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Analysis of active school transportation in hilly urban environments: A case study of Dresden

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ABSTRACT

This paper analyses the way students travel to school and examines the influence of environmental conditions on travel patterns. More specifically, it studies how topographic changes affect the likelihood of choosing cycling as a transport mode. We use mode choice data on students' home-to-school commuting trips from a previous study by Müller et al. (2008). The results show that models perform better when they account for the topographic conditions of the urban environment. We included this information in the model by introducing the "energy exerted" variable, which significantly improves the model and the results. The implications of this study are manifold; it guides the consolidation or expansion of school-based transportation network planning in Germany and prompts further analysis of active transportation systems, such as bike, pedelec and e-bike sharing systems. Overall, transportation policy should seek to foster active transportation, as it provides the greatest benefits for society and has a direct impact on people's well-being, while notably reducing the negative environmental and socioeconomic impacts of motorized transport.

1. Introduction

Trips by children and adolescents constitute a large share of travel patterns in urban areas, as can clearly be seen during the school holidays especially around school areas, when traffic volumes drop and rush hour traffic flows more smoothly. Children, and especially younger children, have limited possibilities of transportation. Independent mobility is more common in some regions, while in others students are more likely to be escorted to school, usually by car. These patterns largely depend on the availability of schools near their place of residence, but also on transportation system attributes such as traffic volumes and pollution levels, safety and accessibility to public transport, coupled with a variety of social factors.

The urban fabric and weather are generally important determinants of active transportation (walking, cycling) mode choice (Curtis et al., 2015; Martín and Páez, 2019; Miranda-Moreno and Nosal, 2011; van Goeverden and de Boer, 2013). People may prefer to walk or cycle in transport-oriented urban developments (TOD) and during the warmer seasons. Studies show that the same holds for children (Kemperman and Timmermans, 2014). Topographic conditions also have an impact on walking and cycling choice. Hilly urban environments may dissuade people from commuting by active modes, an effect that can clearly be seen in traditional bike-sharing systems offering bicycle rentals to users at docking stations: bicycles accumulate in low-lying areas and need to be redistributed by lorry. Empirically, slope appears to play an important role, although as far as we are aware, few studies account for topography when estimating transportation mode choices, as is also highlighted by other authors (Meeder et al., 2017; Rodríguez and Joo, 2004). However, the study of the impact of topography in the case of children and teenagers is very limited.

Authors such as Mackett (2013) and Mitra and Buliung (2015) observe that children's physical activity levels have declined notably worldwide in recent decades, as has the number of children traveling to school by active modes like walking and cycling (Stark et al., 2018c). Obesity and related health problems like child diabetes have similarly increased. As highlighted by various authors, the World Health Organization recommends that children and young people aged 5 to 17 should take moderate to vigorous exercise for at least 60 min a day

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(World Health Organization, 2020). Active School Transportation (AST) contributes to achieving the recommended exercise rates among children and teenagers.

AST has been studied intensively due to its manifold positive effects. The literature confirms that it contributes to improving children's health, as it impacts their physical, social and mental development and overall well-being (Schoeppe et al., 2013; Stark et al., 2018c; Waygood et al., 2020). Independent mobility in children is associated with child health, including good motor skills, cognitive development (Scheiner, 2016) and a better understanding of their surrounding environment (Mitra and Buliung, 2015). Waygood et al. (2017) explore the way AST promotes social interactions for children during their trip to school in Canada, Japan and Sweden, and its importance for their personal well-being. As important spillover effects, AST has direct implications for the environment and sustainable transportation, as it reduces accompanied transport and leads to a decrease in congestion and pollution.

The aim of this paper is to gain a better understanding of mobility patterns in children and teenagers in regard to their travel choice to school in a hilly urban environment, and to discuss measures to improve sustainable mobility. The case study in this work is the city of Dresden in eastern Germany, whose sustainable transport policy was recognized by the Civitas initiative in 2005 (Civitas, 2013). This study focuses on secondary schools (*Gymnasium* in German), attended by students between 10 and 19 years old, and offers a detailed analysis of the factors that contribute to AST by analysing the height profile of the cycling routes taken to school, thus increasing the reliability of the outcomes. One limitation of our study is the lack of additional personal information and environmental variables discussed in the literature.

This paper is divided into seven sections. After the introduction and background, the third section describes the case study. Section four focuses on the methodology and data. The fifth section presents the model specification, and section six reports the results. Finally, section seven contains the conclusions and discusses the main findings and implications of this study.

2. Background

As discussed by various authors (Mackett, 2013; Mitra and Buliung, 2015), the way children and teenagers commute to school has notably evolved in the last few decades. In the past, students would have been more likely to commute unaccompanied to school. Current worldwide trends in car ownership and car-oriented urban developments have directly transformed the way children go to school, as they now tend to be escorted by motorized transport modes, while the distance to the nearest school has also increased.

Several studies deal with AST in various developed countries, such as those by Shaw et al. (2015), Habib and Daisy (2013), Yang and Markowitz (2012), Mitra and Buliung (2015) and Curtis et al. (2015). Many authors point out that apart from personal socio-demographic information, family background, socio-cultural and economic characteristics, along with geographical, spatial, and urban factors, all have a major influence on the preference for a certain mode.

Gender is a controversial topic in the literature. Some authors report that it influences AST whereas others find no influence. For example, the studies by Scheiner et al. (2019a, 2019b) with information from children aged 6 to 10 show that primary school girls are escorted more often than boys, most notably those aged 6–7 years, and that female children are less likely to choose cycling as model choice, especially on morning trips. The study by van Goeverden and de Boer (2013) using data from Dutch and Flemish national travel surveys and information from children attending primary and secondary education shows that girls may travel less independently than boys because they are exposed to higher security risks. This variable is significant in Flanders, whereas in the Netherlands there is no impact. Conversely, Kemperman and Timmermans (2014) found that in children between 4 and 11 years in the Netherlands gender has no relation with either active travel behaviour or with any of the other variables in their analysis. Helbich et al. (2016) focused on a subsample of 97 children aged 6 to 11 years in six elementary schools in mid- to large-sized Dutch cities with GPS available information; they also reported gender to be insignificant, as did Stark et al. (2018c), who only found out that male children rated biking as being "cooler". The latter authors observe that a larger heterogeneous sample would be necessary to get more insights about gender.

