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The influence of slope on walking activity and the pedestrian modal share

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Abstract

The aim of this paper is to research the relation between the slope of the terrain and walking activity, an area that has so far been little researched in transportation science. With the use of pedestrian counts from a busy and steeply sloped street as well as public transport ridership data, the effect of the inclination on the pedestrian modal share is researched. The results show a significant influence of slope on walking attractiveness, which is quantified by representing the walking modal share with a logit model. The model parameters acquired by maximum likelihood estimation suggest that a 1% increase in slope makes a walk roughly 10% less attractive. This value corresponds well with the small number of literature sources that exist on the same topic. The results were obtained with "live" data, acquired in the built environment rather than in a controlled experimental setting. Since this means that the exact origins and destinations or trip purposes of travelers cannot be fully known, the authors express reservation in interpreting the results.

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Keywords: walkability, pedestrian transport, sloped walking, modal split, pedestrian counting data

1. Introduction

Research into sustainable transport modes has become increasingly relevant in the last decades. Walking and cycling specifically can help overcome some of societies' current challenges like energy consumption, climate change,

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an aging population and increasing scarcity of land. For this reason, the relationship between pedestrian activity and various influence factors of the built environment is of great interest. One such influence factor is the height difference between two points along a walk. It has a significant influence on the energy required to travel between them. Whereas fields like biomechanics and movement sciences feature extensive literature on walking on inclined surfaces, the influence of slopes on walking activity has not been researched extensively in transportation science.

By using pedestrian counting data from steeply sloped links in the streets network walkways with high pedestrian volumes and comparing it with traffic and ridership counts of other modes, the effect of the inclination on pedestrian activity will be analyzed. Based on the observed modal split, the disutility of steep slopes for pedestrians can be quantified. With this, a quantitative relationship between elevation difference and walkability will be formulated. Subsequently, the results will be discussed in terms of their validity and applicability in a wider context.

2. Literature review

The influence of slopes and elevation differences on pedestrians is well described in the field of biomechanics. Research in this area was done as early as the 1960s (Dean 1965; Cotes and Meade 1960) and focuses mainly on gait analysis and energy expenditure when walking up and down hill (Kawamura, Tokuhiro, and Takechi 1991; Kawata, Shiozawa, and Makikawa 2007; Hunter, Hendrix, and Dean 2010; Wall-Scheffler 2015; J. Sun et al. 1996).

In transportation engineering, the influence of slopes on pedestrian activity has not been researched as extensively. Still, some exceptions can be found and the results generally confirm that slopes deter people from walking. A number of researchers have attempted to link objectively measured properties of the physical environment to participants' reported propensity to walk in stated or revealed preference surveys (Cervero and Duncan 2003; Borst et al. 2008; Rodriguez et. al. 2014). The latter reported a significant negative correlation between increases in walking time due to the slope of the local terrain and the odds of walking or cycling. However, they also found no influence of topography on the accessibility of bus stops. This might indicate that the time component of slopes does not sufficiently explain their influence on walking.

Olszewski and Wibowo (2005) asserted that besides the actual walking distance, the number of climbed steps and road crossings were the most important parameters contributing to an "equivalent walking distance" which was proposed to characterize the accessibility to metro stations in Singapore. In their study, slopes were expressed in terms of the equivalent number of climbed steps. Using a different approach, G. Sun et al. (2015) and McGinn et al. (2007) found a significant discrepancy between pedestrians' perception of the presences and steepness of hills on the one hand, and objective slope measurements on the other.

A link attractiveness study with elderly survey participants by Borst et al. (2008) came to the surprising result that the presence of slopes and stairs seems positively correlated with walking attractiveness. They hypothesize that stairs and slopes are generally found in locations with a high scenic quality. Lastly, Broach and Dill (2015) reported that "steep upslopes of 10 percent are perceived as twice as costly as travel on less steep ground".

