Journal of Transport Geography 86 (2020) 102740

Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Modeling commuter modal shift from car trips to cycling: Scenario construction and outcomes for Stockholm, Sweden

Magnus Strömgren[a,*], Peter Schantz[b], Johan Nilsson Sommar[c], Wasif Raza[c], Anders Markstedt[d], Bertil Forsberg[c]

[a] Department of Geography, Umeå University, Umeå, Sweden
[b] Research Unit for Movement, Health and Environment, The Swedish School of Sport and Health Sciences, GIH, Stockholm, Sweden
[c] Division of Sustainable Health, Department of Public Health and Clinical Medicine, Umeå University, Umeå, Sweden
[d] WSP Civils, Stockholm, Sweden

ARTICLE INFO

Keywords:
Cycling
Modal shift
Commuting

ABSTRACT

This article presents the construction and outcomes of scenarios modeling commuter modal shift from car trips to cycling in the metropolitan region of Stockholm, the capital of Sweden. Building and improving upon previous studies in terms of both methodological approach and degree of spatial resolution of the modeling output, we examine scenarios where car commuters able to reach their workplace within 30 and 50 minutes of cycling shift commuting mode. Overall, car–bicycle modal shift figures were 31.6% and 48.7%, respectively. However, there were considerable geographical differences. While a substantial number of new bicycle commuters appeared in all five macro-level subdivisions of the study area, relative modal shift was by far the highest among car commuters living in the Inner City and its immediate surroundings.

1. Introduction

There is overwhelming evidence that regular physical activity has important and wide-ranging health benefits including reduced risk of chronic disease, and physical inactivity is mentioned as perhaps the most important public health problem of the 21st century (Blair, 2009). More specifically, active transport in the form of bicycle commuting has been shown to reduce the incidence of several diseases (e.g., Celis-Morales et al., 2017) and premature all-cause mortality (Andersen et al., 2000; Matthews et al., 2007). At the same time, the direct effects of current air pollution emissions is a significant health problem (Brauer et al., 2012), and air pollution-driven climate change constitutes a major global threat (McMichael et al., 2012). Thus, there are substantial potential health benefits of increased active transportation such as cycling instead of traveling by car. The expected results of such modal shifts can be estimated by implementing scenarios of potential change, which in turn can be subject to health impact assessment (HIA). For such scenario evaluations, the validity of the performed HIA will largely be influenced by the quality of the constructed scenarios.

The majority of previous HIA studies have been based on future hypothetical transport scenarios of increased cycling, with exceptions including Otero et al. (2018), Rojas-Rueda et al. (2011) and Woodcock et al. (2014) who evaluated the current benefit of increased cycling due to a public bicycle-sharing program and Dhondt et al. (2013) who evaluated the impact of a policy change leading to increased fuel price on travel. Studies estimating health impacts of hypothetical transport scenarios have constructed modal shifts from current transport by car or public transport to cycling with distance or trip duration as criterion for which travels to shift. The majority of these studies evaluated the change in transport pattern within the whole population, with exceptions including Maizlish et al. (2013) and Woodcock et al. (2009 and 2013) who investigated a sub-population for the modal shift from motorized transport to active transport. Typically, general assumptions about average traveling speed, distance and trip duration were used to estimate the current amount of cycling, walking, travel by public transport and driving (de Hartog et al., 2010; Holm et al., 2012; Lindsay et al., 2011; Rabl and de Nazelle, 2012; Rojas-Rueda et al., 2011; Rojas-Rueda et al., 2012; Rojas-Rueda et al., 2013). Thereafter, future transport scenarios were created transferring trips within a certain distance or with a certain duration to cycling.

In this article, we aim to model commuter modal shift from car trips to cycling in a way that builds and improves upon previous studies in terms of both methodological approach and degree of spatial resolution of the modeling outcomes. Previous endeavors in this field have tended to rely on low-resolution data sources and general assumptions, limiting micro-level influences (such as the effect of sex and age) in both

* Corresponding author.
E-mail address: magnus.stromgren@umu.se (M. Strömgren).

https://doi.org/10.1016/j.jtrangeo.2020.102740
Received 28 June 2019; Received in revised form 2 May 2020
Available online 30 May 2020
0966-6923/ © 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/BY-NC-ND/4.0/).

scenario construction and outcomes. In contrast to previous studies employing average estimates regarding cycling traveling duration and distances, we take the role of individual demographic attributes into account, and are also able to present results with a high level of geographical detail. Our study area is the metropolitan region of Stockholm, the capital of Sweden.

2. Methods

In this section, we present our modeling approach. First, the study area and the way it has been subdivided is described. Second, we account for the scenario implementation. In constructing our scenarios, we make use of two key resources: (1) The individual-level, georeferenced database ASTRID and (2) the transport model LuTRANS. By means of the ASTRID database, we are able to depart from a study population with demographic attributes that is georeferenced in terms of location of home and workplace. We then employ the information in LuTRANS to impute travel modes based on high-resolution probability distributions of commuting patterns. Furthermore, we utilize empirically validated equations of the cycling duration–distance relationship incorporating sex and age, as well as a cycling route network selected as the most appropriate based on the observed behavior of existing cyclists.

Two different scenarios of modal shift from car to bicycle commuting were constructed and evaluated for our study area of Stockholm, Sweden. In the first scenario, car commuters that can travel to their workplace within 30 min of cycling shifted commuting mode. In the second, more ambitious scenario, the commuting mode was shifted for car commuters that can reach their workplace within 50 min of cycling. Previous studies of existing commuter cycling durations in metropolitan Stockholm have shown that the median cycling durations for male single-mode cyclists is about 30 min (Stigell and Schantz, 2015); and that about 90% of all durations are below 50 min (Peter Schantz; personal communication). By implementing both a 30 and a 50 min scenario, we are able to examine outcomes in both a plausible and a quite maximal scenario.

2.1. Study area

The geographical scope of our modeled scenarios is limited to Stockholm County, which comprises 26 of Sweden's 290 municipalities (one of which is Stockholm City – the actual municipality of Stockholm). Since we are interested in not only estimating the overall degree of commuter modal shift from car to bicycle, but also where in the city increased cycling would occur, the geographical subdivision of the study area becomes a pivotal methodological issue. Given the resources and data utilized and the deployed workflow, the smallest spatial “building block” available in creating a subdivision is the modified version of the Statistics Sweden SAMS areas used in LuTRANS ($N = 1240$). While scenario results will be presented for these micro-level geographical units, they are also aggregated to larger, macro-level districts in order to provide a more general picture of spatial scenario outcomes.

In creating a more generalized subdivision, we take departure in the Statistics Sweden delimitation and subdivision of the Stockholm metropolitan area (Statistics Statistics Sweden, 2015). The definition, most recently updated in 2005, is largely constructed based on commuting and migration statistics. The geographical extent of the Stockholm metropolitan area corresponds to the county boundaries. There are five internal subdivisions, one of which is the Inner City (“Inre staden”), a part of Stockholm City that comprises the central business district (CBD) and also contains a substantial residential population. The remainder of Stockholm City is subdivided into Southern City (“Söderort”) and Western City (“Västerort”) based on location relative to the Inner City, while the remaining municipalities make up the Northern and Southern suburban municipalities. Parts of the county outside Stockholm City are, however, located close to and also well integrated with the Inner City both in terms of the urban morphology and in a functional respect. For instance, the officially delimited urban locality (“tätort”) of Stockholm almost fully encompasses the two northern municipalities of Solna and Sundbyberg.

