Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 109C (2017) 923–928

Procedia Computer Science

www.elsevier.com/locate/procedia

6th International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications, ABMTRANS 2017

Modeling bicycle traffic in an agent-based transport simulation

Dominik Ziemke[a,*], Simon Metzler[a], Kai Nagel[a]

[a]*Technische Universität Berlin, Transport Systems Planning and Transport Telematics, Salzufer 17-19, 10587 Berlin, Germany*

Abstract

Cycling as an inexpensive, healthy, and efficient mode of transport for everyday traveling is becoming increasingly popular. While many cities are promoting cycling, it is rarely included in transport models and systematic policy evaluation procedures. The purpose of this study is to extend the agent-based transport simulation framework MATSim to take into account attributes of the infrastructure that are relevant for cycling and the decisions that cyclists take. It is shown that meaningful simulation results are obtained for both an illustrative test scenario and a Berlin scenario. Further attributes (e.g. personal or bicycle-related attributes) that have an effect on the behavior of cyclists can be included into the simulation and, by this, into policy evaluation. Based on the exclusive reliance on open data, the approach is transferable to other spatial contexts.

Keywords: cycling, bicycle traffic, transport simulation, agent-based modeling, agent-based simulation

1. Introduction

Cycling as an inexpensive, fast, healthy, quiet, energy-efficient, less land-consuming, and enjoyable mode of transport for everyday traveling is becoming increasingly popular in many regions of the world[12,11,13]. Aware of the societal, environmental, economic, and public health problems that motorized vehicle traffic has contributed to[16] and recognizing the benefits of cycling, cities around the world are promoting the use of the bicycle for everyday travel[8]. As such, the encouragement of cycling is increasingly included into plans for travel behavior change[12]. In Berlin, for instance, the current city-wide modal share of cycling ranges at 13%, with increasing tendency[2]. At the same time, 64% of all trips in Berlin are shorter than 5km, which illustrates the vast growth potential that cycling still has[2].

Next to other policies, the implementation of a good cycling infrastructures appears to be an important prerequisite for supporting further growth in cycling rates[13]. Many projects ranging from local additions of bicycle lanes and improved intersection designs to ambitious larger-scale projects like the *Radschnellweg Ruhr* (an about 100km long bicycle highway that is sought to shift portions of motorized commuter traffic to bicycles in the Ruhr region in Germany) are currently discussed and implemented. While some cities like Copenhagen have gained a strong reputation

* Corresponding author. Tel.: +49-30-314-21383 ; Fax: +49-30-314-26269.
E-mail address: ziemke@vsp.tu-berlin.de

10.1016/j.procs.2017.05.424

as forerunners in promoting cycling, in many other places limited information about the preferences of cyclists have been an obstacle to effective investments in bicycle infrastructure[8].

Transport models are recognized as an important tool to support the effective planning of transport systems and as a means to evaluate proposed policies in a structured and systematic fashion. While transport models are state-of-the-practice in terms of motorized transport as well as public transport, this is not the case for bicycle transport[13]. The purpose of this study is to extend the agent-based transport simulation framework MATSim[9] to take into account attributes of the infrastructure that are relevant for cycling and the decisions that cyclists take. Additionally, it is shown that this also offers the opportunity to account for personal and vehicle-specific attributes that influence the behavior of cyclists.

In a previous study, Dobler and Lämmel[5] developed an approach to obtain more realistic travel speeds for cyclists and pedestrians than provided by "teleportation" estimates, which constitutes the fallback approach in MATSim when a transport mode cannot be modeled explicitly. Plausibly, they argue that an explicit simulation of cycling agents on the network can be left aside as congestion is very rare compared to vehicular traffic. For computing bicycle-specific speeds, they also show how to incorporate attributes of the individual like gender into the computation. Their approach, however, does not take into account the interaction of different modes on the network.

In the current approach, by contrast, the movement of cyclists on the representation of the physical network is explicitly simulated. While not yet included in the current state of development, this offers the opportunity to consider interactions of cyclists and motorists on the same road segment. A concept for explicit traffic modeling under mixed conditions (i.e. different modes on the same infrastructure and their interactions) has recently been added to MATSim[1].