Deka (2013) studies how parents' mode of travel to work is directly interrelated with children's trip mode to school in the United States. If the parents choose to drive to work, children are likely to be dropped off at school, hence decreasing the possibilities of AST. The study by Stark et al. (2018b) in Austria highlights the importance of parents' attitudes for an understanding of the mobility patterns of primary school children, as they may subsequently influence how their children will commute alone to their secondary and tertiary education. In the study by Pojani and Boussauw (2014) in Albania, most of the children who were driven to school came from higher income families.

Studies such as that of Sharmin and Kamruzzaman (2017) show that the country and regional context also play a major role. For example, Finnish children and young people are traditionally very independent in their mobility (Kyttä et al., 2015); in the study by Sarjala et al. (2016) in two different regions in Finland, children were escorted by parents on only 7% of trips. In contrast to children in developed countries, children in developing countries may rank choices differently. For example, in the case study of Kanpur, India (Singh and Vasudevan, 2018), the authors highlight that children rely on motorized modes such as family cars and paratransit modes in detriment from active modes due to an unbalanced distribution of schools, along with the lack of good-quality school bus services, the low standard of the public transport infrastructure, and the inadequate safety of the pedestrian and cycling infrastructure. They also observe that the students' mode choice reflects a gender-biased society.

Many authors point to the inextricably intertwined relation between active transportation and the built environment. Rodríguez and Joo (2004) highlight the positive effects of active transportation on the built environment, as it fosters the presence of mixed land use and higher employment and population density. Sarjala et al. (2016) analyses children and adolescent mobility in Finland by using a Topographic Dataset produced by the National Land Survey of Finland (SLICES dataset) which includes land use, land cover, soil types and special use and restricted areas. They found that places with large commercial buildings and green environments had the highest proportions of car use. Scheiner et al. (2019a, 2019b) give a thorough analysis with detailed information on the built environment and on many other variables that influence AST in Lünen, Germany. The authors found that traffic calming routes are associated with more independent mobility for children. Helbich et al. (2016) studied commuting patterns of children aged 6–11 years and found that well-connected streets and cycling lanes are positively associated with AST; the authors describe the horizontal dimension with a rich set of built environmental characteristics. The meta-analysis by Sharmin and Kamruzzaman (2017) also suggests that a wide variety of land-use patterns and a convenient street design helps promote policies for children's independent mobility. Broberg and Sarjala (2015) mention that major roads on the school journey lower the odds of cycling to school, and that dense school networks support AST. Other authors also mention that school spatial planning plays an important role in fostering active mobility in schoolchildren; this is the case of Boussauw et al. (2014) for primary schools in northern Belgium. Similarly, Marique et al. (2013) also mention, based on two decennial surveys in Belgium, that well-distributed, decentralised nursery and primary school services reduce the use of private cars and encourage more walking and cycling alternatives.

Longer trips clearly hinder walking and cycling alternatives, especially for children, as confirmed by Stark et al. (2018a) in their study of secondary pupils in Austria and Germany. Although some authors report that active transportation may increase the risk of injury from collisions (Vanparijs et al., 2020) and health risks due to exposure to motor vehicles and their emissions, this risk declines significantly as the number of people using active modes rises (Reynolds et al., 2010). In overall terms, the benefits of physical activity outweigh the traffic-associated disadvantages, as highlighted by Mueller and colleagues (Mueller et al., 2015). Indeed, authors like Lopes et al. (2014) focus on the importance of transforming a motorized city through walkable policies to foster safe AST.

In order to propose specific measures to foster AST, it is important to analyse the factors that promote active school transportation among children and young people. As it plays such a key role, the urban environment must be studied in greater depth. To our knowledge, there are limited examples of the use of technology systems or devices to determine and understand more accurately which other factors in the urban environment influence active transportation for children and adolescents; questionnaires and interviews tend to be used, probably due to legal restrictions. One such study by Verhoeven et al. (2018) considers cycling trips by secondary school adolescents using global positioning systems. However in terms of slope conditions, most studies focus mainly on adults. For example, Rodríguez and Joo (2004), Li et al. (2012), Broach et al. (2012), Paige Willis et al. (2013) and Milakis and Athanasopoulos (2014) analyse cycling route choice in adults, in most cases for commuting purposes. Li et al. (2012) use a dummy variable as a proxy for hilly and flat urban environments to inform perception of cycling comfort. Broach et al. (2012) take three alternatives (categorical variables) for the part of the route with a certain average upslope in order to choose a cycling route. Paige Willis et al. (2013) ask participants about slope satisfaction. Milakis and Athanasopoulos (2014) consider the riding difficulty variable as a function of slope in a certain section to understand cycling route preferences. Table 1 presents detailed information on AST studies and others that take slope into account in their analysis. In this work, we focus on slope as the main topographic condition in the city of Dresden, and seek to understand how this variable influences transport choice in children and teenagers.

3. Case study

Dresden is located in the eastern part of Germany, close to the Czech Republic (Fig. 1). It is the capital of the state of Saxony and a very important cultural and educational hub in Germany (Dresden, 2018a). Dresden is also acknowledged as one of the greenest cities in Europe (Civitas, 2013); woods and green spaces account for 62% of the city's territory. The city is located in a widening of the Elbe valley, surrounded by the foothills of the Eastern Erzgebirge Mountains, the Lusatian Granite Uplands and the Elbe Sandstone Mountains (Dresden, 2018b). The length of the river within the city is about 30 km, and it is crossed by ten bridges at different points. (See Fig. 2.)