For this reason, we created bespoke subdivisions of the study area (Fig. 1), where the Western and Southern City areas are merged with adjacent municipalities – nearby municipalities at least partially located within five kilometers, as the crow flies, from the geometric centroid of the Inner City. Consequently, scenario outcomes are presented using the following five geographical subdivisions: (1) Inner City (“Inre staden”), a part of Stockholm City largely corresponding to the CBD; (2) Northern suburbs, comprising Western City and the municipalities of Sundbyberg, Solna, Danderyd and Lidingö; (3) Southern suburbs, made up of Southern City plus the municipality of Nacka; as well as (4) Northern and (5) Southern County, encompassing the remaining 11 and 9 municipalities, respectively. In the case of Northern and Southern County, parts of these regions can be regarded as remote suburbs, or major cities in their own right, while other areas exhibit a more rural character.

2.2. Scenario implementation

The identification of current commuting patterns within the study area was achieved by synthesizing and leveraging the potential of two separate resources: ASTRID and LuTRANS. ASTRID is a georeferenced database with individual-level demographic and socio-economic data for the entire Swedish population (Stjernström, 2011). LuTRANS is a regional transport model, developed for purposes of evaluating different transport scenarios in the Stockholm region. LuTRANS models travel modes and routes based on travel survey data and traffic counts (Jonsson et al., 2011; WSP, 2018). By using the individual-level characteristics in ASTRID in conjunction with information in LuTRANS concerning commuting, we established a realistic study population for our scenarios of commuter modal shift from car trips to cycling.

LuTRANS contains information about the distribution of commuting modes between homes and workplaces, based on a subdivision of Stockholm County into smaller units, or zones. This geographical subdivision departs from – and partly corresponds to – the delimitation of Sweden by Statistics Sweden into so-called SAMS areas, homogeneous geographic divisions roughly equivalent to, for instance, census blocks in the U.S. However, the subdivision used in LuTRANS has a higher degree of spatial resolution; Stockholm County comprises 1240 such zones, compared to the 889 “normal” SAMS units. For each relevant combination of home and work zone, two probability distributions are provided: one for households with access to a car, and one for households without such access. Using ASTRID data from the year 2010, we retrieved the persons aged 16 years and older that were (1) officially classified as employed and (2) had both their residence and workplace located within Stockholm County. This selection corresponded to 929,472 individuals organized in 686,290 families (based on marriage or cohabitation with joint children in the household). Each household was then assigned as either with or without car access, based on the car registry information included in the ASTRID database. A geographic information system (GIS) was subsequently utilized, in order to assign the individual's residential and workplace coordinates in ASTRID to the corresponding LuTRANS home and work zones.

Since we know that certain employed persons have access to a car provided by their employer – and given that this situation is likely to be especially prominent in big cities – the car access statistics in LuTRANS was compared to that of ASTRID. The comparison showed that while the share of persons with access to a car in LuTRANS was 76%, the corresponding figure in ASTRID was only 63%. We therefore calculated how many persons per residential zone that according to LuTRANS lacked car access, and – giving precedence to households with the highest individual yearly work income – assigned such access to the individuals in ASTRID.

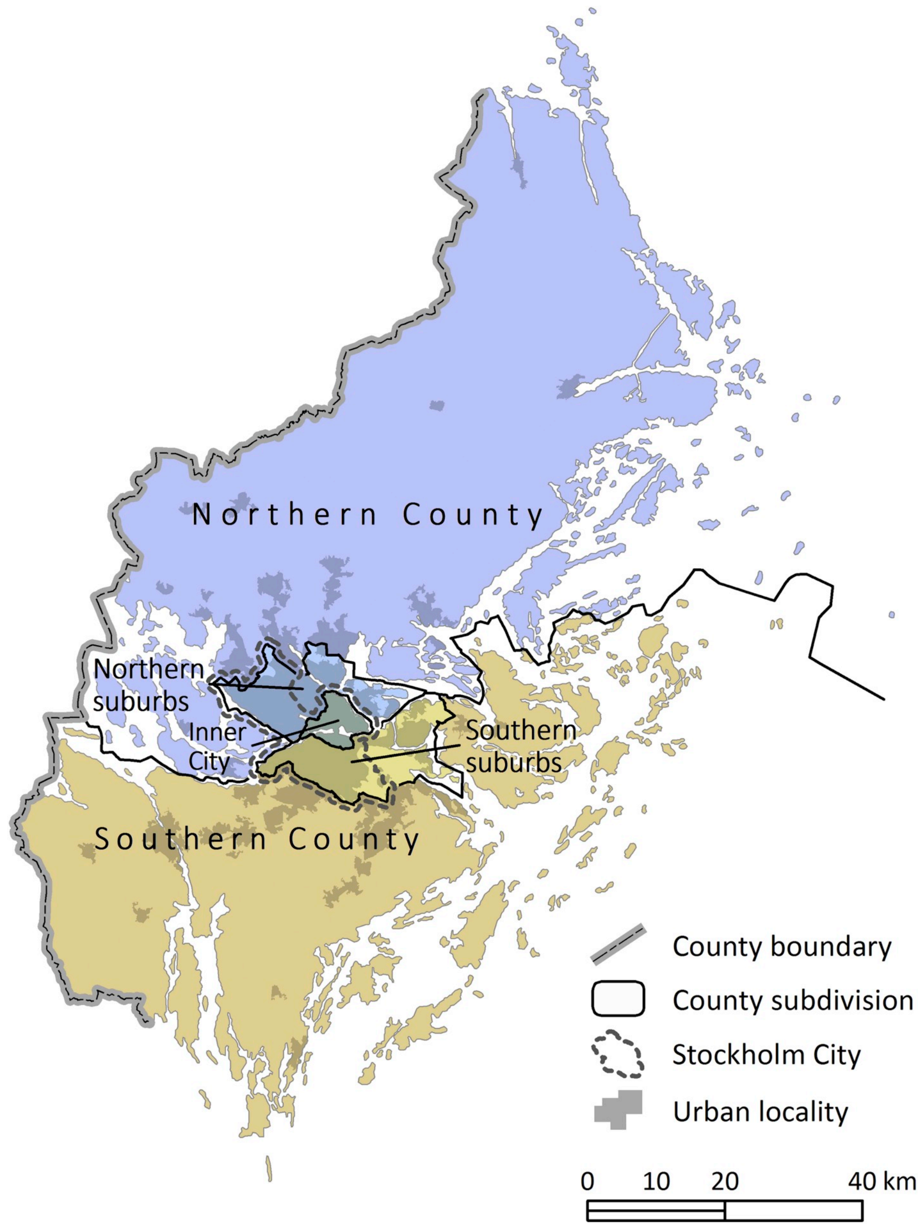

Fig. 1. The study area, Stockholm County, with macro-level geographical subdivisions.

We utilized a simulation procedure to allocate each person one of five commuting modes: by (1) car as driver, (2) car as passenger, (3) public transport, (4) walking or (5) cycling. This was done by random number draws evaluated against the zone pair- and car access-based commuting mode probability distributions. Although such a stochastic imputation method is associated with uncertainty at more detailed levels, we assume that the aggregate results will provide an adequate representation of the overall commuting population. In the two implemented scenarios, all persons designated as car drivers were potentially eligible for a modal shift to cycling. However, whether or not such a modal shift takes place is dependent on (1) how far a certain person with a given sex and age can cycle within a specific time period and (2) the same person's cycling route distance between place of residence and work. Thus, in order to select the individuals that normally drive to their workplaces, but have distances to the destinations that could be cycled in 30 and 50 min, both the cycling duration–distance relationship and cycling route distances needed to be estimated. Therefore, we developed empirically validated equations of the cycling duration–distance relationship incorporating sex and age, which we applied to our study population, as well as utilized a cycling route network selected as the most appropriate based on the observed behavior of existing cyclists (see further Sections 2.3 and 2.4, respectively).