3. Research method

3.1. Location choice

Based on a case study with a distinct uphill origin-destination pattern, pedestrian and public transport ridership counts are combined to calculate the pedestrian modal share and subsequently estimate the contribution of the gradient to the attractiveness of walking as a transport mode. The location of the study is in the city center of Zurich, Switzerland, the east of the main station. An area containing the two biggest universities of Switzerland as well as a large teaching hospital is situated around 400 meters (beeline distance) east of the main station. The actual walking distance is roughly 800 meters. The topography in between features a roughly constant slope of ca. 10%. A map of

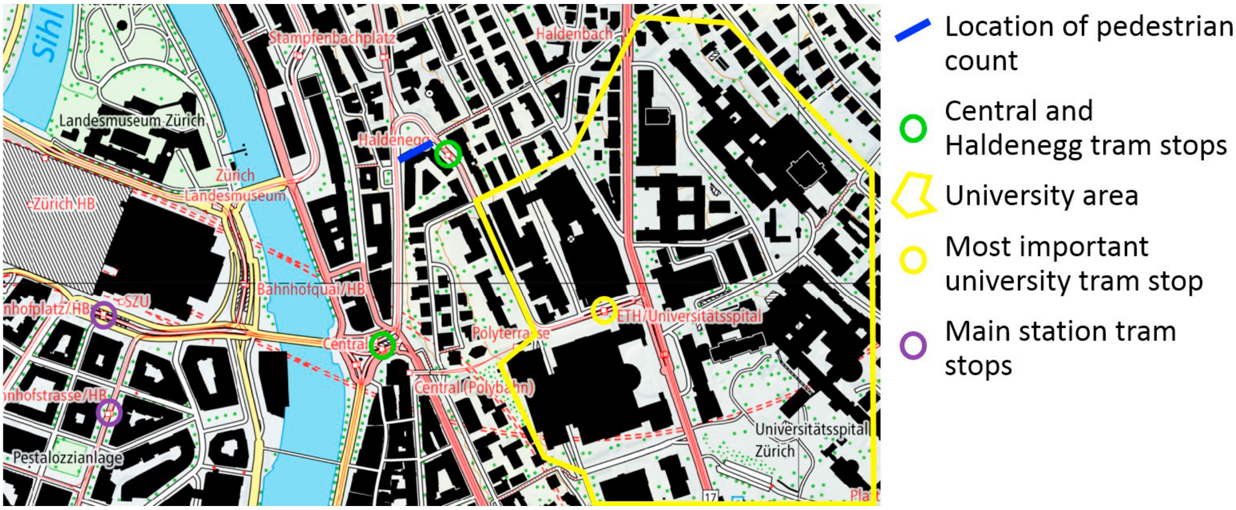

Figure 1. Map of the area, showing the locations of the pedestrian counting sensor, origin and destination areas and tram stops (base map: map.geo.admin.ch).

the area in question is displayed in Figure 1. As is to be expected, high traffic volumes can be observed between the station and the campus, and vice versa.

For most intents and purposes, travelers only have two mode choices: walking or riding a tram on one of two tramlines connecting the campus with the main train station. Cyclist in Zurich represent a small portion of total traffic, roughly 4% citywide (Stadt Zürich 2012). On this particular sloped route, the relative volume might be expected to be even smaller. While car traffic makes up 36% of the total trips in the city, both universities have an extremely low number of parking spaces available. On top of that, the area around the main station is notoriously congested, and a railway station does not typically generate car traffic to a university campus when high quality public transport options are available. The highly specific conditions of a very strong origin-destination pair and limited options for means of transport mean this case is very well suited to analyze influence of slope on the pedestrian modal share.

3.2. Data

Pedestrian counting data are collected using infrared sensors installed by the City of Zurich. Individual pedestrians can be detected as well as their walking direction. Measurement accuracies are generally very high, although bikes can be counted accidentally, which is not an issue at the location in question. In addition, occasionally pedestrians are omitted when they are covered by another person walking in the same direction. The data are corrected for these occurrences by applying a fixed correction factor, which was determined by comparing sensor data with manual counts. The sensor is located on a sloped alleyway called “Weinbergfussweg”, which is located between tram stops “Central” and “Haldenegg”, roughly halfway on the main important pedestrian connection between the train station and the northern half of the university area (see Figure 1). At 16%, the slope on this particular stretch of footway is higher than the average slope on the route of interest. The pedestrian counts used for this study are available on the Open Data portal of the City of Zurich (Stadt Zürich 2017a). In order to be able to compare with tram ridership data, the analyses are carried out with data for the year 2015. Pedestrian counts are available for 15 min intervals and for both directions (uphill and downhill).