According to the state's own statistics (Dresden, 2018b), Dresden's population in 2005 was approximately 487,000, and now stands at 557,000 with a density of about 1696 inhabitants/km^2. It is the fourth largest city in Germany and has a total area of 328 km^2. Built-up areas and their associated open-spaces account for 6310 ha, while 3377 ha are dedicated to traffic. The highest point (Triebenberg) is 383 m a.s.l. and the lowest point (Cossebaude) is 101 m a.s.l.

The city's geographic location directly influences its particular weather conditions. According to the weather statistics (Climate-Data, 2019; WetterKontor, 2018), the average temperatures are −1.8 °C in January, and the maximum temperatures occur in July (19.8 °C). Annual precipitation is 667 mm.

Germany has a longstanding tradition of encouraging active and independent mobility in children. According to the Children's Independent Mobility Report (Shaw et al., 2015), German children come second – after Finnish children – in their freedom to travel independently on local buses. An earlier study by Shaw et al. (2013) found that between 1990 and 2010, students attending secondary school in Germany transitioned from walking and cycling to taking public transport or school buses.

It should be noted that schoolchildren in Germany take a cycling proficiency course and test before entering secondary school. This encourages independent mobility while emphasizing safe cycling at an early age.

In the last decades, the mobility patterns of children have also changed in Germany. Many children are being escorted, leading to a decrease of AST.The German Ministry of Transport recently presented the results of a study on family mobility (Manz et al., 2015). The study by Scheiner (2016) reports that 16% of parental trips in Germany are for the purpose of escorting children, increasing to 22% for families escorting children aged ten or younger. Although this may be done by private car in most cases, 22% of these trips involve active mobility, while escorting children on public transport accounts for only 2% to 7% of all cases, depending on the city type.

Germany has an established policy for school network planning aimed at providing basic social infrastructure, known in German as *Daseinsvorsorge* (Küpper, 2012), including a minimum access to certain public services such as schools and transport (Gawron, 2008). In recent years many towns and cities have seen a drop in the number of students, leading to school closures. When a school closes, it has a direct impact on the way students commute to the other available schools, and on the transport services in the areas of both their former school and their new schools. Various studies show how school closures trigger changes in travel patterns (Haase and Müller, 2013; Müller et al., 2009; Müller, 2011).

4. Methodology and data

This paper covers secondary schools with a focus on high academic performance (*Gymnasium* in German) attended by students between 10 and 19 years old. Only a certain number of students may attend these types of schools. At the time of the survey, around 45% of the students in this age range went to a Gymnasium. Students who normally attend a Gymnasium have higher grades and a better performance in elementary school, while other students go to secondary schools known as *Mittelschule* or *Realschule, Hauptschule, Realschule* and *Gesamtschule*. We chose the Gymnasium because students show more variance in mode choice compared to elementary and middle school. Younger students often walk to school or are escorted by car. Few elementary or middle school students choose public transport (Manz et al., 2015). There are more middle schools than Gymnasium in Dresden, hence the average commuting distances are shorter. Gymnasiums also offer specific learning areas (school profiles) which impact the students' choice of school (Müller et al., 2012), so longer commuting distances and a more diverse mode choice pattern can be seen among Gymnasium students.

This paper uses the data from Müller et al. (2008) as the base model choice. The data is available at GitHub.[1] An analysis of the results reveals singularities in the case study that require further exploration. From the literature review, we know that the built environment plays an important role in the likelihood of riding a bike. In this study we follow a comprehensive approach.

Different hypotheses are tested to improve the original model. First, the predictive quality of the model can be enhanced by choice models that explicitly allow for correlation among transport modes; and second, the model can also be improved by considering the topography of Dresden. We therefore present a methodology that takes account of the "energy exerted" by cycling in the city of Dresden due to its hilly profile. Third, we use age and gender as additional control variables.

The information collected in 2004 covered approximately 4700 of the 14,000 school students at 12 out of the 23 schools in Dresden.

[1] https://github.com/svenne0815/DresdenModeChoiceData

Although the data are over 15 years old, it is reasonable to assume that the basic underlying patterns of mode choice have not changed significantly since then. Most recent studies show the impact of distance and weather. According to Manz et al. (2015), the mobility choices seen in the information on secondary students' travel patterns in Germany between 2002 and 2008 did not change noticeably. The same report also shows that school closures have affected other secondary schools, but not Gymnasiums, whose locations remain similar all over Germany. However, the variance in more recent data may differ from our own, so the alternative-specific constants of our model are likely to be biased. Since this is only of interest in forecasting scenarios, we can disregard this issue in this paper. More importantly, the topography and school locations have not changed since then, and we are therefore convinced our data are still valid for the purpose of our study.

It should be noted that due to data protection laws, students cannot be asked their detailed whereabouts such as their home address, which made it necessary to design a methodology to obtain a proxy for their place of residence and route. Other authors mention data protection laws as a drawback (Stark et al., 2018c), which has also been circumvented by using an alternative approach (Scheiner, 2016).

The students were asked to specify the closest bus stop and the estimated walking time from home to the bus stop. We also had small-scale demographic data at the block level (smallest administrative census units in Dresden). Using this information, we built an isochrone around the bus stop for each student, so each isochrone might be feasible for several students. We then assigned the census blocks intersecting an isochrone to that same isochrone. All the students in an isochrone were distributed to each block in line with the frequency in the census of individuals aged between 10 and 19. Using a shortest-path algorithm, we were able to determine the street network distances between all the blocks in Dresden. These had to be interpreted as walking distances in the absence of information about car accessibility around one-way street systems. As this paper considers only the commute to school, cars and motorcycles did not play an important role. Detailed information on this methodological approach can be found in Müller et al. (2008).

