Incorporating Bicycling into Activity-based Regional Travel Forecasting Models in Denmark:
Identified Needs and Proposed Solutions

Prepared for

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Table of Contents

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Introduction and Executive Overview

Origin and purpose of the study

The idea for the research resulting in this document arose in the early stages of the development of an activity-based (AB) travel demand model for Copenhagen—called COMPAS—as part of the ACTUM research project. It was recognized that, although bicycling is a very important personal transport mode in Copenhagen and, more broadly, in Denmark, neither the existing traffic models nor the AB model under development had all the features needed to model important effects related to bicycling. The author possessed expertise in AB model development for practical application, and longstanding interest in bicycling as a transport mode, but lacked the first-hand experience of living in or developing AB models for places like the cities and towns of Denmark, where bicycling is an established and important mode.

The Danish Road Directorate agreed to fund a Technical University of Denmark (DTU) project in which the author would, while residing temporarily in Copenhagen for several months, (a) learn about the nature and role of bicycling as a transport mode and policy issue through field visits and interviews, (b) evaluate the capabilities and limitations of the AB model under development, (c) design enhancements that would enable the model to better represent bicycle-related behavior and address bicycle policy issues, (d) identify the data needs, and (e) lay out a strategy for implementing data and model improvements. This report is the result of that research effort. In line with the stated research objectives, this is intended as a practical document, one that can be used by those responsible for planning and funding modeling projects aimed at meeting real needs experienced by professionals in Denmark dealing with policies and projects where the likely effects related to bicycling are important to understand as well as possible.

Desired model capabilities

Danish professionals involved with bicycle programs and transport modeling recognize the importance of bicycling as a transport mode in Denmark. They also acknowledge that the current transport models don’t model bicycling well, compared to car traffic and public transport (PT). What is desired in a transport model is one that captures the impact upon bicycle mode share—and related bicycle outcomes such as network flows—of specific projects and policies. This includes efforts aimed at motorized modes, such as road pricing or a new metro line, as well as those dealing directly with bicycling, such as a new bicycle bridge or widened cycle tracks in the PLUSNet, Copenhagen’s high priority high volume bicycle subnetwork. Of special interest is the ability to model the effects of programs addressing the incidence of combined bicycle-PT trips, such as improving parking at stations or further enabling people to take their bicycle with them on PT vehicles. There is also desire to model the effects on the transport system of programs—such as marketing campaigns and education programs—even if it isn’t possible to predict the change in bicycle mode share. In those cases it would be useful to understand the impacts on all modes and traffic flows assuming that the program increases bicycle mode share by an assumed amount.

Literature review

A review of the literature provides helpful insights into the factors that have been shown by others to be important in persons' choices related to bicycling. Some of these results are specific to the Danish situation and may be especially valuable sources of information in subsequent modeling efforts to improve the representation of bicycling in the AB travel demand model system through the introduction of specific explanatory variables. The literature also provides information about the state of the practice with regard to the inclusion of bicycling in real world model systems used for project and policy analysis. In particular, examples now exist of bicycle route choice models that have been incorporated into model systems and integrated with mode choice models, so that the effects of route attributes impact the model's mode choice function. The operational examples are in the United States, where bicycle facilities are primitive and bicycle mode share is low. Therefore, although the examples provide useful demonstrations of modeling methods that work, they lack the richness of explanatory variables and associated model coefficients needed in Denmark. But important work is underway at DTU to model route choice in Copenhagen, and it is expected that this will be directly useable in the future. In the important area of modeling trips where bicycling and PT are used in combination, the research is scarce, and there are no examples of working model systems that represent these trips effectively.

The Danish modeling context

The Ørestad Traffic Model (OTM), the operative traffic model for the Greater Copenhagen Area (GCA), has been in use and evolving since 1994, and represents the state of the practice in Denmark. Some characteristics of OTM limit its effectiveness in accurately modeling bicycles. These include using less than a thousand zones to span the GCA, using only inter-zonal distance to measure attractiveness of the bicycle mode, and not explicitly modeling bicycle access to PT.

The Danish National Transport Model (LTM), under ongoing development at DTU, uses a passenger demand model component similar to OTM in design but spatially less detailed, leaving it with the same weaknesses as OTM with respect to the modeling of bicycle transport. However, the LTM project calls for region-specific submodels that can be more detailed than the base LTM. Also, it includes the development of a bicycle route choice model and the associated bicycle network with important attributes that affect bicycle route choice. Thus it provides some of the foundation needed for improved modeling of the bicycle mode.

The Copenhagen Model for Person Activity Scheduling (COMPAS), under development in DTU's ACTUM research project, uses a disaggregate AB demand microsimulation model (COMPAS DaySim) coupled with disaggregate assignment models. An initial working implementation of COMPAS DaySim uses the 878 zones of OTM, but an enhanced 9,710 zone system has been developed and will be used for the second draft. COMPAS DaySim explicitly models joint travel and intermediate stops on tours. It also provides a suitable platform for explicitly simulating PT access and egress by car or bicycle, although this feature has not been implemented in the first draft. COMPAS is expected to use a first draft of the disaggregate bicycle route choice model being developed for LTM. Thus, COMPAS provides an excellent starting point for achieving many of the desired bicycle modeling capabilities.