Due to occasional missing information concerning commuting probability distributions and/or cycling route distances, the final research population for which the scenarios are implemented amounts to 923,970 rather than 929,472 persons, a dropout of 5502 individuals (0.6%). Using the duration–distance relationship equations, we then calculated how far each car commuter would be able to travel by cycling in 30 and 50 min. These potential distances were then compared to the cycling route distances between home and workplace. If the calculated potential distance equaled or exceeded the shortest route cycling distance, a modal shift was recorded. Car passengers affected by modal shift of the driver were switched to using public transportation. In this context, it should also be noted that our research population includes a small subset of people below 20 (15,786 persons; 1.7%) and above 65 (27,199 persons; 2.9%) years of age, for which the duration–distance relationship equations have not been fully calibrated.

Finally, the results were summarized for subsequent description and analysis. The aggregated output, comprising summations by sex and age, initial and eventual new commuting mode, cycling duration and distance, as well as micro- and macro-level geographical units, forms the basis for this article's presentation of general and spatial scenario outcomes. Spatial scenario outcomes are displayed using tables and graphs (macro-level results) and maps (micro-level results). Micro-level statistics are available and presented for 1008 out of 1240 geographical units. There are 66 zones that were uninhabited, or ended up with no residents as a result of dropout. In addition, we chose not to display results for the 166 zones where the total study population amounted to less than 100 persons.

2.3. Estimating the cycling duration–distance relationship

The methodology to obtain the duration–distance relationship involved several steps, described in more detail by Schantz et al. (2018); see also Schantz et al. (2019a, 2019b). The first step was to describe the relation between duration and cycling speed in a sample of 1683 existing bicycle commuters in Stockholm, Sweden. These participants were all recruited through advertisements in newspapers (Stigell and Schantz, 2015). The participants drew their own normal bicycle-commuting route to work on a map, and its distance was measured using a digital curvimetric distance measurement device (Schantz and Stigell, 2009). Due to a systematic over-reporting of the time used when trip durations were stated with the last digits being 0 and 5 (Schantz, 2017), the relation between cycling duration and distance covered was based on those subjects that used other last digits in reporting their durations. In this way, linear duration–distance relations were established for each sex; for women: distance (D, kilometers) = 0.268 km/min × time (T, minutes), and for men: distance (D, kilometers) = 0.347 km/min × time (T, minutes).

The next step of analysis aimed at adapting the relationship noted among the studied bicycle commuters to the general population, taking into account body and bicycle weight as well as maximal aerobic power. The basis for this analysis was the possibility that the studied bicycle commuters could be a subgroup within the population with a higher maximal aerobic power, as well as a lower body mass index (BMI), than those present in the general Swedish population, in turn leading to overestimated levels of cycling speed. The need for this analysis was also related to the fact that the maximal aerobic power is dependent on both sex and age, which necessitated extrapolations to ages other than those dominant in the advertisement-recruited groups of commuting cyclists (Schantz et al., 2018, 2019a, 2019b; Stigell and Schantz, 2015). For this purpose, we estimated the maximal aerobic power of the bicycle commuters and compared it with population data attained in the same fashion. We then noted lower levels of maximal aerobic power in the population groups. We compensated for that, as well as the body weight of different age groups. It resulted in the following equation predicting the distance (D, kilometers) based on duration (T, minutes) and age (A, years) for males cycling in the age span of 20–65 years:

$$D = T \times 0.347\ \text{kilometers/minute} \times 0.717 \times (1.612 - 0.0142 \times A) \qquad (1)$$

where the factor 0.717 reflects the bicycle commuter to population effect. For females in the same age span, the equation is:

$$D = T \times 0.268\ \text{kilometers/minute} \times 0.752 \times (1.532 - 0.0123 \times A) \qquad (2)$$

where 0.752 reflects the bicycle commuter to population effect.

2.4. Modeling the cycling route network

A specific route network was used for calculating the route distances for cyclists. Two modeling options existed in LuTRANS: (1) a route choice based on the shortest route distance, or (2) a route choice based on the assumption that certain route attributes are preferred by cyclists and decisive for their route choices (Berglund and Engelson, 2014). The route distances between given origin and destination points differed between these models, and it was therefore of importance to evaluate which model to use. To that end, we made use of 1102 individual cycling commuters' origin and destination points based on their home and workplace addresses, which were geocoded using GIS by Metria AB (Gävle, Sweden). The same individuals had drawn their individual cycling commuting route on a map, and their route distances had thereafter been measured with a digital curvimetric distance measurement device (Schantz and Stigell, 2009). In order to validate the geocoding, the straight-line distances between home and workplace were measured with a ruler. These distances were used to validate the geocoding of the concerned home and workplace addresses. An almost complete concordance between map-based and GIS-based measured straight-line distances was noted. That created a basis for comparisons between actual map-based route distances and the GIS-calculated distances with LuTRANS using the same origins and destinations. It was then noted that the shortest route distances were those that most closely matched the actual route distances based on the commuters' drawn routes. The average deviation was less than 5% for women and less than 1% for men. The GIS modeling of route distances of car drivers switching to cycling was therefore based on the shortest route algorithm in LuTRANS.

3. Results

3.1. Descriptives

The calculated baseline characteristics of our study population are presented in Table 1. Almost eight out of ten individuals commute to work by either driving a car or using public transport. Of the 38% making up the car commuters, the average age is 43 years; 48% are women. The 38% using public transport (subway, commuter train, and/or bus) are on average slightly younger (40 years) and more evenly distributed by sex (51% women). With the exception of traveling to work as a car passenger, cycling is the least common mode of commuting. About 6% of the population use a bicycle for their commute. Applying eqs. (1) and (2), we find that the one-way cycling route averages 4.5 km in length; the standard deviation is 3.7 km. In terms of trip duration, the corresponding figures are 20.2 and 17.1 min, respectively. Concerning demographic characteristics, 53% of the cyclists are female and the average age is 41 years.

When the study population is summarized in relation to place of residence, based on our bespoke study area classification with five geographical subdivisions (Fig. 1), it turns out that each subdivision contains about one fifth of the population (Table 2). Taking this geographical subdivision of Stockholm into account, considerable differences in commuting patterns emerges. In general, the more peripheral the place of residence, the higher is the reliance on car as a mode of commuting. While in Northern and Southern County about 50% commute by car, the corresponding figures are substantially lower in the remainder of the study area. In the Northern and Southern suburbs, the corresponding figures are 35% and 30%, respectively. In the Inner City, less than one fifth of the population drives a car to work. The commuting patterns for public transport, walking and cycling exhibit

Table 1
Study population characteristics by commuting mode.

Commuting mode	No. of persons	Share of pop. (%)	Women (%)	Average age (years)
Car, driver	352,614	38.2	48.2	43
Car, passenger	35,297	3.8	47.5	43
Public transport	352,412	38.1	50.7	40
Walking	130,441	14.1	48.8	43
Cycling	53,206	5.8	53.1	41

Table 2
Mode of commuting by geographical subdivisions (place of residence).

Geographical subdivision	No. of persons	Share of pop. (%)	Commuting mode (%)				
			Car, driver	Car, passenger	Public transport	Walking	Cycling
Inner City	163,779	17.7	18.2	3.8	44.4	23.7	9.9
Northern suburbs	170,320	18.4	35.3	4.0	41.6	13.1	6.0
Southern suburbs	189,871	20.5	30.0	3.9	47.2	12.5	6.3
Northern County	198,757	21.5	53.2	3.7	28.1	11.4	3.6
Southern County	201,243	21.8	49.7	3.7	31.5	11.4	3.8

opposite geographical patterns. Bicycle is the commuting mode for 10% of the residents in the Inner City, a figure almost three times as high as in Northern as well as Southern County.