The focus of the current work is to incorporate attributes of the physical world that are of particular importance for cyclists and the decisions cyclists take (e.g. route choice). The intention is to show how to retrieve such attributes from open-data platforms in a structured, reproducible, and regionally transferable fashion and to include them into the simulation and test according sensitivities. Relevant such attributes have been identified in a literature review that is summarized in the following section. Sec. 3 describes the methodology and utilized data. In Sec. 4, results for an illustrative scenario as well as initial results for a real-world application of the approach to Berlin are presented. In Sec. 5, the methodology, the findings, and the potential of the approach are discussed and an outlook on potential further steps is given.

2. Literature Review

Choices of cyclists, in particular cyclists' route choice, have been surveyed in various studies, mostly in terms of stated preference analyses[3,13,16,11], but recently also in terms of GPS-based revealed preference analyses[12,8]. Most studies report that their results are partially in agreement with findings from previous studies, while other findings stand in contradiction[8,13,12].

Travel time and route length have generally been found to be important factors in route selection[8,16]. Studies also largely agree that cyclist tend to avoid **slopes**[12,8,11]. Menghini et al.[12] also find that average slopes – in contrast to maximum slopes – have no effect, which seems quite plausible. Sener et al.[16] and Hood et al.[8] find that steep hills were disfavored more by women and commuters. There is also agreement that cyclists strongly prefer a **continuous cycling infrastructure**[16,11]. Hood et al.[8] specifically find that cyclists prefer bicycle lanes over other types of cycling facilities. Menghini et al.[12] state that their results underline the importance of direct and marked routes for cyclists, which is confirmed by other studies[10]. The finding that shared-lane bicycle routes are slightly preferred to bicycle lanes by Sener et al.[16] seems to be attributable to differences in specific designs of these infrastructures in different regions rather than to a general dislike of the latter facilities. Studies also agree that **pavement surface conditions and riding smoothness** are important factors[10,7,13]. Cyclists also generally try to avoid signal-controlled **junctions**[12,16,13]. Additionally, some stated-preference studies find the type of **parking along cycling facilities**[16,11] and existence of **bus stops**[11] to be influential. Next to travel time, Sener et al.[16] find **motorized traffic volumes** to be one of the most important attributes in bicycle route choice. Li et al.[11] also find motorized traffic as an important factor, which stands in contradiction to Hood et al.[8] and Milakis and Athanasopoulos[13].

Given that the quality of the surface is relevant for routing, it is important to know how cyclists evaluate different road surface types. Hölzel et al.[7] – using a one-degree-of-freedom pendulum attached to a bicycle to quantify rolling resistance – find that asphalt is associated with the lowest rolling resistance and level of vibrations, followed by concrete slabs and self-binding gravel. The highest rolling resistance is measured for cobblestones. Its quantitative value differs significantly from that of the three other surface materials. In a similar approach, Bíl et al.[4] – using an accelerometer attached to a bicycle – find old cobblestone pavements to be associated with significantly higher vibrations and, thus, rolling resistance than other types of pavement including asphalt (new, worn, and uneven), concrete (uneven and interlocking) and unpaved roads. Ayachi et al.[3], based on a stated preference survey, confirm that asphalt roads and concrete roads are more comfortable than other types of roads.

3. Methodology

To simulate bicycle traffic, MATSim[9], an agent-based demand adaptation and traffic assignment model, is used. In MATSim, each synthetic person (*agent*) has one or more *plans*. A plan is a chain of activities (e.g. *home–work–shop–home*), including their locations and end times. Activities at different locations are connected by transport. The iterative MATSim loop consists of the following important elements: In the *network loading* (also called *mobility simulation*), all selected plans are simultaneously executed in a synthetic reality. Next, all executed plans are *scored*, e.g. by a utility function, based on their actual performance. Finally, all synthetic persons are allowed to *replan*, e.g. by switching to another plan in their memory, or by generating a new plan, e.g. using other routes or other modes of transport. This loop is iterated until the system is sufficiently "relaxed" as determined, for instance, based on the development of agents' plan scores.