Proposed new model features

The proposed new features build on the strengths of the COMPAS architecture, namely demand microsimulation and disaggregate assignment. The most fundamental requirement is the addition of a **bicycle route choice model** that uses important attributes of the network links and nodes that are important to cyclists making their route choices, such as presence and width of cycle tracks. This will open up the entire model system to be sensitive to those attributes, since they affect not only route choice, but also choices of mode, destination and timing.

There are several ways that the **mode, destination and timing choice models** can be improved to better represent bicycling in the traffic model system. These include (a) enhancing the bicycle mode's utility function in the models to capture the effects of travel and parking conditions, (b) explicitly modeling the bicycle portions of trips in which bike is used for PT access (and sometimes egress), (c) explicitly modeling the use of bicycles for partially joint half tours (typically, journeys where a parent chauffeurs one or more children to or from school on their way to or from work), and (d) enabling scenario analysis in which the model responds to the assumption that bike mode share changes to a specified level for a selected population segment as a result of some unmodeled change such as an education or promotion program.

Achieving the benefits of the enhanced model features requires developing, enhancing or augmenting **data** of five types. These include: (a) spatial and network data that are more detailed than those which have been used in OTM and the first draft of COMPAS DaySim, (b) additional observed route choice data, (c) a large household diary survey that collects diary data from all members of each household, (d) stated preference data to supplement the household survey and route choice data, and (e) updated and re-categorized base-year trip matrix data used for grounding the details of model forecasts in reality.

Modeling needs addressed by the model features

Several summary comments can be made about the correspondence between the desired capabilities identified through interviews, and the proposed features laid out in this document:

1. A basic AB microsimulation model that uses detailed microzone geography and detailed bicycle network, such as the COMPAS model being developed as a prototype for Copenhagen in the ACTUM research project, is a pre-requisite for achieving any of the desired features. For most desired capabilities, this must be accompanied by further implementation of other proposed features. However, this in itself should be enough to improve the estimation of impacts associated with major road infrastructure and policy projects.
2. Because of the high usage of bicycle as a PT access mode, it is important to model PT access and egress modes explicitly in order to achieve improved estimates of the effects of PT infrastructure and policy, bicycle infrastructure, and programs aimed at dealing with bicycle access to PT.
3. To estimate the effects of bicycle infrastructure projects or programs aimed at bicycle access to PT, enhanced bicycle mode choice modeling is needed.
4. For any infrastructure or policy that directly affects bicycle route attributes, such as the presence, capacity or quality of cycle tracks, or signal coordination, a bicycle route choice model

is needed that directly incorporates the attributes of interest, and the mode choice model must use the summary accessibility results (logsums) generated by the route choice model.

5. The scenario analysis feature can be used to estimate effects that are not directly modeled.
6. This research does not deal directly with features aimed at effectively modeling new bicycle modes, such as E-bikes and the new bike share program. It may be possible to model them effectively, but further research would be needed.

The remainder of this document examines in greater detail each of the topics introduced above.

Desired Model Capabilities Related to Bicycling

Interviews were conducted to identify the model capabilities that would be of value for public decision making. Appendix 1 provides a list of the interviewees, which includes representatives of the four largest cities in Denmark, the Road Directorate, DTU and one consulting firm.

Respondents who are familiar with an existing model almost universally emphasize that it is not useful for estimating the impact on bicycling of road, PT or bicycle infrastructure or policy projects. For the most part, the model does not predict changes in bicycle usage, or the changes are barely perceptible. Sometimes the changes are counterintuitive and unrealistic. This stands in contrast to the car and PT modes, for which models are used extensively and provide reasonably good estimates for decision making. This is troubling in light of the fact that bicycling is an important mode of transport in Danish cities—as important as cars and PT—and many policies and programs are aimed at further increasing the use of bicycles. A model that is able to provide reasonable estimates related to important projects would be welcomed. In particular, the following capabilities are viewed as valuable:

1. Estimate the impact on bicycle mode share, traffic flow, travel times or health impacts of a major road or PT infrastructure project or policy, such as:
    a. New Metro line
    b. Expanded or reduced highway capacity
    c. Increased or reduced vehicle purchase taxes
    d. Increased or reduced fuel prices
    e. Peak period congestion charges or road pricing
    f. PT fare changes
    g. Changes in parking availability and price
2. Estimate the change in bicycle mode share, flows, travel times or health impacts of a bike infrastructure project, such as:
    a. new cycle track that fills a continuity gap
    b. new green wave, widened cycle track, cycle superhighway or other traffic engineering improvement that increases bicycle capacity and/or speed
    c. increased availability of secure parking at employment centers and residences
    d. increased availability of convenient parking in commercial districts
    e. additional traffic calmed neighborhood streets
    f. intersection improvement that increases safety of a known dangerous location

