov-speed-model itself should be re-estimated based on larger datasets of bicycling-speeds.

5.2 Improvements of the current Markov-model for network analyses

Due to the limited number of variables present in the current GIS-model of the bicycle route network, the analyses presented in this paper include only geometry-variables and a simplified version of junction impedances. As previously shown (Manum et al., 2018), the current Markov-speed-model also includes other variables of the route network that are highly significant for speed of bicycling, such as route surface material, bicycle route type and entrance density; the latter being a proxy for the speed reducing effect of vibrant urban context. Therefore, making more extensive GIS-models that incorporate these variables, would be a simple way to improve the analyses.

In relation to junction impedances, even within this simplified scheme of the three categories of junctions proposed in section 3.2, several improvements can be considered. One is related to the assumed speed through “average junctions”, which in the current model determines both the time spent at segments within the junction (the small segments within the circle in fig. 2) and the speeds that the Markov-model calculates for the segments connected to the junction. In the current study, this speed is assumed based on measuring speeds through one particular junction in Trondheim. The model would benefit from larger empirical studies for setting this speed, maybe also resulting in adjusting or supplementing the current three categories of junction impedances. For real Markov-modelling of speed through junctions, both time impedance due to signals and speeds in- and out of junctions should be addressed particularly for any option of route through a junction. For estimating such a Markov-model, more extensive empirical studies of bicycling is needed, for instance by GPS-tracking. Given that the relevant datasets are available, time delay at signal junctions can be taken from traffic signal data.

5.3 Further development of the Markov-model applied in network analyses

For providing a basis for developing the new model, there is need for more extensive network analyses than those presented here. This should imply comparing analyses by the new model more closely with analyses by fixed distance models and comparing both models with empirical data of bicycling. In this paper, the two models are compared by examining the geometry of catchment areas of the two models based on a derived polygon from a single point of origin. Another way of comparison, looking more closely at all parts of the network, is to compare accessibility to (or from) each point. Accessibility of each point can be represented by measuring the quantity of built network within a suitable network distance from each output area; this quantity has been shown to correlate with cycling mode share (Cooper, 2018, 2017; Cooper and Chan, 2018).

Fully adapting the Markov-model to predict fastest route requires more sophisticated algorithms than are currently employed in spatial network analysis software, which to date has been designed around routing algorithms running fast in order to facilitate detailed analysis of large networks. The Markov prediction of speed through any link or junction depends on the speed of approach, which in turn depends on the exit speed of the previous link, and so on until the point of origin. This turns what in the case of catchment area calculations here described is a single criterion route choice problem of minimising time, to a multi criteria routing problem where any midpoint on any route could be reached with a number of non-dominated speed/time combinations, which become significant even if the overall aim is only to minimise time. Exhaustive search of the speed/time Pareto front will likely increase both
computation time and memory requirements beyond what is practical, therefore heuristic methods are required. Literature on this topic suggests various approaches to optimization (Chen et al., 2015; Hart et al., 1968), including (1) pruning the search tree if a shorter time route is not found within a set number of extra links deviation from the existing shortest time route; (2) removing routes which take more time to build additional speed unless the extra speed exceeds a significant threshold.

Considering that the Markov-model is moving towards multicriteria routing, it makes more sense to keep travel-time as one of many criteria, rather than altering travel times to account for factors affecting bicycling. In the future, the routing algorithm could produce a choice set from the Pareto front allowing for some heterogeneity in route choice among different categories of bicyclists with different preferences.

5.4 Applications of the methodology

In areas where routes’ properties are evenly distributed across the network, distance thresholds assuming equal speed all over the network works fine. However, for traffic flows on particular routes that for good or for bad differ from the average, the new model will likely perform better also in such areas. Different from constant speed models, the new model grasps travel time consequences of route properties, the routes being existing or proposals. For evaluating proposals for new bicycle routes, the realistic travel-time based model, grasping the differences between fast and slow routes, should reveal differences between proposals that cannot be distinguished by constant-speed models. In real urban planning, which is about comparing cost and benefits of alternative projects and choosing the investments to be carried out, the new model should therefore have potential for being highly useful. One example is catchment area analyses mapping number of residents within appropriate time-thresholds and comparing this for alternative proposals of urban planning and transportation infrastructure investments. For people choosing bicycling or not, both one-way travel time and the total time of to- and from-travel should be relevant. Regarding people’s “travel-time budgets”, the total travel time per day should be the key. Regarding convenience of travel, where the disadvantage of steep and slow uphill is likely larger than the advantage of easy downhill, the maximum of to- and from-time is likely to also be relevant on its own. Therefore, both one-way travel times and to- and from-time combined are likely useful as thresholds. The travel-time threshold should also be highly relevant for betweenness analyses, which are shown to grasp modal share of bicycling (Cooper and Chan, 2018) as well as bicycle flow potentials of individual routes (Raford et al. 2007, Manum and Nordström, 2013; Manum et al., 2017). Betweenness analyses within time-threshold or within combinations of time- and distance-thresholds, should be an improvement compared to analyses based solely on distance-thresholds.

6. CONCLUSION

This paper presents a model for travel-time based analyses of accessibility on bicycle in street networks, taking speed variations due to slope, curvatures and junctions into account. When properties of routes show little variation or are evenly distributed across a network, the traditional method of using a set distance along routes as proxy for travel time is simple and useful, at least at aggregated level. In cases where speeds vary significantly between or along routes due to terrain or other condition, the new model which grasps differences of speeds at a very detailed level, provides more realistic network analyses, as here illustrated by testing the new model in the case of Trondheim.

The methodology here described is under development along several tracks. One is to re-estimate the Markov-model itself, based on larger GPS-based datasets of speeds along routes, preferably distinguishing between categories of bicyclist and bicycles, particularly between conventional and electric bikes/pedelecs. The second is to refine data and algorithms for handling junction impedances in network calculations, allowing to fully exploit the Markov-speed-model at network level. In doing this, the new model which grasps real travel times, can be applied in more advanced network analyses, such as origin-destination betweenness at network level (different from catchment area calculations to and from a fixed origin, as illustrated in this paper). The third is to bring travel time based measures together with methods capturing other issues essential for bicycling, for instance models for modal share estimates that, in addition to travel-time here presented, includes distance, traffic safety, comfort and social safety and where the different issues can be weighted in accordance with the particular purpose. Together, these can be steps contributing to a new generation of tools applicable in planning for sustainable urban development.
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