While these figures may seem to suggest that the potential for modal shift from car to bicycle increases with distance from central Stockholm, it also needs to be kept in mind that actual commuting distances vary substantially by place of residence. Obviously, ceteris paribus, the longer the commute the less likelihood of bicycling being a feasible alternative. In Northern and Southern County, the car commuters' potential one-way distance to work by bicycle averages 18.7 and 17.5 km, respectively. The corresponding potential distances are considerably smaller in the Northern and Southern suburbs (10.2 and 11.6 km, respectively) as well as – and in particular – the Inner City (6.7 km). Given these pronounced spatial differences in cycling route distances, it becomes apparent that the ways the scenarios will manifest themselves spatially is far from self-evident.

3.2. General scenario outcomes

The overall change in commuting that took place in the two scenarios is presented in Table 3. The implementation of the 30-minute scenario resulted in 111,487 persons (12.1% of the entire study population) switching from car to bicycle as their mode of commuting. This change, which brought the total share of bicycle commuters to 17.9%, corresponds to a modal shift of 31.6% and a 210% increase in the number of individuals cycling to work. The more ambitious 50-minute scenario resulted in 171,956 new bicycle commuters (18.6% of the entire study population). This change – which resulted in cyclists making up 24.4% of the commuters – corresponds to a modal shift of 48.7% and a 323% increase in the number of individuals cycling to work. In terms of composition by sex and age, old and new cyclists exhibited quite similar characteristics. However, the new cyclists were slightly older and to a lesser degree female (cf. Table 1); the latter translating into a slight predominance of male cyclists in both scenarios.

In the 30-minute scenario, the new bicycle commuters' average commuting distance and duration were 3.4 km (standard deviation: 2.2 km) and 14.6 min (standard deviation: 8.8 min), respectively. This represents lower values than those exhibited by already existing bicycle commuters. In the 50-minute scenario, the new bicycle commuters instead tended to undertake longer journeys. Average route length was 5.4 km (standard deviation: 3.5 km) and mean duration 23.4 min (standard deviation: 14.3 min).

Scenario outcomes in these and other respects were clearly stratified by sex and age, as Table 4 illustrates. Although the relative levels of modal shift taking place were the highest among young persons (aged ≤ 35 years), this did not translate into the largest volume of new bicycle commuters. Instead, the most substantial addition of new cyclists appeared in the age category 36–50 years. Not surprisingly, given the duration–distance relationship established in Eqs. (1) and (2), average cycling distances were the highest among young men.

Table 3
Demographic characteristics of remaining car commuters, as well as all and new cyclists.

Commuting mode	No. of persons	Share of pop. (%)	Women (%)	Average age (years)
30-minute scenario				
Car, driver	241,127	26.1	48.4	44
Cycling	164,693	17.8	49.5	42
of which new cyclists	111,487	12.1	47.8	42
50-minute scenario				
Car, driver	180,658	19.6	48.7	45
Cycling	225,162	24.4	48.9	42
of which new cyclists	171,956	18.6	47.7	42

3.3. Spatial scenario outcomes

The macro-level spatial distribution of the new bicycle commuters, summarized by their place of residence, is presented in Table 5. In both the 30- and the 50-minute scenario, a substantial number of new bicycle commuters emerged in all five geographical subdivisions of the study area (Fig. 1) However, the relative levels of modal shift differed not only between scenarios but also by geography. Modal shift was by far the highest among car commuters living in the Inner City: 71.4% in the 30-minute and 84.2% in the 50-minute scenario. This corresponds to a 133% and 155% increase in cycling, respectively. The main difference between the 30-minute and 50-minute scenarios were substantially increased shares of modal shift – and thus more new bicycle commuters – in the Northern and Southern suburbs. In both scenarios,

Table 4
New cyclists by sex and age.

Sex and age	No. of persons	Modal shift (%)	Increase in cyclists (%)	Distance (km)		Duration (minutes)	
				Mean	Std. dev.	Mean	Std. dev.
30-minute scenario							
Women							
≤ 35	15,610	36.0	137	3.7	1.9	15.3	8.1
36–50	22,475	29.3	242	3.0	1.8	14.9	8.6
≥ 51	15,192	30.4	200	2.4	1.5	14.6	8.8
Men							
≤ 35	20,335	41.0	198	4.4	2.5	14.7	8.3
36–50	23,010	29.1	273	3.7	2.3	14.6	9.1
≥ 51	14,865	27.5	239	2.6	1.9	13.1	9.6
50-minute scenario							
Women							
≤ 35	23,708	54.6	208	5.6	3.3	23.5	13.6
36–50	35,632	46.5	383	4.9	2.9	24.1	14.3
≥ 51	22,608	45.3	298	3.8	2.4	22.8	14.2
Men							
≤ 35	29,853	60.2	290	6.8	4.2	22.6	13.8
36–50	37,420	47.3	444	6.1	3.7	24.3	14.6
≥ 51	22,735	42.1	365	4.4	3.1	22.4	15.3

Table 5
New cyclists by geographical subdivisions (place of residence).

Geographical subdivision	New cyclists	Modal shift (%)	Increase in cyclists (%)	Distance (km)		Duration (min.)	
				Mean	Std. dev.	Mean	Std. dev.
30-minute scenario							
Inner City	21,278	71.4	132	3.2	1.7	14.1	7.6
Northern suburbs	22,286	37.1	217	3.9	2.2	16.6	8.8
Southern suburbs	17,566	30.8	146	4.0	2.3	17.1	8.8
Northern County	24,234	22.9	338	2.9	2.1	12.8	8.9
Southern County	26,123	26.1	344	3.0	2.1	13.2	8.6
50-minute scenario							
Inner City	25,096	84.2	155	4.0	2.6	17.8	11.4
Northern suburbs	39,801	66.2	388	6.1	3.3	26.7	13.7
Southern suburbs	33,010	57.9	274	6.4	3.3	27.6	13.5
Northern County	36,572	34.6	510	5.1	3.8	22.1	15.3
Southern County	37,477	37.5	493	4.9	3.7	21.4	14.7