Data. In general, a MATSim network consists of nodes and links. Nodes store coordinates, while links have start and end nodes, free-flow speed, link length, flow capacity, storage capacity, and allowed modes. OpenStreetMap (OSM)[15] is the typical main data source for MATSim, especially for the creation of networks. OSM also constitutes the main data source of this study, where additional attributes used to describe properties of the infrastructure, which are relevant for the decisions of cyclist, are included. OSM objects have tags, which are key-value pairs. Ways which represent roads can, amongst others, have the tags `highway` and `cycleway`. Additional information like bicycle-specific restrictions can be captured by the tag `bicycle`. As such, a main road with a bicycle lane will be tagged as `highway=?` and `cycleway=lane`. In case the cycling infrastructure is located on the sidewalk, the road will have the tag `cycleway=track`. A bicycle track away from roads for motorized traffic is tagged as `highway=cycleway`.

The attribute `smoothness` represents an evaluation of the surface, ranging from `excellent` to `impassable`. It constitutes the information that is required to evaluate *riding comfort* (cf. Sec. 2). However, only 12% of all links in Berlin carry that attribute. Therefore, it does currently not seem to be reasonable to base a model on this attribute. As a proxy, the attribute `surface`, which reflects the type of pavement surface, can be used. In Berlin, 58% of all links are provided with a `surface` tag. Additionally, some `highway` types are assigned with defaults (e.g. `primary` highways are assumed to be `asphalt` roads), such that the surface type of most links can be identified by OSM.

As pointed out in Sec. 2, *slopes* are another important determinant of cyclist's route choice. Because of the absence of such information in OSM, a digital elevation model (DEM) is used. Broadly, there are two types of DEMs: (1) Digital surface models (DSM) are mostly created based on satellite imaging and reflect the surface of the earth including all objects on it, e.g. buildings and trees. Some DSMs like SRTM (Shuttle Radar Topography Mission), provided by NASA, are openly available. As DSMs are, however, not able to capture the surface of the bare ground, these models are not suited for the task at hand as their use would create unrealistic slopes, e.g. in the vicinity of larger buildings. (2) Digital terrain models (DTM), by contrast, represent the ground surface of the earth without any objects on it. They are created by photogrammetric measurement using aerial picturing and laser scanning, but are rarely openly available. There are, however, algorithms which are able to compute a DTM from a high resolution DSM. In this study, EU-DEM (European Digital Elevation Model)[6] is used, which is a hybrid of SRTM and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer, also provided by NASA) data. By this combination, a high number of artifacts could be removed. EU-DEM is free to download and has a resolution of 25m. A test against SRTM data confirmed that unrealistic slopes due to buildings are significantly decreased in Berlin.

Adaptions to simulate bicycle traffic. A `BicycleOsmNetworkReader` was written to create a MATSim network suited to simulate bicycle traffic. It extends the default network generation procedure in two ways: (1) Besides OSM, the EU-DEM elevation model is used, which provides land elevations in the GeoTiff format. (2) Next to the MATSim network, an object attributes file holding additional bike-specific attributes is created*. For each node, its elevation is queried from the EU-DEM model. In conjunction with the link length, the average link slope can be computed. This information is stored in the object attributes file. Based on information of OSM, values of the other additional attributes like `highway` type, `cycleway` type, and `surface` are stored in that file as well. Using highway type, surface, and slope, the free speeds for bicycles of each link are computed as follows: First, the minimum of the speeds according to the highway type and surface as outlined in Tables 1 and 2 are determined. This speed is then increased or decreased by a factor depending on the link's slope. Ensuring that a link speed is never assigned lower than a defined minimum of 4km/h, the resulting speed is stored in the network file. Via relatable identifiers, information from the network file and the attributes file can be matched for the computation of the utility function.

Table 1: Speed according to surface type (not all values shown)

Surface	Speed [km/h]
`asphalt`	18
`concrete_plates`	16
`compressed`	14
`gravel`	10
`cobblestone`	9

Table 2: Speed according to highway type (not all values shown)

Highway type	Speed [km/h]
`primary`	18
`residential`	18
`track`	16
`pedestrian` + `bicycle=yes/designated`	15
`pedestrian`	8

The created network consists of two parts: (1) The first part is dense and includes most links open to cyclists. It covers the center of Berlin (approximately the area encircled by the *S-Bahn-Ring* (circular commuter rail line)) and consists of 52,618 links and 26,534 nodes. (2) The second part has a coarser resolution and contains larger roads that can be traveled by cars. Via relatable identifiers, links that are contained in both parts of the networks can be matched, which is relevant for approaches that consider dependencies of cars and bicycles that travel on the same infrastructure.