To be able to compare the two modes, the public transport data has to represent a (partial) route for which the alternative on foot goes exactly through the pedestrian counting location. In order to achieve this, the ridership numbers between the aforementioned tram stops “Central” and “Haldenegg” are used. “Central” is the first stop after the main station, while “Haldenegg” is the last stop before the university campus (see Figure 1). On foot, the two tram stops are roughly 350 m apart. Tram ridership data is available for each individual vehicle and ride for the entire year 2015, albeit aggregated to daily averages for different categories of weekdays (Monday-Thursday, Friday, Saturday, and Sunday). Since this means a complete day-to-day comparison is not possible, for this study it was decided to compare one week of pedestrian counting data with the daily averages for a typical week of tram rides. Serving this particular route are lines 6 and 10 of "Verkehrsbetriebe Zürich" (VBZ), the city's public transport operator. The tram ridership data are collected using infrared sensors mounted in the doorframes of the vehicles, equipped on ca. 20% of VBZ's trams and buses (Stadt Zürich 2017b).

3.3. Analysis

For a start, the development of both tram ridership numbers and pedestrian numbers over the course of a typical weekday are compared. This allows for drawing first qualitative conclusions about the relative attractiveness of walking as a transport mode with regard to the steepness of the walk. For further analysis, the data for both uphill and downhill situations are summed and the modal shares of walking and public transport are calculated. A common way of modelling the modal split in transportation engineering is the use of a logit model (see e.g. Ortuzar and Willumsen 2001 or Backhaus et al. 2015). As shown above, it can approximately be assumed that travelers have two alternatives on the route in question. Therefore, using a logit model, the pedestrian modal share can be represented as:

$$P_F = \frac{e^{V_F}}{1+e^{V_F}} \quad (1)$$

where P_F is the chance a traveler decides to go on foot, and V_F is the utility function representing the overall cost (or negative attractiveness) of going on foot, compared to the available alternatives. Note that the base utility of taking the tram is implied in this formula, since it is the only available alternative. In its simplest form, the utility function for walking can be written as:

$$V_F = \beta_0 + \beta_1 * s_F \quad (2)$$

with

- β_0 the base cost of going on foot
- β_1 the cost factor for 1% of slope
- s_F the uphill slope in %.

For negative slopes, i.e. when descending, β_1 is assumed zero. This simplification is not entirely correct, but the potential positive utility of walking downhill is certainly lower than the disutility of walking uphill on a similar slope. Depending on the type of person, walking on a flat surface might actually be more comfortable than experiencing a negative slope despite the theoretical energetic advantage in the latter case. Furthermore, at a certain point going downhill ceases to be energetically advantageous since increasing one's speed would lead to an instable gait (Hunter, Hendrix, and Dean 2010). Note that the utility function of public transport is not dependent on the slope. From a passenger's point of view, the terrain is irrelevant. Thus, for riding the tram the same base utility γ_0 is assumed for both directions.

Note that β_0 includes all other attributes of the walk including attractiveness of surroundings, safety and security factors and the time cost. Based on the known modal share for walking, the known steepness of the walk and this representation of the cost function, the parameters β_0 and β_1 can be determined by maximum likelihood estimation. The ratio between β_1 and β_0 is then a measure for how much less likely it is for a person to walk, per percent of uphill slope. To account for the fact that part of the disutility of walking on hilly terrain is the increased walking time the model can be extended by including the time difference between walking and alternative modes as a new attribute. The utility function for going on foot then becomes:

$$V_F{}^* = \beta_0 + \beta_1 * s_F + \beta_2 * \Delta t \quad (3)$$

where Δt is the walking time for the route in question minus the time for the alternative by tram, and β_2 the corresponding factor.