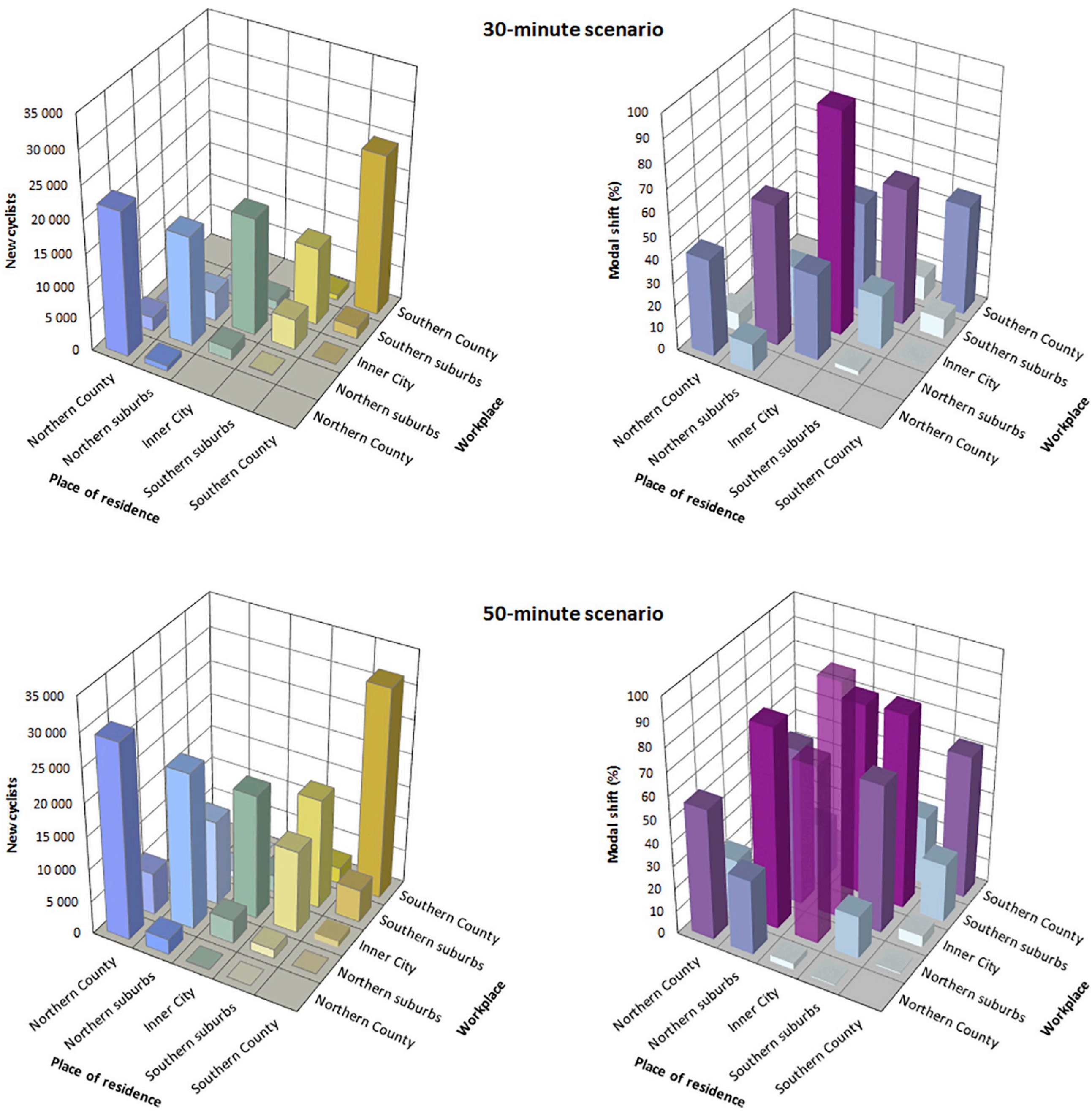

Fig. 2. Number of new cyclists (left) and modal shift (%) (right) by place of residence and workplace in the 30-minute and 50-minute scenarios.

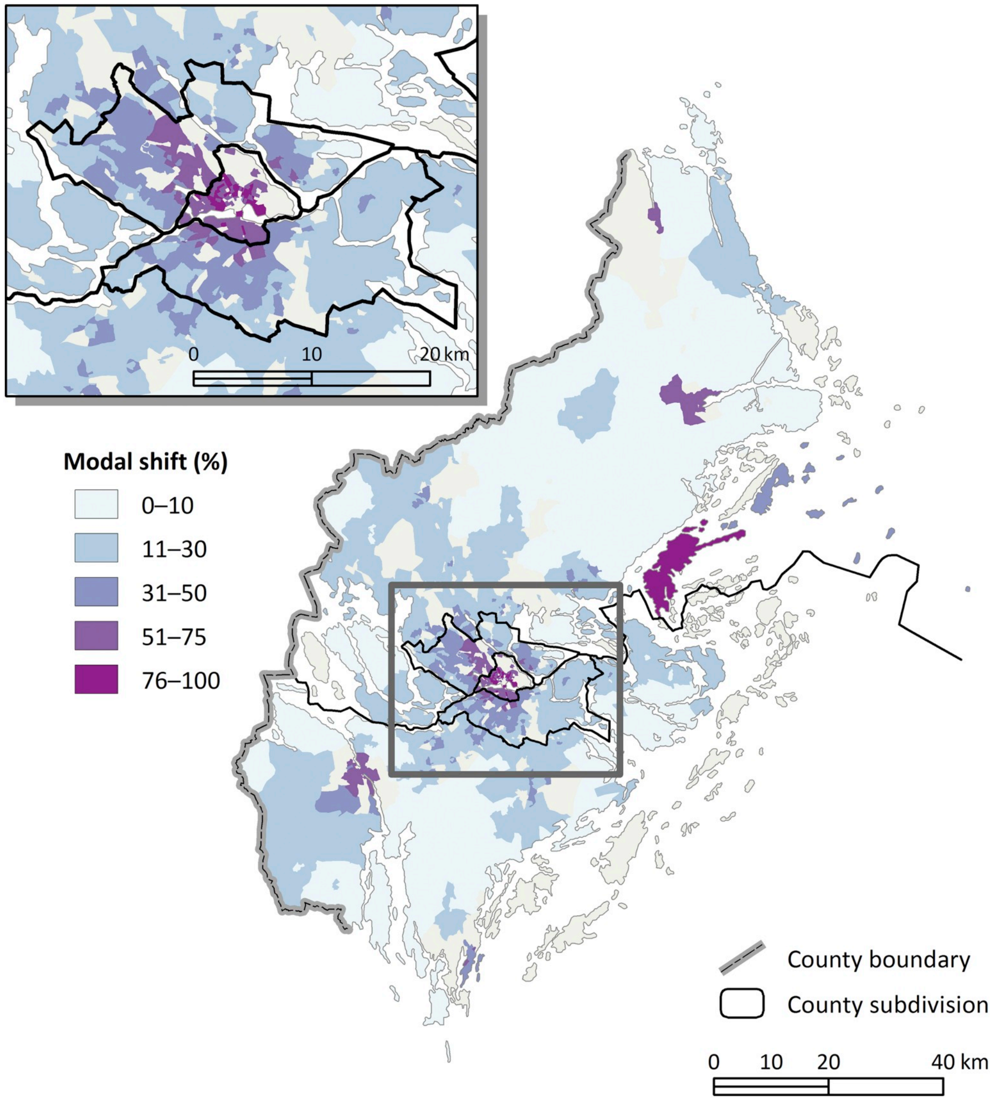

Fig. 3. Modal shift (%) in the 30-minute scenario (place of residence).

new cyclists in these two subdivisions exhibited the longest average trip distances and durations.

With both place of residence and location of the workplace taken into account (Fig. 2; Appendix A), macro-level spatial outcomes become more detailed but also more complex. For a large share of the new bicycle commuters (83.7% in the 30-minute and 69.9% in the 50-minute scenario), the workplace was located in the same geographical subdivision as their place of residence. These spatially overlapping combinations of home and workplace consistently exhibited high relative levels of modal shift. In the 30-minute scenario, this was especially the case for individuals both living and working in the Inner City, where 95% of car commuters switched to cycling. In the 30-minute scenario, comparatively high degrees of modal shift (38% and 48%, respectively) also occurred involving car commuters living in the Inner City and working in either the Northern or Southern suburbs. However, this did not translate into that many new bicycle commuters (1786 and 1468, respectively). Concerning the reverse combinations of home and work, i.e., living in either the Northern or Southern suburbs and working in the Inner City, the shares of modal shift were much lower (23% and 24%, respectively), but the number of new cyclists on the other hand substantially larger (4429 and 4665, respectively). In the 50-minute scenario, the outcomes for these four home–work combinations were more pronounced. For instance, about 25,000 persons living in either the Northern or Southern suburbs and working in the Inner City transferred from commuting by car to cycling.