In order to take into account properties of the route that are of particular relevance for cyclists (as discussed in Sec. 2), but which do not affect travel speeds (as they are already considered by computing bicycle-specific speeds as described above), the standard MATSim utility function[14] is extended. In addition to travel time, an *infrastructure* and a *comfort* component are taken into account. As such, the disutility of traveling leg q by bicycle is given as

$$S_{trav,q} = C_{bicycle} + \beta_{trav,bicycle} \cdot t_{trav,q} + \sum_{a \in q} \left(\beta_{inf(a),bicycle} + \beta_{comfort(a),bicycle} \right) \cdot \ell_a \tag{1}$$

where $C_{bicycle}$ is the bicycle-specific constant, $\beta_{trav,bicycle}$ is the marginal utility of time spent traveling by bicycle, $t_{trav,q}$ is the travel time on leg q, $\beta_{inf(a),bicycle}$ is the marginal utility of distance on the infrastructure type of link a, $\beta_{comfort(a),bicycle}$ is the marginal utility of distance on link a at a certain level of comfort, and ℓ_a is the length of link a.

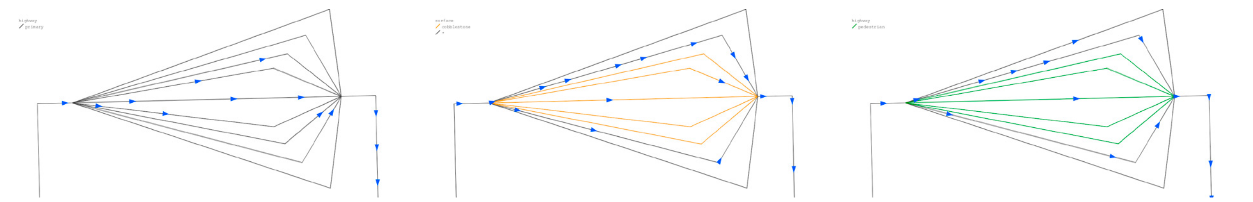
The parameter $\beta_{inf(q),bicycle}$ is intended to pick up aspects of *continuous and well-marked cycling infrastructure* (cf. Sec. 2). Its value ranges from 0 for dedicated cycleways down to $-0.019/m$ for unprotected cycling on trunk roads. $\beta_{comfort(a),bicycle}$ is intended to reflect *pavement conditions and riding smoothness* (cf. Sec. 2). The smoother the surface, the higher the utility value. Values range from 0 down to $-0.14/m$. The marginal utility of time spent traveling was set to $-1/sec$. While the relation among these values is inspired by the findings mentioned in Sec. 2, their concrete values have been chosen based on own plausibility checks (cf. Sec. 4).

4. Results

Illustrative scenario. Before results are applied to the real-world network representation, the method is tested in a small illustrative scenario†, a modification of the *equil scenario*[9], which contains nine alternative, identical routes (cf. Fig. 1). For testing, the equil scenario has been modified such that the length of the routes increase from the central route to the outer routes: The central route has a lengths of 2,400m between the nodes where the nine alternative

* The procedure of creating an additional file for additional attributes is not required after latest MATSim updates. Now, it is possible to set arbitrary additional attributes directly in the network file. The approach described in this study will be adapted to the new feature soon.

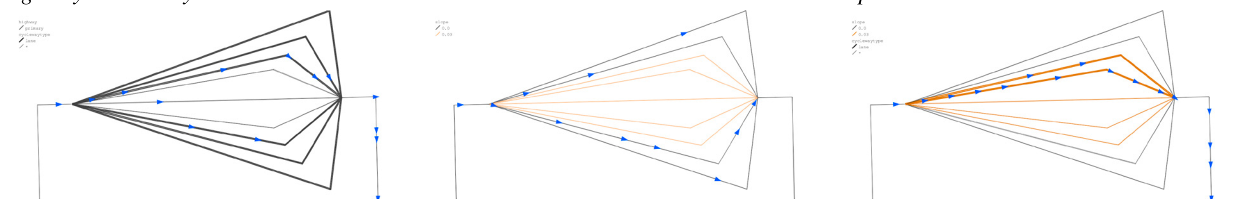
† This scenario can be run by invoking `RunBicycleExample`; cf. `http://matsim.org/javadoc` → `bicycle` → `RunBicycleExample`.