4. Results

Figure 2 shows the comparison between the average daily pedestrian count and the tram ridership data. The week from which the pedestrian data are taken is 19-23 January 2015. For the investigated origin-destination pair, the average daily traffic volumes of the two modes combined was ca. 17´300 persons uphill and 16´800 persons downhill. The results clearly show a significant difference in the attractiveness of walking up versus down, for commuter traffic. In both directions, the daily travel patterns are very similar between the two modes. Going uphill from main station to campus, 10.4% of travelers on a typical weekday decide to walk. The highest demand is in the morning rush hour, as

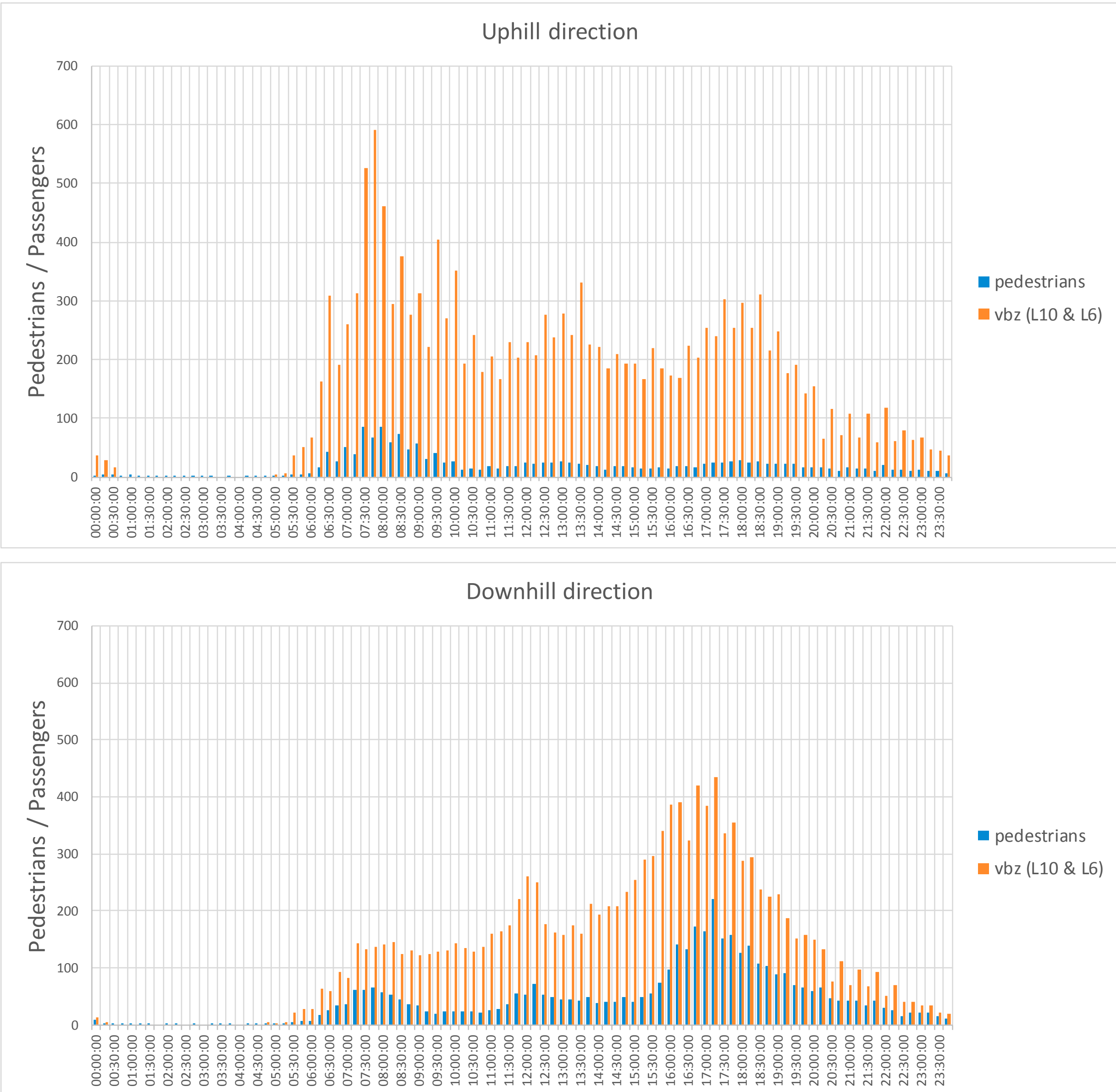

Figure 2. Comparison of pedestrians counts and tram ridership counts per 15 minutes, uphill (top figure) and downhill direction.

expected. In the opposite direction, 25.1% of travelers walk down to the main station with the afternoon rush hour peak being more pronounced than the one in the morning.