    g. addition of a major bicycle bridge or many minor bicycle shortcuts
3. Estimate the incidence of trips made by a combination of bicycle and PT. Estimate the change in PT usage, bicycle usage, shared bike-PT trips, bicycle parking and bicycles on PT vehicles induced by bike-PT programs, such as:
    a. Increased provision of secure and convenient parking at train stations
    b. New or increased bicycle capacity on trains or buses
4. Estimate the change in mode shares, volumes and speeds of new bike modes, such as:
    a. E bikes
    b. Bike share program
5. Estimate the impact, on traffic volumes and speeds (or travel times) by each mode (auto, PT, bike, walk), of an assumed increase in bike mode share induced by any type of non-infrastructure program, such as increased school education, marketing campaign, smartphone apps, bike pumps or footrests, or a program aimed at a particular population subgroup defined by age, income, gender, household composition, geographic neighborhood or auto ownership.
6. Estimate the impact of infrastructure or policies on particular population subgroups defined by age, income, gender, household composition, geographic neighborhood or auto ownership. Estimate the amount of bicycle use by particular population subgroups for particular purposes, such as:
    a. workers for work commute
    b. students for school commute
    c. parents and children traveling together for school trips
    d. families traveling together for activities other than the work and school commutes
    e. young adults for socializing and eating out
    f. retired adults
    g. adults for escorting others

Literature Review

A review of the literature provides helpful insights into the factors that have been shown by others to be important in persons' choices related to bicycling. Some of the literature provides information that may enable reasonable assumptions about model coefficient values in cases where it is believed that a factor is important but corresponding research has not yet been conducted using local data. The following review is divided into several categories: route choice analysis, mode choice analysis, route choice and mode choice models implemented in forecasting model systems, bike and ride, other valuable research, and Danish bicyclist values.

Route choice analysis

Most studies of route choice have relied on stated preference data. They have identified significant factors affecting choice, including bike facility type, on-street parking, pavement surface, grade, intersection spacing, cycling signal treatments, completeness of cycle infrastructure, availability of showers and parking, motor vehicle traffic and speeds, and pedestrian interactions (See, for example, DeGruyter, 2002; Stinson and Bhat, 2003 and 2005; Hunt and Abraham, 2007; Tilahun, et al, 2007;

Sener, et al, 2009; Torrance, et al, 2009. Reviews of this literature can be found in Hunt and Abraham, 2007; and Sener, et al, 2009). At least one route choice model has been developed from revealed choice data collected from GPS traces, demonstrating the value of this method for developing route choice models (Menghini, et al, 2010). A challenge exists to provide the input data needed to incorporate the factors identified in the various studies into a real world model system.

Mode choice analysis

Few studies have been conducted to understand the important factors that affect bicycle mode choice. This is probably because the important factors lie in the link and path attributes associated more directly with route choice. Therefore, fully understanding the impact on mode choice would require analyzing the effects on mode and route choice jointly. Buehler (2011), and Christensen and Jensen (2011) both develop mode choice models that address factors affecting bicycle as a mode, without considering route choice, and therefore must limit the included factors to those that depend only on the traveler characteristics and, in the case of Christensen, a summary travel time measure and parking attributes. While these are valuable studies, they are limited by the absence of important route attributes from the model specification.

Route choice and mode choice models implemented in forecasting model systems

Examples now exist of route choice models, developed using data from observed bicyclist route choices, that have been incorporated into practical travel demand forecasting model systems. The model of Broach, et al (2012) has been implemented in Portland, Oregon's, trip-based model system, and adapted for use in New Zealand (Rendall, et al, 2012). The model of Hood, et al (2011) has been implemented in the AB model system of San Francisco County, California. These two models are being adapted for use in the AB model system of San Diego, California, where a logsum summary measure of route attractiveness is also being incorporated into the mode choice component (Hood Transportation Consulting, 2013).

Bike and ride

Two studies focus on bike and ride, which is of special importance in Denmark. Martens (2004) studies bike and ride statistics from The Netherlands, Germany and the UK, and observes that the share of bicycle as a feeder mode is comparable to bicycle use in general, that bike and ride is used primarily for work and school, and that it is used more with faster PT modes. Taylor and Mahmassani (1996) conduct Stated Preference analysis of choice by Texas bicycle riders among car, park and ride, and bike and ride. Their most important conclusion is the importance of presence and awareness of secure bicycle parking. They also conclude that, in their case, a nested logit structure is needed, in which the choice of PT versus car conditions the choice of access mode.

Other valuable research

Mekuria, et al (2012) and Furth and Mekuria (2013) develop a measure of network connectivity associated with the stress level encountered by a bicyclist along the entire path from trip origin to destination. Stress level—on a four point scale—with level 1 suitable for children, level 2 suitable for stress-averse adults, and levels 3 and 4 being progressively more stressful—is measured for each link, intersection approach and intersection crossing, and the entire path is assigned a stress level equal to the greatest stress level encountered among all the path's links, intersection approaches and intersection crossings. The stress levels are evaluated using measurable criteria based on attributes that are widely available in practice. The criteria for level 2 correspond closely to the established Dutch street design criteria. Their work highlights the importance of all aspects of a route, including intersection approaches and crossings, and their criteria identify measurements that might effectively be used in the development of an enhanced route choice model, either by using their route stress level measure in the route utility function, by testing other similar route stress measures, or by incorporating the elements of their stress measures separately into the model.