(a) Base Case: All links designated as *highway = Primary*

(b) Five central links with cobblestones

(c) Five central links designated as *highway = pedestrian*



(d) Six outer links have a bicycle lane (i.e. designated as *cycleway = lane*)

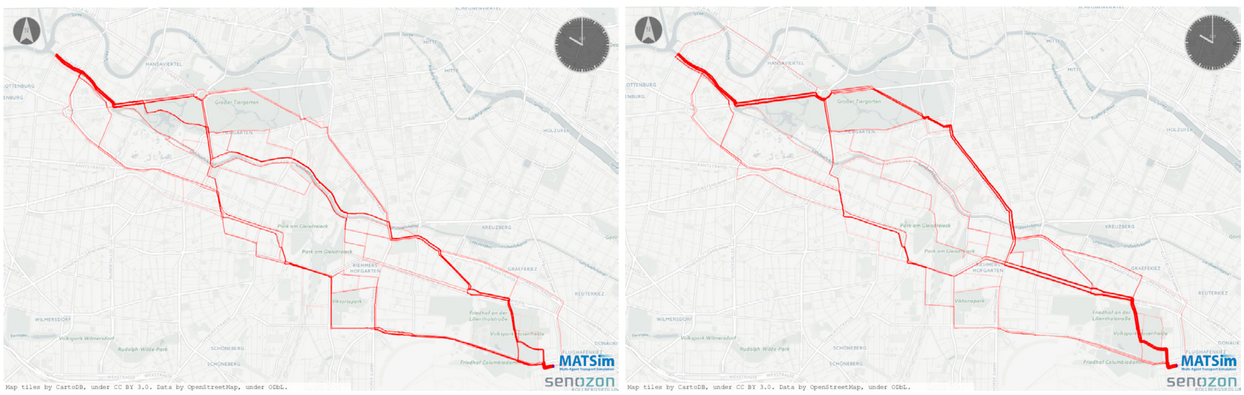
(e) Five central links have a slope of 3%

(f) Five central links have a slope of 3%. Two upper ones of these have a bicycle lane

Fig. 1: Results of illustrative scenario

routes fork and merge again, while the other routes have – ascending toward the outermost routes – lengths of 2,500m, 2,600m, 2,800m, and 3,200m. All links are characterized as primary roads. 20 agents travel from the left to the right. The only choice they can make is selecting one of the nine routes. As the router includes a random component to create some variation, agents may also choose a non-optimal route, while the probability to do so decreases with the extent to which a route deviates from the optimum.

Fig. 1a represents the base case where all links have identical properties (except link lengths as described above). Expectedly, agents choose the more central routes because of their lower distances. In Fig. 1b, the five central links are converted into roads that are paved with cobblestones. As described Sec. 3, this reduces travel speeds and comfort such that agents tend to divert to outer routes to avoid traveling on cobblestones, but, in exchange, cover longer distances. Next, the five central links are designated as pedestrian zones, where cyclists can only travel with reduced speeds. Also their infrastructure utility is somewhat lower (cf. Fig. 1c). Again, agents rather accept longer distances. In Fig. 1d agents divert to outer routes because these routes are equipped with bicycle lanes which increases agents' infrastructure utility. Expectedly, agents avoid slopes (cf. Fig. 1e). Fig. 1f shows a tradeoff situation between link length, slope, and infrastructure (bicycle lanes).



(a) Based on travel times only

(b) Based on travel times, infrastructure, and comfort

Fig. 2: Route choice in a real-world scenario (Berlin)

Real-world scenario. Fig. 2 illustrates the routes chosen by 50 agents making trips by bicycle from Neukölln (lower right of the picture) to the main campus of TU Berlin. For Fig. 2a, the marginal utilities for infrastructure and comfort are set to zero, such that only travel times are taken into account. It can be seen that many agents use the central route (along the Landwehrkanal), which is a major road without any dedicated cycling infrastructure. In Fig. 2b, by contrast, agents avoid this route and divert to smaller roads with cycling infrastructure and to paved paths of Tiergarten, a vast park in the center of the city, which illustrates that agents take various properties of routes into account in the intended way. Further experiments show that the addition bicycle lanes to all primary and secondary roads (*Hauptverkehrsstraßen*), a topic of current public debate in Berlin, would lead to discernible savings in cyclists' travel times. Upcoming calibration of model parameters will allow to measure the policy's economic benefits.