Presenting outcomes from the micro-level spatial perspective – the LuTRANS zones that the scenario construction departed from – allows for the display of geographically varying outcomes within each macro-level geographical subdivision. Fig. 3 and Fig. 4 illustrate the place of residence-based relative levels of modal shift in the 30- and 50-minute scenario, respectively. As reported earlier, the overall modal shift in the 30-minute scenario was 31.6%. A change from car to bicycle commuting of that magnitude or higher was achieved in 45.2% of the micro level-units, corresponding to 16.8% of the geographical extent of the study area. As the inset map in Fig. 3 reveals, modal shift levels were over 75% in parts of the Inner City. The remainder of the Inner City, as well as some portions of the Northern and Southern suburbs, experienced a modal shift between 51% and 75%. In the latter case, the relative change from car to bicycle commuting was especially prominent in the northern municipalities of Solna and Sundbyberg – two municipalities which are almost fully contained by the officially delimited urban locality of Stockholm. Otherwise, most parts of the Northern and Southern suburbs that overlap with Stockholm City, i.e., the actual municipality of Stockholm (Fig. 1), exhibited modal shifts between 31% and 50%. Turning to the rest of the county, two major urban areas in their own right – Södertälje in the south and Norrtälje in the north –

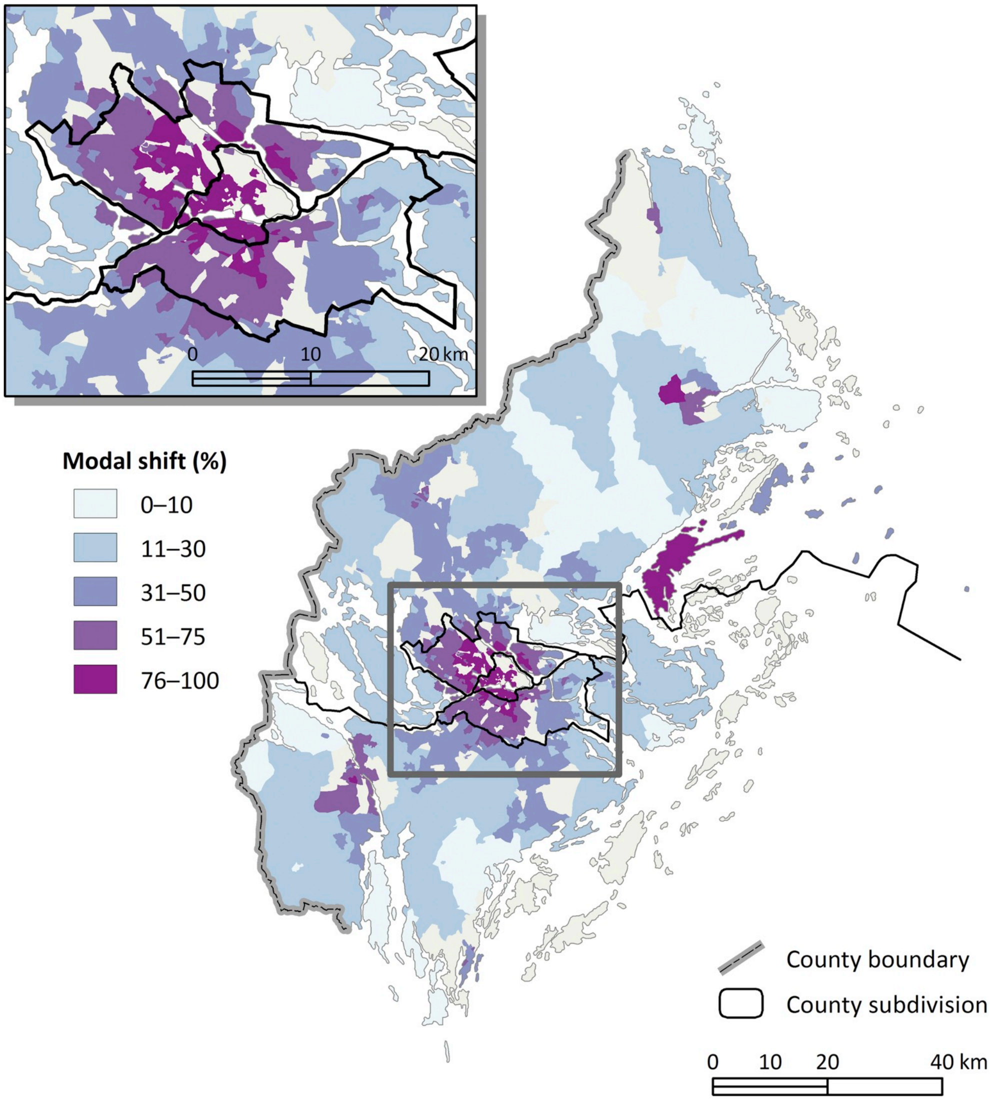

Fig. 4. Modal shift (%) in the 50-minute scenario (place of residence).

stand out as having comparatively high shares of modal shift. High relative levels of change from car to bicycle commuting can also be observed in the small urban locality of Hallstavik in the far north, as well as on the island of Ljusterö.

In the 50-minute scenario, relative levels of modal shift are more pronounced in a substantial number of micro-level units (Fig. 4). In this scenario, the overall degree of modal shift was 48.7%. A change from car to bicycle commuting of that magnitude or higher was achieved in 54.1% of the micro level-units, corresponding to 18.5% of the geographical extent of the study area. As the inset map in Fig. 4 reveals, the Inner City, as well as most of its immediate surroundings in the Northern and Southern suburbs, experienced a modal shift of over 75%. Concerning the remainder of these two geographical subdivions, modal shift levels were generally in the 51–75% range; the main exception was the eastern part of the Southern suburbs. As far as the rest of the study area is concerned, in the bulk of the remote parts of Stockholm urban locality (Fig. 1) between 31% and 50% changed from car to bicycle commuting; in the 30-minute scenario, modal shifts of 11–30% was the corresponding outcome.

4. Discussion

There are substantial potential health benefits of increased active transportation such as cycling instead of traveling by car. In this paper, we have presented two scenarios modeling commuter modal shift from car trips to cycling in Stockholm, Sweden. Our ambition was to build and improve upon previous studies in terms of both methodological approach and degree of spatial resolution of the modeling outcomes. Departing from a study population that is georeferenced in terms of actual location of home and workplace, as well as characterized in terms of having access to a car or not, initial commuting mode was assigned by stochastic imputation based on high-resolution empirical probability distributions of commuting patterns. The implemented scenarios then assumed that car commuters in Stockholm County that can travel to their workplace within 30 and 50 min, respectively, undertake a modal shift. These particular thresholds were selected so that we could examine outcomes in both a plausible and a quite maximal scenario. In order to determine who fulfilled these criteria, we made use of individual-level information on sex and age, an empirically validated formula of the cycling duration–distance relationship incorporating these factors and a cycling route network that was selected as the most appropriate based on observed behavior of existing cyclists.

Cycling is currently an uncommon commuting mode in the Stockholm metropolitan region, strongly affected by seasonality (Stigell and Schantz, 2015). Among the almost one million persons both living and working within the study area, on average 5.8% (53,206 persons) commute to work by bicycle. Not surprisingly, the figure is substantially higher (9.9%) for individuals living in the Inner City – the location of the central business district (CBD). Our scenarios show that bicycle-commuting figures could potentially be much higher. The 30-minute scenario has the potential to transfer 111,487 persons from car to bicycle commuting; the corresponding figure for the 50-minute scenario is 171,956 persons. This translates to car–bicycle modal shifts of 31.6% and 48.7%, respectively.

There were slightly more women than men among the new cyclists, with women making up about 48% of the new cyclists in both scenarios. In terms of age distribution, the highest relative levels of modal shift occurred among persons aged 35 years and younger, while the most new cyclists belonged to the age category 36–50 years. The new bicycle commuters' average commuting distance and duration in the 30-minute scenario were 3.4 km and 14.6 min, respectively. In the 50-minute scenario, the corresponding figures were 5.4 km and 23.4 min. Given the baseline population cycling distance of 4.5 km and duration of 20.2 min, as well as the corresponding Swedish national travel survey estimates of 5.3 km and 20.6 min for a largely overlapping geographical area (Trafikanalys, 2017a,b), one can conclude that the new bicycle trips in the scenarios exhibit reasonable characteristics – at least when compared to the routes and commuting times experienced by already existing bicycle commuters.