Danish bicyclist values

Much of the research cited above comes from studies done outside Denmark, such as the United States, where bicycling conditions are less conducive to cycling, bicycle mode share is far lower, and the demographic profile of those who cycle is quite different. Three valuable sources of information about the factors important to Danes in their decisions about bicycling are Jensen (2007), the 2012 Copenhagen Bicycle Account (City of Copenhagen, 2013) and Wind (2013). Quoting Rendall, et al (2012) in its review of Jensen (2007): "The Danish Road Directorate sponsored a study to develop methods for objectively quantifying pedestrian and bicyclist stated satisfaction with road sections between intersections (Jensen 2007). This SP study, in which 407 participants were shown video clips taken by pedestrians and cyclists on 56 road segments, found that motorised traffic volume and speed, land uses, width of facilities, number and width of vehicle lanes, volumes of pedestrians, cyclists and parked cars, and presence of median, trees and bus stops all significantly influence the level of satisfaction. Logit models for walking and cycling were created to calculate the satisfaction level dependent upon a variety of inputs." Jensen uses statistical analysis to develop a Level of Service function dependent on the relative importance of the above factors to cyclist satisfaction. The relative weights identified in the formula might be useful in incorporating these factors into a route choice model or validating separately estimated route choice model coefficients.

The 2012 edition of the Copenhagen Bicycle Account (City of Copenhagen, 2013) provides some insight into factors that are probably important to people who bicycle in Copenhagen. At the top of the list are travel time and convenience. Other likely factors include combination with PT, width of cycle track, bicycle parking, road condition, cycle track condition, safety and number of stops.

Wind (2013) includes detailed interviews in which respondents explain why they use bicycle and how they choose their route.

The Danish Modeling Context

Denmark has a rich modeling tradition and an active research and development program that provide an excellent headstart for implementing many of the desired capabilities.

Ørestad Traffic Model (OTM)

OTM is the operative traffic model for the Greater Copenhagen Area (GCA), and has been in use and evolving since 1994. Other regions in Denmark have their own models, but they are for the most part similar to or simpler than OTM and are not reviewed here. OTM divides the GCA into 878 zones, models the flows of passengers and freight among those zones, and assigns the zone-to-zone flows of auto and PT trips to the respective networks. The passenger component of OTM generates tours originating in each zone for several purposes (work, business, education, shopping and leisure) taking into consideration the distribution of income and age among persons living in the zone. A discrete choice model distributes the tours among the destination zones and five transport modes (Auto driver, auto passenger, PT, bicycle and walk), resulting in matrices of mode-specific trips that can be assigned to the network along with separately generated “non-home-based” passenger trips and freight trips. Before the auto and PT trips are assigned to the network they are split into ten time-of-day categories, using a time-of-day choice model. (Fox and Baak, 2006; Jovicic and Hansen, 2003; Vuk, 2013)

Some characteristics of OTM limit its effectiveness in accurately modeling bicycles. In measuring the attractiveness of bicycling for a trip, OTM takes into consideration only the average distance between zone centroids. In using only distance it ignores characteristics of the various possible routes, such as the presence and quality of cycle tracks, and of the parking facilities at the destination. Given that many bicycle trips occur over fairly short distances, and OTM divides the region into only 878 zones, the average distance between zones provides a weak representation of the actual distance encountered among the various trips between a pair of zones. In modeling the choice of PT as a mode, OTM ignores the modes used for PT access and egress. Thus, it has no way of explicitly representing the many bicycle trips that are made to and from PT, or the effects of bicycle parking conditions or boarding permission upon the transport choices.

Danish National Transport Model (LTM)

LTM is a new model being developed by DTU. A primary focus of this model is to provide a common modeling framework for all of Denmark, enabling better comparison of projects from different regions, and making it easier to develop and maintain the needed data foundation (Rich, et al, 2010). LTM divides Denmark into 907 zones, which are larger in size than the 878 zones used by OTM for the GCA. It also uses a tour-based passenger demand model component that is similar to OTM’s, though without the time-of-day model. These characteristics leave LTM weaker than OTM with respect to the modeling of bicycle transport. However, the LTM development project includes provision for the development of region-specific submodels that can be more detailed than the base LTM. Also, it includes the development of a bicycle route choice model and the associated bicycle network with important attributes that affect bicycle route choice. Thus it provides some of the foundation needed for improved modeling of the bicycle mode.