4.1. Topographical analysis and its transformation in energy

This study considers Dresden's topographic profile. There are major differences in elevation across the city. For example, the Klotzsche District is 227 m above sea level, whereas the inner city is only 112 m above (see Fig. 3). To improve the model, topographical patterns are used to obtain the energy required by students on their individual commuting trip to school when they cycle.

We use a digital terrain model with the exact topographic information for the area of Dresden (Federal Office of Cartography and Geodesy (BKG) (bkg, 2018)) to obtain a height profile for the commute to school on the shortest path for each student in our sample. To calculate the expected energy expended by a cycling student, we consider

$$E_n = F_n \cdot v_n. \tag{1}$$

The exogenous variable, power (E_n), is formed of force F_n and speed v_n, according to Gressmann (2005)

$$F_n = F^{\text{roll}} \bullet F_n^{\text{drag}} \bullet F_n^{\text{slope}} \tag{2}$$

The rolling friction F_n^{roll} is derived from the contact of the tyre with the surface. It is calculated as

$$F^{\text{roll}} = 0.0058 \bullet 9.81 \frac{\text{m}}{\text{s}} \bullet (15\text{kg} + 65\text{kg}) \tag{3}$$

which is the product of a given constant, gravity, and the weight of the systems (i.e., the sum of the weight of the student and the bike). Due to lack of data, we assume an average student weighs 65 kg and a bike is about 15 kg. The drag

$$F_n^{\text{drag}} = 0.5 \bullet c \bullet A \bullet \rho \bullet v_n^2 \tag{4}$$

comprises a drag coefficient $c = 1.1$, air density $\rho = 1.25\,\text{kg/m}^3$, and the squared speed of student n. Due to lack of data, we assume the surface area (A) of a student to be 0.42m^2. We subdivide the route length of student n from home to school into sections k_n. Each section k_n is distinctly characterized by either positive, negative or zero slope. The topography is considered in the friction due to slope

$$F_n^{\text{slope}} = 9.81 \frac{\text{m}}{\text{s}} \bullet (15\text{kg} + 65\text{kg}) \sum_{k_n} \frac{H_{k_n} - H_{k+1_n}}{D_{k_n}} \tag{5}$$

where H_{k_n} is the height of k_n in metres above sea level and D_{k_n} is the length of k_n in metres (see Fig. 3 for some numerical examples of how F_n^{slope} is computed). Since the topography differs between the route to and from school, we consider F_n^{slope1} for the route to school and F_n^{slope2} for the route back home.

To determine speed v_n, we use the GoogleMaps API (Googlemaps, 2015), which allows us to query the distance travelled on the shortest path and the expected travel time depending on the topography (Fig. 4). We then calculate the expected speed on the shortest path from student's home n to school v_n^1 and back v_n^2. So (2) is rewritten as

$$F_n^l = F^{\text{roll}} \bullet F_n^{\text{drag}} \bullet F_n^{\text{slope}\,l} \quad l = 1, 2 \tag{6}$$

and (1) becomes

$$E_n = F_n^1 \bullet v_n^1 + F_n^2 \bullet v_n^2 \tag{7}$$

In addition to the energy variable, we consider further exogenous variables to understand students' mode choice behaviour. Our

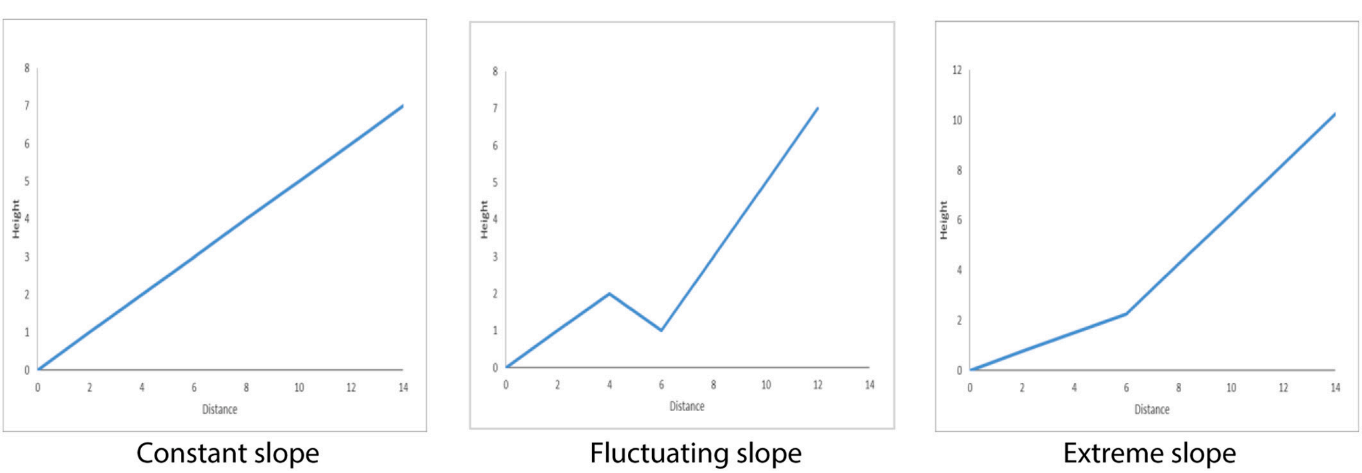

Fig. 3. Examples of power required.