5. Discussion and outlook

It has been shown how attributes of the infrastructure that have an impact on the behavior of cyclists can be included into MATSim by adaptions in the network creation and the utility function. Considered attributes encompass *travel time*, *slopes*, *cycling infrastructure* and *pavement surface* (cf. Sec. 2). As cycling agents are, in contrast to earlier approaches, simulated on the network, the approach can also be extended to account for *interaction between cyclists and motorists*, which may – according to findings presented in Sec. 2 – further improve modeling the behavior of cyclists. Similar to the already included attributes also *bus stops*, *parking facilites* and *junctions* can be included if desired. More importantly, researchers found cycling behavior to be highly dependent on personal and other attributes, e.g. women tend to avoid slopes more than men and commuters stick more strongly to the shortest route (cf. Sec. 2). Both phenomena can be modeled in MATSim, the former by assigning demographics to agents and making decisions dependent on them, the latter by observing the sequence of activities in the daily plans of agents and making decisions dependent on subsequent activities (e.g. work vs. leisure activities). The presented approach should be seen as a demonstration of the capabilities required to implement these aspects. Marginal utilities have been chosen arbitrarily such that they could withstand plausibility checks. Marginal rates of substitution (MRS) between different utility components like they have been examined by some authors[8] could be applied to adjust these values. As only openly accessible input data have been used, the approach is reproducible and easy to transfer to other spatial context.

References

1. Agarwal, A., Zilske, M., Rao, K., and Nagel, K. An elegant and computationally efficient approach for heterogeneous traffic modelling using agent based simulation. *Procedia Computer Science 52*, C (2015), 962–967.
2. Ahrens, G.-A., Liesske, F., Wittwer, R., Hubrich, S., and Wittig, S. Tabellenbericht zum Forschungsprojekt 'Mobilität in Städten – SrV 2013' in Berlin. `http://www.stadtentwicklung.berlin.de/verkehr/politik_planung/zahlen_fakten/mobilitaet_2013/`, 2014.
3. Ayachi, F., Dorey, J., and Guastavino, C. Identifying factors of bicycle comfort: An online survey with enthusiast cyclists. *Applied Ergonomics 46* (2015), 124–136.
4. Bíl, M., Andrášik, R., and Kubuček, J. How comfortable are your cycling tracks? A new method for objective bicycle vibration measurement. *Transportation Research Part C 56* (2015), 415–425.
5. Dobler, C., and Lämmel, G. The multi-modal contribution. In Horni et al.[9], ch. 21.
6. European Digital Elevation Model, accessed 30 Jan 2017. `http://data.eox.at/eudem`.
7. Hölzel, C., Höchtl., F., and Sener, V. Cycling comfort on different road surfaces. *Procedia Engineering 34* (2012), 479–484.
8. Hood, J., Sall, E., and Charlton, B. A GPS-based bicycle route choice model for San Francisco, California. *Transportation Letters*, 3 (2011), 63–75.
9. Horni, A., Nagel, K., and Axhausen, K. W., Eds. *The Multi-Agent Transport Simulation MATSim*. Ubiquity, London, 2016.
10. Landis, B., Vattikuti, V., and Brannick, M. Real-time human perceptions: Toward a bicycle level of service. *Transportation Research Record*, 1578 (1997), 119–126.
11. Li, Z., Wang, W., Liu, P., and Ragland, D. Physical environments influencing bicyclists perception of comfort on separated and on-street bicycle facilities. *Transportation Research Part D 17* (2012), 256–261.
12. Menghini, G., Carrasco, N., Schüssler, N., and Axhausen, K. Route choice of cyclists in Zurich. *Transportation Research Part A 44* (2009), 754–765.
13. Milakis, D., and Athanasopoulos, K. What about people in cycle network planning? Applying participative multicriteria GIS analysis in the case of the Athens metropolitan cycle network. *Journal of Transport Geography 35* (2014), 120–129.
14. Nagel, K., Kickhöfer, B., Horni, A., and Charypar, D. A closer look at scoring. In Horni et al.[9], ch. 3.
15. OpenStreetMap, accessed 30 Jan 2017. `www.openstreetmap.org`.
16. Sener, I., Eluru, N., and Bhat, C. An analysis of bicycle route choice preferences in Texas, US. *Transportation 36* (2009), 511–539.