Copenhagen Model for Person Activity Scheduling (COMPAS)

COMPAS is a new model being developed in a project called ACTUM by a consortium of researchers under the leadership of DTU. A primary focus of this model is the use of a disaggregate AB demand microsimulation model (COMPAS DaySim) coupled with disaggregate assignment models (Hansen, et al, 2010). An initial working implementation of COMPAS DaySim uses the 878 zones of OTM, but an enhanced 9,710 zone system has been developed that will be used for the second draft. COMPAS DaySim explicitly models joint travel and intermediate stops on tours. It also provides a suitable platform for explicitly simulating PT access and egress by car or bicycle, although this feature has not been implemented in the first draft. COMPAS is expected to use a first draft of the disaggregate bicycle route choice model being developed for LTM. Thus, the COMPAS model provides an excellent starting point for achieving many of the desired bicycle modeling capabilities.

Proposed New Model Features

Introduction

As mentioned above, COMPAS is well-suited for enhancement to satisfy additional needs. Key among the reasons for this is the use of demand microsimulation and disaggregate assignment. This section proposes such COMPAS enhancements, focusing on two aspects of the model system: route choice and mode choice[1]. The following subsections describe the proposed route choice and mode choice features in more detail, as well as the associated data needs.

Bicycle route choice

The bicycle route choice model would select a route for each bicycle trip, including trips of access to or egress from public PT stations (“bike and ride”), as modeled by the AB demand model. It would be implemented as a logit or probit model with accounting for the partial overlapping of different paths available to the bicyclist. Recent examples of bicycle route choice models now in use include those in Portland, Oregon (Broach, et al, 2012), and San Francisco, California (Hood, et al, 2011), and examples of those under development include San Diego, California (Hood Transportation Consulting, 2013) and Copenhagen. The Copenhagen model should be able to serve as the basis for an initial implementation in COMPAS, with the possibility of implementing subsequent enhancements as important data is made available and research in this area continues to advance.

Some desirable features include:

1. Disaggregate assignment of each trip, with utility functions that vary for at least four population segments:
    a. Commute to school involving child under age 13
    b. Commute to work or school not involving child under age 13
    c. Non-commute trip involving child under age 13 or adult age 65 or older
    d. Non-commute trip not involving child under age 13 or adult age 65 or older

   The reason for this segmentation is that the importance of factors affecting route choice varies across persons and travel purposes. The above segmentation uses age as a proxy for ‘ruggedness’ of the traveler, which affects the willingness to tolerate motor traffic. It also recognizes that

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[1] In the AB demand models, the choices of destination, mode and time of day are closely related, and interdependent. They are typically modeled in a conditional hierarchy, and the structure of the hierarchy is determined through empirical analysis of the data used for model estimation. For most purposes in this document, these distinctions are not necessary, and references are made to mode choice or mode utility function for the sake of simple communication. The text makes it clear in cases where distinctions between the three choice categories are important.

commuters may place a high priority on speed. The above segmentation should be tested empirically. From a behavioral standpoint, more extensive segmentation is probably desirable. However, greater segmentation requires more data for estimating parameters and more computation in the assignment of trips to the network and calculation of the resulting network attributes and accessibility measures.

2. Use of microzone centroids and PT stop locations as origins and destinations
3. Detailed network, including all streets and bicycle facilities
   This is more important for bicycle than for cars, because increased detail benefits the measurement of short trips more than that of long trips.
4. A route choice utility function that realistically identifies sensitivity of bicyclists to link and route attributes that are important to them when they make their route choices. Including important factors other than distance enables the model to capture the tendency of some bicyclists to accept a longer route if it avoids, for example, heavy car traffic, poor bike facilities or hills. Appendix 2 lists link attributes that were developed for the Greater Copenhagen Area and used to develop a route choice model in the context of the LTM development project. These attributes provide a good starting point, but in the course of developing the route choice model, some deficiencies were identified. In addition, the interviews of Danish bicycle experts conducted in this project have identified additional data needs. Appendix 3 lists and provides brief notes on needed additional network data. It includes a few important items that would be derived from basic data and/or external information. The notes explain the importance of each type of item and identify those for which stated preference analysis is probably needed. The LTM route choice model development work may lead to an enhancement and refinement of the Appendix 3 list.
5. Accounting for link capacities that restrict flows and reduce speeds. This is important to the extent that congestion and reduced speeds affect bicyclist route and mode choice, such as inducing some bicyclists to find parallel routes in order to avoid congestion. It involves assignment that depends on demand-sensitive link performance functions and relies on iteration to achieve consistency of performance assumptions with resulting link flow levels. This would require speed-flow functions for links and intersections, which might be based on empirical research using traffic counts, GPS data, and bicycle flow simulation tools. A significant issue with iterative bicycle assignment is that disaggregate route choice and assignment using an all-streets network would be computationally intensive. If such computation is too slow, a fallback approach might be to implement dynamic assignment that accounts for capacity constraints without requiring iteration of demand and assignment models.

Mode choice

As mentioned in the overview, there are several ways that the mode choice models can be improved to better represent bicycling in the traffic model system.