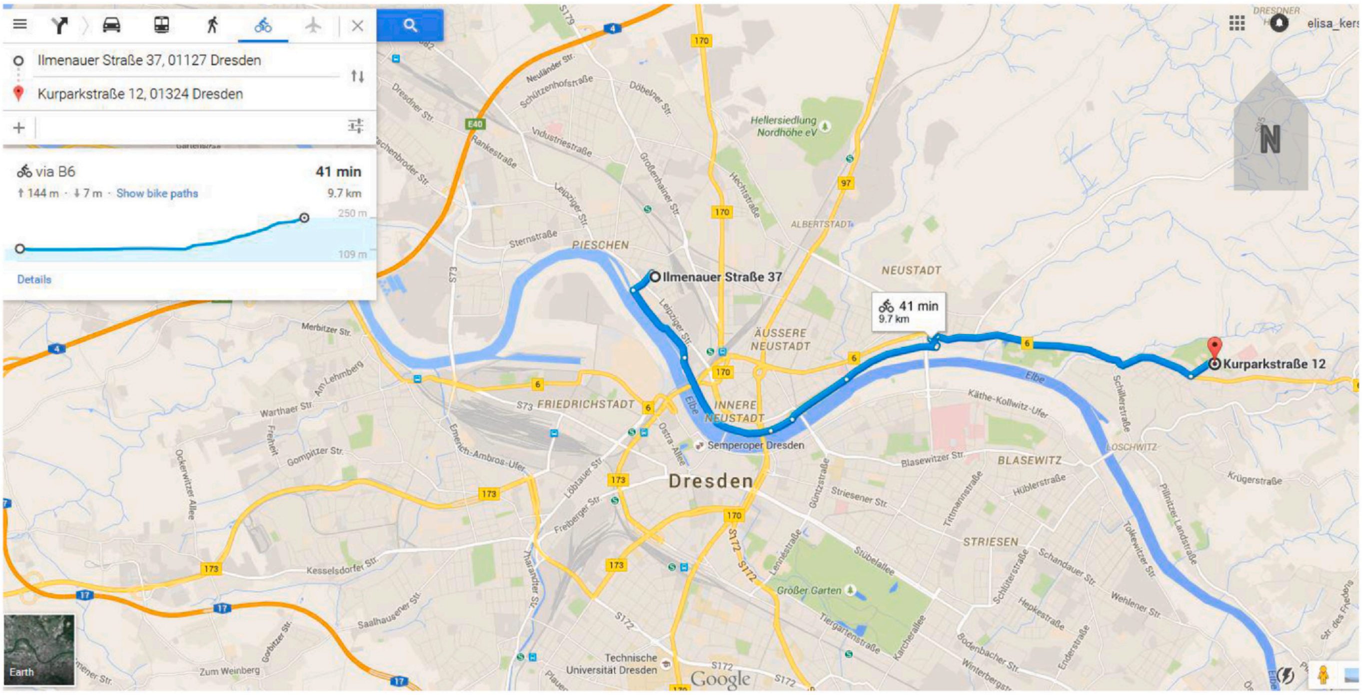

Fig. 4. Example of a bike route in Dresden (Googlemaps, 2018) (Kersten, 2015).

Table 2
Description of variables and modal share.

Variable	Description	Unit	Mean	S.D.	Min	Max
Distance	Distance between school and place of residence	Km	3.40	2.66	0.04	17.80
Class	School class	Grade	8.73	2.11	5.00	12.00
Age	Student's age	Years	14.71	2.50	10.00	39.00
Gender	=1, if female	Dummy variable	0.56	0.50	0.00	1.00
Availability	=1, if car is always available	Dummy variable	0.08	0.27	0.00	1.00
Season	=1, if winter season	Dummy variable	0.50	0.50	0.00	1.00
Energy exerted	Energy spent when cycling (E_n)	Watt	242.45	379.40	0.13	3131.95

Seasonal modal share	Car	Public transport	Bike	Walk
Winter	10%	61%	8%	21%
Summer	6%	52%	24%	18%

n = 8556.

dataset also contains information about the distance in kilometres from a student's home to school by the shortest path. We use the "season" variable to consider the impact of weather conditions on the mode choice, since many people in Germany alter their travel behaviour depending on the season and weather conditions, as in many other cities with adverse meteorological conditions (Amiri and Sadeghpour, 2015). The survey contains two questions regarding the commute-to-school mode choice: one for winter and one for summer. As can be clearly seen in Table 1, there is a significant difference in bike share between summer and winter, as expected. Our control variables are the students' age, class and gender, and whether a car is always available or not. The descriptive statistics are shown in Table 2. For further details, see Müller et al. (2008).

5. Mode choice model specification

We assume that student n chooses exactly one main commuting mode i from a given choice set {walk, bike, public transport, car}. Choosing alternative i yields utility

$$U_{ni} = V_{ni} + \epsilon_{ni} \tag{8}$$

with V_{ni} representing the deterministic part of the derived utility, and ϵ_{ni} the stochastic part. The deterministic utility is defined as

$$V_{ni} = \sum_m \beta_{im} \bullet X_{nim} \tag{9}$$

The exogenous variables X_{nim} are age, distance, energy E_n, etc. The coefficients β_{im} represent the marginal contribution to utility and are estimated via maximum likelihood. We further assume that student n chooses the alternative i that maximizes her utility:

$$U_{ni} > V_{nj} \quad \forall j \neq i \tag{10}$$

Since utility (8) is a stochastic quantity, we can only make probability statements about (10); i.e., the probability that n chooses i is:

$$P_{ni} = \text{Prob}(U_{ni} > V_{nj} \quad \forall j \neq i) \tag{11}$$

If we now assume that ϵ_{ni} is an identically and independently distributed (IID) extreme value, then (11) becomes the multinomial logit model (MNL):