Using a georeferenced study population and geographically detailed data on commuting patterns, we were able to present scenario outcomes with a high degree of spatial resolution. A substantial number of new bicycle commuters appeared in all five macro-level subdivisions of the study area. However, relative levels of modal shift were by far the highest among car commuters living in the Inner City and its immediate surroundings. Taking both place of residence and location of workplace into account revealed especially high shares of modal shift – as well as number of new cyclists – in situations where home and workplace are located in the same geographical subdivision. There were also high shares of modal shift involving car commuters living in the Inner City and working in either the Northern or Southern suburbs. With regard to the reverse combinations of home and work, i.e., living in either the Northern or Southern suburbs and working in the Inner City, the shares of modal shift were much lower but the number of new cyclists on the other hand substantially larger. At the micro level, additional spatial patterns were revealed. For instance, the percentage change from car to bicycle commuting in the Northern suburbs was especially prominent in the northern municipalities of Solna and Sundbyberg – two municipalities which are almost fully contained by the officially delimited urban locality of Stockholm.

For all its merits, there are caveats and potential limitations to be noted when it comes to our scenario construction. The simulation procedure that underlies the matching between individual characteristics and commuting modes raises a fair point of contention concerning the study population – to what extent it is real(istic) as opposed to synthetic. However, the answer seems to be that it – despite the touch of generalized modeling – corresponds quite well to actual conditions. We assumed that the aggregate results would provide an adequate representation of the overall commuting population, and post-hoc attempts at validation did indeed turn out in a reassuring manner. For instance, in our calculated baseline population, using a bicycle to commute to work is slightly more common among women (53.1% of the study population). This is in line with generally observed patterns in high-cycling countries (Aldred et al., 2016), as well as – and more importantly – the Swedish National Travel Survey (Trafikanalys, 2017a, 2017b), which reported a figure of 54.3% female cyclists within a largely overlapping geographical area. In any case, however, the general applicability of specified workflow across different countries and contexts will largely be dependent on access to and quality of relevant data sources.

The results described form part of a broader research endeavor where the scenarios are not only presented in terms of construction and outcomes, but also evaluated in terms of impact on air pollution, as well as commuter and overall population health effects. As demonstrated in Johansson et al. (2017), a fully realized 30-minute scenario would correspond to 449 annual years of life saved just by virtue of reduced vehicle emissions; and, as reported in Kriit et al. (2019), the outcomes would be highly cost-effective from an health economic point of view even if only a subset of the relevant population switched from car to bicycle commuting.

However, there is still the outstanding question of how the scenario outcomes are related to a reasonable potential for modal shift. Obviously, the ability and willingness to undertake a modal shift from car to bicycle commuting is dependent on both structural conditions and individual characteristics. Indeed, individual demographic and socio-economic characteristics may strongly influence the ability and willingness to shift mode of commuting in favor of cycling. While sex and age are accounted for in our scenarios in terms of cycling capability, we do not consider the relation between individual attributes on the one hand, and attitudes toward cycling in general – and willingness to consider a modal shift in particular – on the other. There are a number of factors of relevance here, with varying views concerning comfort and safety in relation to cycling being just two out of many examples. It should also be noted that if either scenarios were realized partly or in full, new challenges such as bicycle congestion would likely occur and need to be addressed.

The degree to which cycling is used for everyday travel needs – including commuting – vary a lot across different Global North countries. For instance, the bicycle share of trips is far lower in Anglo-Saxon countries such as the US and the UK than in continental Europe. Cycling for everyday travel is the most widespread in the Netherlands, followed by Denmark, but it is also a comparably common mode of transport in Finland, Sweden and Germany. While the reasons for these variations in cycling propensity are multifaceted, they can to a certain extent be attributed to country-level planning and policy differences (Pucher and Buehler, 2008).

There are also substantial variations in bicycle utilization between cities – a pattern that appears in countries with both low and high overall levels of cycling. This is hardly surprising, given that conditions for cycling manifest themselves at the local level and thus are particularly influenced by urban and regional planning and policy (Pucher and Buehler, 2008). The situation in Copenhagen, the capital of and largest city in neighboring Denmark, makes for an interesting contrast to the case of metropolitan Stockholm. Cycling in general is more prominent in Denmark than in Sweden, but the difference between the two capital regions are much more pronounced. While the climate in Stockholm during the winter season is less favorable, other factors – one of which is urban design in general and cycling infrastructure in particular – constitute more likely major determinants (Emanuel, 2018; Koglin, 2015). Hence, in order to promote modal shift for car to bicycle commuting, changes to the built, traffic and natural environment that make cycling a more feasible mode of transport are called for (Wahlgren and Schantz, 2011, 2012, 2014; Winters and Teschke, 2010).

Author statement

Magnus Strömgren: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration. Peter Schantz: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - review & editing, Funding acquisition. Johan Nilsson Sommar: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - review & editing. Wasif Raza: Writing - original draft. Anders Markstedt: Methodology, Resources. Bertil Forsberg: Conceptualization, Methodology, Writing - review & editing, Project administration, Funding acquisition.

Acknowledgements

This research was supported by funding from the Swedish Research Council for Health, Working Life and Welfare (FORTE: 2012-1296) and the Swedish Transport Administration (TRV: 2017/63917-6522).

Appendix A

Table A
Number of new cyclists and modal shift (%) by place of residence and workplace in the 30-minute and 50-minute scenarios.

30-minute scenario

Number of new cyclists by place of residence and workplace

		Workplace				
		Northern County	Northern suburbs	Inner City	Southern suburbs	Southern County
Place of residence	Northern County	22,128	2,105	1	0	0
	Northern suburbs	872	16,831	4,429	0	0
	Inner City	0	1,786	18,024	1,468	0
	Southern suburbs	0	139	4,665	11,907	855
	Southern County	0	0	7	1,731	24,385

Modal shift (%) by place of residence and workplace

		Workplace				
		Northern County	Northern suburbs	Inner City	Southern suburbs	Southern County
Place of residence	Northern County	42.5	7.9	0.005	0	0
	Northern suburbs	12.1	61.3	23.3	3.6	0
	Inner City	0	37.7	95.5	47.6	0
	Southern suburbs	0	1.9	23.9	59.4	10.5
	Southern County	0	0	0.04	8.9	47.7

50-minute scenario

Number of new cyclists by place of residence and workplace

		Workplace				
		Northern County	Northern suburbs	Inner City	Southern suburbs	Southern County
Place of residence	Northern County	29,465	6,414	691	2	0
	Northern suburbs	2,347	23,600	12,795	1,044	15
	Inner City	38	3,587	18,866	2,535	70
	Southern suburbs	6	1,391	12,549	16,667	2,397
	Southern County	0	39	921	4,954	31,563

Modal shift (%) by place of residence and workplace

		Workplace				
		Northern County	Northern suburbs	Inner City	Southern suburbs	Southern County
Place of residence	Northern County	56.6	24.0	3.4	0.04	0
	Northern suburbs	32.5	86.0	67.3	24.1	0.7
	Inner City	2.7	76.0	100	82.0	4.1
	Southern suburbs	0.3	18.6	64.0	83.0	29.3
	Southern County	0	0.4	4.9	25.4	61.8