Enhance bicycle mode’s utility function

Mode choice is modeled for a trip or tour between two known locations without knowledge of the exact route. The bicycle mode utility function needs a composite measure of attractiveness among the potentially many routes that are available for the journey. This is important for policy analysis and planning because changes to the attractiveness of any one of the feasible routes can affect the likelihood of choosing bicycle. If the route choice is specified as a logit model, a composite measure comes naturally from the 'logsum'; that is, the log of the sum of the exponentiated utilities of the alternatives considered in the route choice model. Another composite measure would be a probability-weighted route choice utility function.

Because route choice involves the selection of a single path that can overlap with many available unchosen paths, and because route choice models necessarily use only a sample of available paths, it is easy to inadvertently implement the sampling and route choice in a way that distorts the calculated logsum, undermining its ability to accurately reflect the impact of network changes on the attractiveness of the bicycle mode. For example, if a major improvement is made to a sequence of links in a transport corridor, those links might dominate the sampling for origin-destination pairs in the corridor, so that most sampled routes include the improved links. With some sampling and route choice procedures this would essentially reduce the effective size of the sample, and as a result cause the logsum to get worse instead of better as a result of the infrastructure improvement. Hood Transportation Consulting (2013) describes one sampling method that has been developed to avoid this problem.

The decision to use the bicycle mode for a journey depends not only on attributes of the network, but also upon attributes of the destination. The availability, quality and price of bicycle parking at the destination are especially important, and should be included in the bicycle mode utility function. This is needed in order to use the model to estimate the impact of changes in parking supply. Appendix 4 includes a preliminary definition of these desirable attributes.

Explicitly model bicycle access to PT

In Copenhagen many journeys are made using a combination of bicycle and PT, especially for the work commute. In some cases the cyclist parks and leaves the bicycle at the PT boarding location, and either walks or uses another bicycle at the PT destination. In other cases, the cyclist takes the bicycle on board and uses it again at the PT destination. In choosing to use bicycle in combination with PT, the cyclist considers the feasibility and attractiveness of the entire journey, including the bicycle, PT and walking portions, the available PT boarding and alighting locations, and the options for parking and taking the bicycle on board. In order to use the model to estimate the number and type of journeys for which bicycle and PT are combined, and to estimate the effects of policy and infrastructure improvements upon those numbers, it is necessary to model those combined-mode journeys explicitly, taking into consideration the factors that affect the choice. Fortunately, methods for explicitly modeling auto park-and-ride already exist, and methods for explicitly modeling the walk access and egress to PT are in development, and in both cases the implementation is similar to what is needed for modeling bicycle access to PT. The basic approach involves (a) breaking the trip into three components—access, PT, and egress—(b) using attributes of each component as generated by its corresponding route choice model, (c) explicitly modeling the choice of the station pair for access and egress, taking into consideration whether the station pair allows the bicycle to be taken on board, and (d) also taking into consideration the conditions at the access and egress locations, especially parking. Appendix 5 describes aspects of a feasible initial implementation and discusses additional desirable enhancements. Also, since the same basic approach can be used for explicitly modeling other PT access and egress modes, it would be advisable to do this for car park-and-ride, car kiss-and-ride, and PT with walk access.

Model the use of bicycle for escorting children to school

In Copenhagen a large number of trips that people take are made jointly with one or more other members of the household. The initial implementation of COMPAS DaySim explicitly models many of these trips as joint travel, in particular those on “joint tours” for non-work/non-school purposes, and those on “joint half tours” for work or school purposes (including day care or kindergarten for very young children). In joint tours, everybody on the tour travels together for the entire tour, and it is modeled that way. However, for work and school, joint travel is modeled in “half tours” because people often travel home from work or school by a different means than they employ to get there in the morning. For example, sometimes one parent will take their children to school in the morning and the other parent will bring them back home in the afternoon. The choice of bicycle as a mode is supported in COMPAS DaySim for joint tours and for some joint half tours, but it is not currently supported for one type of joint half tour, called a “partially joint half tour”. A partially joint half tour is one in which one person accompanies another from home to their workplace or school, and then travels alone the rest of the way to their own workplace or school; or it involves picking the other family member up on the way back home. For partially joint half tours, COMPAS DaySim assumes that the joint travel occurs by car, but in reality many Danish parents accompany their children to school by bicycle and then proceed to their own workplace by bicycle and possibly also by PT. This limitation needs to be overcome by explicitly modeling mode choice for partially joint half tours, with bicycle and PT as available alternatives. This enhancement, implemented in conjunction with the explicit modeling of bicycle access to PT, as described above and in Appendix 5, would support partially joint half tours where the chauffeur uses bicycle for the entire half tour, or switches from bicycle to PT after dropping off the other family member(s).

In some cases, people may conduct partially joint half tours for purposes other than work or school. For example, a parent may drop a child at an athletic or leisure activity and return home or go shopping. This type of chauffeur activity has not yet been modeled explicitly as joint travel in AB models, by any mode, let alone bicycle, and remains a future objective that is not addressed in this paper.