$$P_{ni} = \frac{e^{V_{ni}}}{\sum_j e^{V_{nj}}} \tag{12}$$

The MNL model (12) exhibits the property known as independence from irrelevant alternatives (IIA), which states that every alternative j is an equal substitute to i. Technically speaking, by using the MNL we assume there is no correlation between the alternative modes, although we can easily find situations that violate this assumption. For instance, the alternatives “walk” and “bike” might both be sensitive to the weather and therefore share some unobserved effects, which could in turn cause correlations between “walk” and “bike” that are neglected by the MNL. We use the McFadden omitted variables test to verify whether the IIA assumption holds or not. If the assumption does not hold, we must make different assumptions about the distribution of ϵ_{ni}. Here we assume ϵ_{ni} to be a multivariate extreme value distribution. Thus from (11) we obtain the nested logit model (NL):

$$P_{ni} = \frac{e^{\mu_s V_{ni}}}{\sum_{j\in B_s} e^{\mu_s V_{nj}}} \frac{\left(\sum_{j\in B_s} e^{\mu_s V_{nj}}\right)^{\frac{\mu}{\mu_s}}}{\sum_{t=1}^{S}\left(\sum_{j\in B_t} e^{\mu_t V_{ni}}\right)^{\frac{\mu}{\mu_t}}} \tag{13}$$

where (13) is the choice probability of alternative i in nest B_t. We partition the choice set into S nonoverlapping subsets denoted B_1, B_2, …, B_S and call them nests from hereon. The parameter μ_s is a measure of the degree of independence in unobserved utility among the alternatives in nest s. Scale parameter μ is normalized to 1. The NL exhibits the following properties:

1. For any two alternatives that are in the same nest, the ratio of probabilities is independent of the attributes or existence of all other alternatives. That is, the IIA property holds within each nest.
2. For any two alternatives in different nests, the ratio of probabilities can depend on the attributes of other alternatives in the two nests. IIA does not hold in general for alternatives in different nests.

The assignment of alternatives to nests is arbitrary. We test the nest specifications shown in Fig. 5. We understand that walk and bike may have unobservable sources of correlation (as AST modes) and we therefore test different alternatives to improve the model. We also test whether car and public transport (PuTr) – as non-active transportation –, and the environmentally friendly choice of PuTr, bike and walking, share unobserved characteristics. Fig. 5 shows the models tested in this study.

6. Results

Table 3 contains the respective estimated coefficients $\widehat{\beta}_{im}$ and other parameters within the base model and the nested models. For comparison we added a MNL specification. We tested different MNL specifications (see Table A1 in the appendix) and decided to maintain the one in Table 3. As expected, we found a decline in utility with distance between students' home and school. The slope is steeper for non-motorized modes than for motorized modes. Car availability increases the likelihood of commuting by car, and winter particularly decreases the utility of walk and bike. These results are in line with the findings of Müller et al. (2008).

However, this study adds to these findings by using a gender dummy, an age (or rather class) variable, an interaction between distance and season, and of course our energy variable. Interestingly, we found that female students are less likely than male students to choose bike, while gender has no impact on the other commuting modes.

The class variable reveals that higher classes are more likely to choose “parent-independent” commuting modes, and the utility of cycling specifically increases with class. We assume that older students are more likely to be allowed to take “riskier” or more independent modes rather than being driven by their parents, which can be seen as a sign of the students' growing independence. The interaction between distance and season reveals some interesting insights. The magnitude of the distance slope for walk and public transport declines in winter compared to bike and car, showing that students are more willing to walk longer distances in winter than in summer. We can assume that it is more convenient for students to walk in snow or rain than taking the bike (an umbrella can be used while walking, for instance).

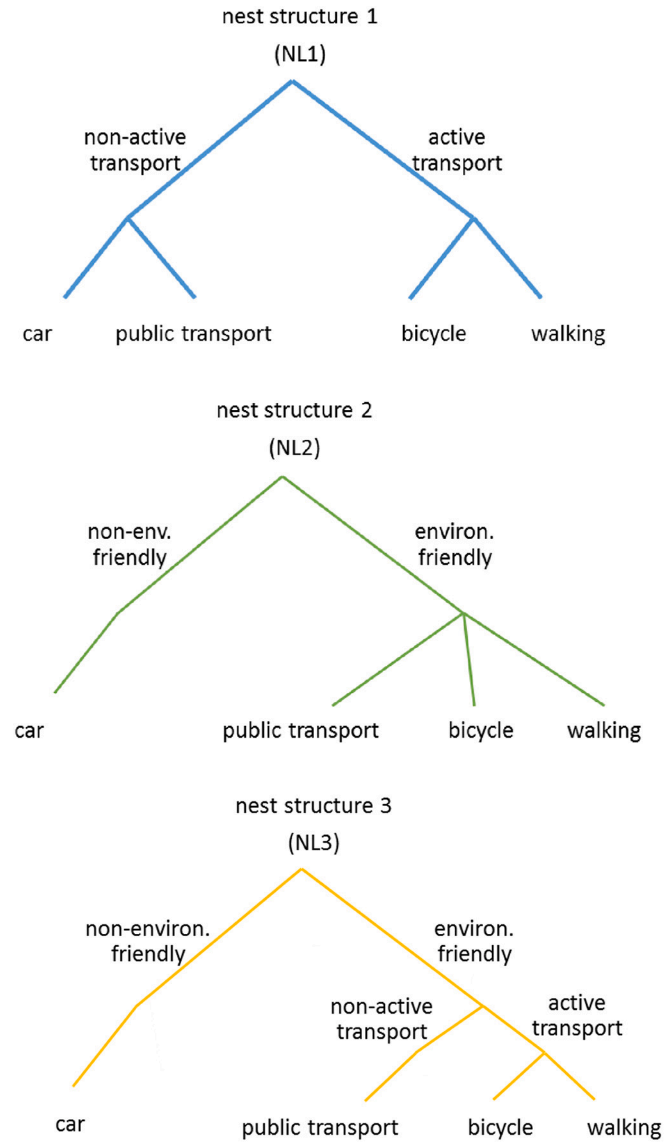

Fig. 5. Nested models tested.