References

Aldred, R., Woodcock, J., Goodman, A., 2016. Does more cycling mean more diversity in cycling? Transp. Rev. 36 (1), 28–44.
Andersen, L.B., Schnohr, P., Schroll, M., Hein, H.O., 2000. All-cause mortality associated with physical activity during leisure time, work, sports, and cycling to work. Arch. Intern. Med. 160 (11), 1621–1628.
Berglund, S., Engelson, L., 2014. Nätverksutläggning för cykel. CTS working paper (No. 2014:12). Centre for Transport Studies, Royal Institute of Technology/WSP, Stockholm.
Blair, S.N., 2009. Physical inactivity: the biggest public health problem of the 21st century. Br. J. Sports Med. 43 (1), 1–2.
Brauer, M., Amann, M., Burnett, R.T., Cohen, A., Dentener, F., Ezzati, M., ... Thurston, G.D., 2012. Exposure assessment for estimation of the global burden of disease attributable to outdoor air pollution. Environmental Science & Technology 46 (2), 652–660.
Celis-Morales, C.A., Lyall, D.M., Welsh, P., Anderson, J., Steell, L., Guo, Y., ... Gill, J.M., 2017. Association between active commuting and incident cardiovascular disease, cancer, and mortality: prospective cohort study. BMJ 357, j1456.
Dhondt, S., Kochan, B., Beckx, C., Lefebvre, W., Pirdavani, A., Degraeuwe, B., ... Putman, K., 2013. Integrated health impact assessment of travel behaviour: model exploration and application to a fuel price increase. Environ. Int. 51, 45–58.
Emanuel, M., 2018. Making a bicycle city: infrastructure and cycling in Copenhagen since 1880. Urban History 1–25.
de Hartog, J.J., Boogaard, H., Nijland, H., Hoek, G., 2010. Do the health benefits of cycling outweigh the risks? Environ. Health Perspect. 118 (8), 1109–1116.
Holm, A.L., Glümer, C., Diderichsen, F., 2012. Health impact assessment of increased cycling to place of work or education in Copenhagen. BMJ Open 2 (4), e001135.
Johansson, C., Lövenheim, B., Schantz, P., Wahlgren, L., Almström, P., Markstedt, A., ... Sommar, J.N., 2017. Impacts on air pollution and health by changing commuting from car to bicycle. Sci. Total Environ. 584–585, 55–63.
Jonsson, D., Berglund, S., Almström, P., Algers, S., 2011. The usefulness of transport models in Swedish planning practice. Transp. Rev. 31 (2), 251–265.
Koglin, T., 2015. Organisation does matter: planning for cycling in Stockholm and Copenhagen. Transp. Policy 39, 55–62.
Kriit, H.K., Williams, J.S., Lindholm, L., Forsberg, B., Sommar, J.N., 2019. Health economic assessment of a scenario to promote bicycling as active transport in Stockholm, Sweden. BMJ Open 9 (9), e030466.
Lindsay, G., Macmillan, A., Woodward, A., 2011. Moving urban trips from cars to bicycles: impact on health and emissions. Aust. N. Z. J. Public Health 35 (1), 54–60.
Maizlish, N., Woodcock, J., Co, S., Ostro, B., Fanai, A., Fairley, D., 2013. Health cobenefits and transportation-related reductions in greenhouse gas emissions in the San Francisco Bay area. Am. J. Public Health 103 (4), 703–709.
Matthews, C.E., Jurj, A.L., Shu, X.O., Li, H.L., Yang, G., Li, Q., ... Zheng, W., 2007. Influence of exercise, walking, cycling, and overall nonexercise physical activity on mortality in Chinese women. Am. J. Epidemiol. 165 (12), 1343–1350.
McMichael, T., Montgomery, H., Costello, A., 2012. Health risks, present and future, from global climate change. BMJ 344, e1359.
Otero, I., Nieuwenhuijsen, M.J., Rojas-Rueda, D., 2018. Health impacts of bike sharing systems in Europe. Environ. Int. 115, 387–394.
Pucher, J., Buehler, R., 2008. Making cycling irresistible: lessons from the Netherlands,

Denmark and Germany. Transp. Rev. 28 (4), 495–528.
Rabl, A., de Nazelle, A., 2012. Benefits of shift from car to active transport. Transp. Policy 19 (1), 121–131.
Rojas-Rueda, D., de Nazelle, A., Tainio, M., Nieuwenhuijsen, M.J., 2011. The health risks and benefits of cycling in urban environments compared with car use: health impact assessment study. BMJ 343, d4521.
Rojas-Rueda, D., de Nazelle, A., Teixidó, O., Nieuwenhuijsen, M.J., 2012. Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: a health impact assessment study. Environ. Int. 49, 100–109.
Rojas-Rueda, D., de Nazelle, A., Teixidó, O., Nieuwenhuijsen, M.J., 2013. Health impact assessment of increasing public transport and cycling use in Barcelona: a morbidity and burden of disease approach. Prev. Med. 57 (5), 573–579.
Schantz, P., 2017. Distance, duration, and velocity in cycle commuting: analyses of relations and determinants of velocity. Int. J. Environ. Res. Public Health 14 (10), 1166.
Schantz, P., Stigell, E., 2009. A criterion method for measuring route distance in physically active commuting. Med. Sci. Sports Exerc. 41 (2), 472–478.
Schantz, P., Wahlgren, L., Eriksson, J.S., Sommar, J.N., Rosdahl, H., 2018. Estimating duration-distance relations in cycle commuting in the general population. PLoS One 13 (11), e0207573.
Schantz, P., Wahlgren, L., Eriksson, J.S., Sommar, J.N., Rosdahl, H., 2019a. Correction: estimating duration-distance relations in cycle commuting in the general population. PLoS One 14 (6), e0218221.
Schantz, P., Wahlgren, L., Eriksson, J.S., Sommar, J.N., Rosdahl, H., 2019b. Correction: correction: estimating duration-distance relations in cycle commuting in the general population. PLoS One 14 (6), e0218866.
Stigell, E., Schantz, P., 2015. Active commuting behaviors in a Nordic metropolitan setting in relation to modality, gender, and health recommendations. Int. J. Environ. Res. Public Health 12 (12), 15626–15648.
Stjernström, O., 2011. Databasen ASTRID och befolkningsgeografi: exemplen integration och branfamiljernas geografi. Geografiska notiser 69 (2), 79–86.
Statistics Sweden, 2015. Regionala indelningar i Sverige den 1 januari 2015. Meddelanden i samordningsfrågor för Sveriges officiella statistik (No. 2015:1). Statistics Sweden, Örebro.
Trafikanalys, 2017a. RVU Sverige: Den nationella resvaneundersökningen 2015–2016, Kvalitetsdeklaration. Trafikanalys, Stockholm.
Trafikanalys, 2017b. RVU Sverige: Den nationella resvaneundersökningen 2015–2016, Statistik 2017:13. Trafikanalys, Stockholm.
Wahlgren, L., Schantz, P., 2011. Bikeability and methodological issues using the active commuting route environment scale (ACRES) in a metropolitan setting. BMC Med. Res. Methodol. 11 (6).
Wahlgren, L., Schantz, P., 2012. Exploring bikeability in a metropolitan setting: stimulating and hindering factors in commuting route environments. BMC Public Health 12 (168).
Wahlgren, L., Schantz, P., 2014. Exploring bikeability in a suburban metropolitan area using the active commuting route environment scale (ACRES). Int. J. Environ. Res. Public Health 11 (8), 8276–8300.
Winters, M., Teschke, K., 2010. Route preferences among adults in the near market for bicycling: findings of the cycling in cities study. Am. J. Health Promot. 25 (1), 40–47.
Woodcock, J., Edwards, P., Tonne, C., Armstrong, B.G., Ashiru, O., Banister, D., ... Franco, O.H., 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport. Lancet 374 (9705), 1930–1943.
Woodcock, J., Givoni, M., Morgan, A.S., 2013. Health impact modelling of active travel visions for England and Wales using an integrated transport and health impact modelling tool (ITHIM). PLoS One 8 (1), e51462.
Woodcock, J., Tainio, M., Cheshire, J., O'Brien, O., Goodman, A., 2014. Health effects of the London bicycle sharing system: health impact modelling study. BMJ 348, g425.
WSP, 2018. LuTRANS V4: Dokumentation. WSP, Stockholm.