Scenario analysis for assumed bicycle mode share changes

A model will be unable to estimate changes in mode share induced by a policy or program if the factors affected by the policy or program are not included in the model and associated with it. Likely examples of this include education or promotion programs. However, it may be desirable to understand the impacts to the transportation system if an assumption is made about the change in mode share. For example, it may be desirable to understand the impact on auto congestion, or bicycle congestion, or bike-on-PT usage, if an education or promotion program successfully increases bicycle commuting mode share from 35% to 40%. This type of analysis could be supported with COMPAS by allowing the model user to specify at runtime the target bicycle (and/or bike-PT) mode share. The software would then run iteratively, adjusting the bicycle mode choice constants in the mode utility function until the target percentage of trips was made by bicycle. The model system’s output would then be available to understand the other outcomes associated with that constraint.

Data

As mentioned in the overview, achieving the benefits associated with demand microsimulation, disaggregate assignment, enhanced mode choice and bicycle route choice requires developing, enhancing or augmenting data of five types, including (a) spatial and network data that is more detailed than those that have been used in OTM and the first draft of COMPAS DaySim, (b) additional observed route choice data, (c) a large household diary survey that collects diary data from all members of each household, (d) stated preference data to supplement the household survey and route choice data for the estimation of some model coefficients, and (e) updated and re-categorized trip matrix data used for grounding the details of model forecasts in reality.

Spatial and network data

Increasing the number of traffic analysis zones in the Greater Copenhagen spatial data from under a thousand to nearly 10,000 (microzones) and defining a realistically detailed network enable improved measurement of the spatial and transportation attributes that affect peoples' choices. Using those attributes in the model formulas helps explain choices and capture policy and project effects more realistically. Appendices 2 through 4 describe the network and spatial data needed to support enhanced route choice and mode choice models.

Household diary data

When advanced AB models—such as COMPAS DaySim—estimate travel demand, they take into consideration the household's impact on individual behavior, and also explicitly model joint activity and travel. They require a large quantity of survey diary data similar to the existing TU data, for both the bicycle and non-bicycle dimensions of the models. However, because of the household basis of the models, it is essential to collect diary data for all members of each surveyed household, rather than only one member, as has traditionally been done with the TU data. A small household-based data set comprising 800 households was collected in the ACTUM project for development of the COMPAS DaySim prototype. Development of a production-quality model system will require collection of a much larger data set, initially of at least 6,000 households and growing over time. Before this effort is begun, the detailed composition of the survey should be re-evaluated and enhanced, in light of what has been learned in the development of COMPAS DaySim. In addition, the data requirements of the proposed enhanced model features should be carefully considered, so that the collected data will support them. Given the increasing difficulty of collecting data through traditional surveys, advanced data collection methods should be considered. Such methods involve a combination of GPS tracking, software-based inference of choices, and cell-phone assist and/or prompted recall to correct inferred results and add non-inferable data such as purpose. Although the advanced data collection methods are early in their life cycle, there is growing evidence that they can yield higher quality data than traditional methods, while substantially reducing the burden on survey respondents and those who collect the data.

Route choice data

Enhanced route choice modeling requires the collection of information about the actual route choices that people on bicycles make. This is similar to the data collected via GPS for the prototype route choice model under development at DTU for the LTM. However, the existing data should be reviewed for quality and quantity, and probably augmented with additional improved data, in light of its desired use as part of an AB model system. Such data can then be used in the estimation of enhanced route choice models for implementation in a production system.

It is important that the route choice data include the same kind of background and trip purpose information that are collected in the household diary data and used for developing the AB model. Given the high mode share of bicycling, it would be possible and desirable to collect the route choice data in the context of the household diary survey using GPS data collection as described in the previous section.

Stated preference data

When enhanced spatial and network data are combined with large route choice and household diary data sets, many of the needed model coefficients can probably be estimated. However, in order to estimate some coefficients, it may still be necessary to collect and analyze stated preference (SP) data designed specifically for that purpose, preferably using the SP data jointly with the household diary or route choice data. Appendix 3 notes some of the attributes for which it is most likely that stated preference analysis would be needed, although other attributes in Appendices 2 through 4 might require it also.

Trip matrix data

In Denmark there is a well-established practice of using estimated trip matrices for a base year to ground the details of model forecasts in reality. The trip matrices used with OTM categorize the trips in ways that work well with the OTM structure and function, but they need to be adjusted and updated to work well for COMPAS DaySim. In particular, they should probably not distinguish home-based from non-home-based trips, or trip purposes, neither of which work well for trips that are intermediate stops (in trip chains) on tours. Also, with explicit modeling of PT access and egress modes the trip matrices should explicitly estimate the access and egress trips, by mode, in addition to the PT trips themselves.

Modeling Needs Addressed by the Model Features

In preceding sections the desired model capabilities are listed and the proposed model features are described. This section draws those two efforts together by identifying proposed features that are most important for each of the desired model features. Table 1 does this in tabular form, with a row for each desired capability and a column for each of the major proposed features. The major capability categories are numbered, and the subcategories are lettered. An ‘x’ in a cell indicates that the feature is especially important for achieving the desired capability. An ‘x’ in a major capability category’s row indicates that the feature is important for all its subcategories.