As expected, the energy consumption on the commute to school by bike reduces the bike utility. Specifically, for one unit increase in the energy variable we expect a $\exp.(-0.188) = 0.83$; i.e., a 17% decrease in the odds of choosing bike assuming MNL.

The nominal explanatory power of nested models 2 and 3 is very similar. The nest parameters *non-active transportation,* and *active transportation* are not statistically significant for nest structure 1. The nest coefficients do not support utility maximization theory as they are larger than one. The ratio of the significant alternative variables compared to the initial model also decreases from 78% to 46%. Above all, the significance of the vehicle availability variable drops sharply when using the nest structure compared with the base model.

In the nested logit model 2, the nest *environmentally friendly* is statistically significant. The distance variable for the public transport alternative is also significant. Within Nest B, the increased system speed of public transport is stronger than non-motorized transport. The IIA property may be violated because more than two alternatives belong to Nest B. For this reason, a McFadden omitted variable test was

Table 3
Results for the base model (MNL) and nested logit models. Alternative *Car* is the reference alternative.

	MNL		Nested 1		Nested 2		Nested 3	
	$\widehat{\beta}_{im}$	Robust *t*-test	$\widehat{\beta}_{im}$	Robust t-test	$\widehat{\beta}_{im}$	Robust t-test	$\widehat{\beta}_{im}$	Robust t-test
Alternative-specific constants (ASC)								
walk	11.37***	22.38	14.78***	2.73	9.59***	13.35	9.84***	12.46
bike	4.70***	12.38	7.77	1.44	4.83***	13.54	4.78***	13.25
public transport	4.15***	11.84	7.22	1.36	4.43***	12.47	4.44***	12.52
Distance								
walk	−5.74***	−21.34	−5.97***	−11.67	−4.15***	−7.27	−4.35***	−6.90
bike	−0.79***	−15.45	−0.76***	−8.27	−0.62***	−8.99	−0.60***	−8.37
public transport	−0.03	−0.86	−0.01	−0.13	−0.08**	−2.18	−0.08*	−2.27
Distance * Season "Winter"								
walk	2.26***	7.39	2.48***	2.48	1.62***	5.27	1.79***	4.91
bike	−0.02	−0.21	0.07	0.07	0.03	0.36	0.06	0.82
public transport	0.15***	3.23	0.22*	0.22	0.16***	3.60	0.16***	3.61
Car always available								
walk	−4.84***	−18.94	−7.94	−1.38	−4.69***	−23.43	−4.70***	−23.05
bike	−4.56***	−22.79	−7.78	−1.31	−4.66***	−25.57	−4.67***	−25.45
public transport	−5.35***	−34.88	−10.04	−1.15	−5.28***	−35.88	−5.28***	−35.90
Female students								
walk	−0.18	−1.06	−0.13	−0.47	−0.18	−1.20	−0.17	−1.10
bike	−0.88***	−5.75	−0.84***	−3.18	−0.68***	−4.46	−0.68***	−4.40
public transport	−0.03	−0.23	0.01	0.03	−0.08	−0.57	−0.08	−0.60
Class								
walk	0.11**	2.82	0.14	1.48	0.09**	2.69	0.09**	2.47
bike	0.26***	7.36	0.30***	3.12	0.20***	5.41	0.20***	5.37
public transport	0.02	0.62	0.06	0.60	0.03	1.03	0.03	1.07
Season "Winter"								
walk	−3.72***	−8.21	−4.33***	−5.77	−3.00***	−7.07	−3.19***	−6.70
bike	−2.45***	−7.89	−2.97***	−4.75	−2.14***	−7.41	−2.23***	−7.28
public transport	−1.14***	−4.27	−1.62**	−2.56	−1.23***	−4.93	−1.24***	−4.94
Energy bike (En)/100	−0.19***	−7.80	−0.19***	−7.68	−0.13***	−5.03	−0.13***	−4.75
Nest coefficients μ_s								
non-active transport +			1.06	0.55				
active transport +			1.88	0.54			0.77*	−1.94
environmentally friendly +					0.71**	−2.97	0.69***	−3.12
log-likelihood		−4469.97		−4469.12		−4466.73		−4466.12
adj. $\bar{\rho}^2$		0.62		0.62		0.62		0.62

Notes: test of statistical significance. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$ (+ test against 1).

conducted for the alternatives *public transport, bicycle,* and *walking*. The inaccuracies in the unobserved characteristics between *bicycle* and *walking* and between all three alternatives in the nest increased in relation to the initial model. A third nest structure was therefore evaluated to determine whether it might be a better alternative.

The additional sub-nest proposed in nested model 3 minimizes the likelihood ratio value compared to the other models. The significance values of the variables also change minimally. At a significance level of 95%, the network parameter *active mobility* is not significant. We prefer the Nested 2 or Nested 3 specification due to their significance, conformity with utility theory and complexity.

Table 4 presents different statistical measures, known as the classification function. Although these values must be carefully analysed, they provide good information on the reliability of the different models. We analyse two situations, one for summer and one for winter. For the basic model, the Nested 3 model presents better explanatory results for the *walking* and *bike* alternatives. The number of students using motorized traffic is 40% lower than in the original model. 95% of this decline comes from the drop in the number of public transport users. Only 61% of all car and public transport users are correctly assigned in the nested logit model, while 89% of public transport users and 76% of motorists are still correctly calculated in the initial model. The rate of

Table 4
Results for base model vs nested logit model 3.