Based on these modal splits, the maximum likelihood estimation of the logit model is carried out. The results are shown in Table 1. Since β_1 in the simple model is roughly 1/10th of the base attractiveness β_0, the results imply that a 1% slope makes travelers 10% less likely to walk. For calculating Δt for the second model, the traveling time according to the timetable is used for the tram alternative, with an additional waiting time of half the tram headway for a total of 6 minutes travel time. For walking, the trip time was calculated using a walking speed of 1.2m/s uphill and 1.4m/s downhill (Buchmüller and Weidmann 2006; Bosina and Weidmann 2017), resulting in a duration of 4:50min from Central to Haldenegg and 4:10min vice versa. This corresponds well with values obtained from Google Maps: 5 minutes uphill and 4 minutes downhill. This results in a Δt of -1 minute uphill and -2 minutes downhill. Going by the p-values, both models appear to be a better representation of the attractiveness of walking in hilly terrain than a model assuming constant attractiveness of walking. It can therefore be concluded that slope has a significant influence on walking activity. After removing the time component from the equation, this still seems to be true, judging by the β_1 / β_0 ratio of 0.06 for the second model.

Table 1. Results of maximum likelihood estimation of the logit model for walking modal share.

Utility function	V_F	V_F *
Walking modal share up/down (%)	10/25	10/25
β_0	-1.10	-1.52
β_1	-0.11	-0.089
β_2	-	-0.21
p-value	0.018	0.046

5. Discussion

The results show that steep slopes have a significant negative influence on walking attractiveness. The case study results based on data from a real world situation confirm the existing literature, which is mostly based on stated or revealed preference data of survey participants. More specifically, the one publication found that attempted to quantify the influence of slope on walking attractiveness (Broach and Dill 2015) reported a value similar to the results found in this paper (a 100% reduction of walking attractiveness for a slope of 10% and a 10% reduction per 1% of inclination, respectively). As this study has some limitations, in particular the fact that public transport data was only available in the form of yearly averages, further research will be needed for more confirmation. In particular, it is advised to analyze data from locations with slopes between 0% and 10% in order to find out whether the contribution of 1% of slope changes depending on the current value.

The validity of the results presented is obviously affected by how many trips were actually taking place between the main station and the university area. As reasoned in Section 3, the assumption that this was at least the case for a large majority of pedestrians is quite reasonable, as the location of the sensor is directly on the shortest route between the main station and the northern half of the perimeter containing the two universities and the academic hospital. Furthermore, there are no large attractors like big companies or institutions further up the hill. For the tramlines, the picture is less clear. The trams do continue towards other important travel destinations, albeit not with the same significance as a university campus. Furthermore, the argument that the travel range is limited and therefore farther destinations are infeasible, which applies to pedestrians, is not feasible. Therefore, it is expected that the actual walking modal share is even higher than the values reported in Section 4.

The City of Zurich regularly carries out control measurements to gauge the quality of the recorded pedestrian counts by its sensors throughout the city. Based on these measurements, a 9% correction factor should be added to the pedestrian counts. This would cause an additional, much smaller, increase in the walking modal shares, in addition to the effect mentioned in the previous paragraph.

To make sure the numbers are representative of normal conditions, the counting data from January were compared to different months in 2015. For June, September and December the absolute numbers of travelers were different, mainly depending on whether the dates concerned fell within a semester or not, but the results in terms of the pedestrian modal share were very similar for each season, in either walking direction. The ratio of the uphill to downhill modal shares did go up significantly in June and September (from 0.41 to ca. 0.55). This might imply that the influence of bad surface conditions (snow or sleet) outweighs the influence of high temperatures. None withstanding, the latter influence is more difficult to estimate, since warm weather might make walking uphill in the early morning more attractive but at the same time, the additional effort in combination with high temperatures might cause heavy sweating or other inconveniences. More research is needed in this area too, to be better able to measure the seasonal effects of slope walking.

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