Alternative	*Real obs.*	*Base model*	*NL3*	*Alternative*	*Base model*	*NL3*	
Walking				**PuTr**			
Total	1858	2026	2310	Total	4675	4930	3033
True positive		87.5%	91.2%	True positive		88.6%	61.0%
False positive		12.5%	8.8%	False positive		11.4%	39.0%
Sensitivity		109.0%	124.3%	Sensitivity		105.5%	64.9%
Specificity		97.5%	93.3%	Specificity		93.4%	142.3%
Bike				**Car**			
Total	1484	1031	2791	Total	539	569	422
True positive		43.6%	73.0%	True positive		75.9%	61.0%
False positive		56.4%	27.0%	False positive		24.1%	39.0%
Sensitivity		69.5%	188.1%	Sensitivity		105.6%	78.3%
Specificity		106.4%	81.5%	Specificity		99.6%	101.5%

correct assignment decreases with each level of the nested logit model. At level 1 (car/non-environmentally-friendly vs. environmentally friendly), 94% of all allocations are still correct, while only 81% are correct at level 2 (PuTr/non-active vs. active transport).

Fig. 6 presents the results, and shows the difference between the alternatives *bicycle* and *public transport* in the base model (left) and nested logit 3 (right). The alternative *bike* has increased the overall probability values. For both models, the distance is about two kilometres. It is worth noting that the selection probability of the NL model remains above zero over a wider distance interval than in the initial model. The alternative *public transport* is complementary. Assuming that no vehicle is available, the probability of selecting the base model for the alternative *public transport* from a distance of more than five kilometres is close to 100%. In the case of Nested 3 model, such a high level of probability of choosing public transport is valid only between five and ten kilometres, depending on the energy expenditure. The greater influence of the energy variable in the NL model can also be seen in the same figure.

The energy variable only affects the *cycling* alternative, so an increase in the probability of the *public transport (PuTr)* alternative, with increasing energy consumption, negatively influences the benefits of the *cycling* alternative.

Car availability mainly affects the decision in the first nest level. Fig. 6b shows the probability of selecting the two *environmentally-friendly* nests at the first decision-making level (top of the figure) and *active transportation* at the second level (at the bottom of Fig. 6b), each without (left) and with (right) individual vehicle availability. Clearly, when a vehicle is not available, 99-100% choose an alternative in the environmentally friendly nest, whereas when it is, this figure is between 50 and 100%. The probability depends mainly on the distance. In the lower decision-making level, the choice between the *active transportation* nest and the *non-active* alternative (in other words, *public transport*), vehicle availability is almost non-existent. These results confirm the logical correctness of the nested approach.

7. Conclusions and final discussion

This paper seeks to understand the mobility patterns of children and teenagers on their travel choice to school and to discuss measures to improve sustainable mobility in a hilly urban environment. It uses a wide variety of models, only three of which are presented here. These models slightly improve the base model, although all offer a very good level of explanation. However, the nested logit structures circumvent the violation of the IIA property in the initial model.

Active transportation is clearly sensitive to different characteristics of the urban environment such as changes in topography. This study identifies that the energy exerted in overcoming differences in level is a significant parameter. More specifically, the energy variable, which describes the effort made by students when cycling to school while considering the topographic differences during the whole trip, improves the results. A failure to take into account the energy expenditure in hilly environments evidently produces misleading results.

In terms of policy implications, this study sheds new light on the analysis of active transportation. One significant measure for promoting AST is the cycling proficiency test for students in Germany, but other alternatives such as "walking buses" should be promoted for younger students. Hilly environments undoubtedly play a role in the choice of a certain transport mode; a similar analysis is therefore recommended for bike-sharing systems to ensure realistic results. This type of analysis could be used to inform city planners about better locations for docking stations in hilly urban environments, taking into account the topographic conditions and making the relocation of bicycles more efficient as a result.

As highlighted in the literature review, a dense and equitable school network positively influences AST. In contrast, a school's closing may affect students' modal choice, as they are forced to change their travel patterns according to the location of their new school, in many cases by using less environmentally friendly modal choices. This discussion needs to be part of a fairer social infrastructure planning ("*Daseinsvorsorge*"). Disadvantages in transport may increase the likelihood of people moving away from sparsely populated areas, thus further increasing their unattractiveness and leading to higher social costs.

It is important for the city to favour transport policies that promote environmentally friendly modal choices for students, and particularly choices that support active transportation to schools. The models show that environmentally and non-environmentally friendly alternatives are being considered when making a decision. AST has traditionally enjoyed positive support in German society, so public authorities should increase the measures to promote it. Special attention should be paid to policies that support female AST, since this paper shows that gender plays a role in the choice of bike for commuting; the reasons for this require further analysis. It is also necessary to provide support for environmentally friendly modes and especially for active transportation, even if children are escorted to school.

This study also opens up many avenues for further research: for example, a comparative study of other areas with important topographic changes, as in this case study; testing other detailed spatial characteristics of the urban environment and school transport policy concepts; the factors underlying gender and AST shares, detailed weather information, or a new survey to understand the changes in mobility choices in the same city in light of the new mobility alternatives. It would help to include other important information from students and their families, such as socio-cultural and economic characteristics. Finally, Pedelecs (pedal electric cycle) are becoming increasingly popular among various sectors of the population in Germany, and their use is being widely promoted by different authorities (RadKULTUR BW, 2019). Given the results, and in light of the new micro-mobility alternatives and citizens' greater environmental concern, the perception and acceptability of e-mobility assistance in hilly environments could be further explored among different population groups such as escorting parents in different areas of Germany.

Credit Authorship contribution statement

Sven Müller: Conceptualization, Methodology, Supervision. Lucia Mejia-Dorantes: Conceptualization, Investigation, Writing - original draft, Writing - review & editing. Elisa Kersten: Data curation, Formal analysis.

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Appendix A. Appendix: Table A1. Comparison of the different discrete choice models tested.

	MNL 1	MNL 2	MNL 3	MNL 4
1:(intercept)	8.868***	8.832***	9.436***	11.374***
	(0.391)	(0.392)	(0.414)	(0.498)