Table 1: Features important to achieve desired capabilities

	Features important to achieve the capability (marked 'x')									
Desired Capabilities	Basic AB Model with microzone Os and Ds and detailed bike network	Route Choice	Link and route attributes	Link capacity accounting	Mode Choice	Route choice logsum	Parking data	Transit access and egress	Bike chauffeur to school	Scenario analysis
1. Estimate the impact on bicycle mode share, traffic flow, travel times or health impacts of a major road or PT infrastructure project or policy, such as:										
a. New Metro line	x				x		x	x		
b. Expanded or reduced highway capacity	x									
c. Increased or reduced vehicle purchase taxes	x									
d. Increased or reduced fuel prices	x									
e. Peak period congestion charges	x									
f. PT fare changes	x									
2. Estimate the change in bicycle mode share, flows, travel times or health impacts of a bike infrastructure project, such as:	x							x	x	
a. new cycle track that fills a continuity gap	x	x	x		x	x		x	x	
b. new green wave, widened cycle track, cycle superhighway or other traffic engineering improvement that increases bicycle capacity and/or speed	x	x	x	x	x	x		x	x	
c. increased availability of secure parking at employment centers and residences	x				x		x	x	x	x
d. increased availability of convenient parking in commercial districts	x				x		x	x	x	
e. additional traffic calmed neighborhood streets	x							x	x	
f. intersection improvement that increases safety of a known red spot	x	x	x		x	x		x	x	
g. addition of a major bicycle bridge or many minor bicycle shortcuts	x	x	x		x	x		x	x	
3. Estimate the incidence of trips made by a combination of bicycle and PT. Estimate the change in PT usage, bicycle usage, shared bike-PT trips, bicycle parking and bicycles on PT vehicles induced by bike-PT programs, such as:	x							x		
a. Increased provision of secure and convenient parking at train stations	x				x		x	x		
b. New or increased bicycle capacity on trains or buses	x				x			x		
4. Estimate the change in mode shares, volumes and speeds of new bike modes, such as:	Not addressed in this research and design									
a. E bikes										
b. Bike share program										
5. Estimate the impact, on traffic volumes and speeds (or travel times) by each mode (auto, PT, bike, walk), of an assumed increase in bike mode share induced by any type of non-infrastructure program, such as increased school education, marketing campaign, smartphone apps, bike pumps or footrests, or a program aimed at a particular population subgroup defined by age, income, gender, household composition, geographic neighborhood or auto ownership.	x									x
6. Estimate the impact of infrastructure or policies on particular population subgroups defined by age, income, gender, household composition, geographic neighborhood or auto ownership. Estimate the amount of bicycle use by particular population subgroups for particular purposes, such as:	x									
a. workers for work commute	x								x	
b. students for school commute	x								x	
c. parents and children traveling together for school trips	x								x	
d. families traveling together for activities other than the work and school commutes	x								x	
e. young adults for socializing and eating out	x									
f. retired adults	x									
g. adults for escorting others	x								x	

Several summary comments can be made about the correspondence of desired capabilities with the proposed features:

1. A basic AB microsimulation model that uses detailed microzone geography and detailed bicycle network, such as the COMPAS model being developed as a prototype for Copenhagen in the ACTUM research project is a pre-requisite for achieving any of the desired features. For most desired capabilities, this must be accompanied by further implementation of other proposed features. However, this in itself should be enough to improve the estimation of impacts associated with major road infrastructure and policy projects.
2. Because of the high usage of bicycle as a PT access mode, it is important to model PT access and egress modes explicitly in order to achieve improved estimates of the effects of PT infrastructure and policy, bicycle infrastructure, and programs aimed at dealing with bicycle access to PT.
3. To estimate the effects of bicycle infrastructure projects or programs aimed at bicycle access to PT, enhanced bicycle mode choice modeling is needed.
4. For any infrastructure or policy that directly affects bicycle route attributes, such as the presence, capacity or quality of cycle tracks, or signal coordination, a bicycle route choice model is needed that directly incorporates the attributes of interest, and the mode choice model must use the summary accessibility results (logsums) generated by the route choice model.
5. The scenario analysis feature can be used to estimate effects that are not directly modeled.
6. This research does not deal directly with features aimed at effectively modeling new bicycle modes, such as E-bikes and the new bike share program. It may be possible to model them effectively, but further research would be needed.

Implementation Strategy

Given the research investment that has been made in developing the prototype COMPAS AB model system in the ACTUM project, and the suitability of COMPAS for incorporating the proposed features related to the bicycle mode, the proposed implementation strategy is to incorporate the bicycle features into an enhanced version of COMPAS developed with the primary purpose of serving as a production model system for travel demand forecasts and policy analysis in the Greater Copenhagen Area. This model system could also serve as one of the regional model implementations as part of the new LTM. A five phase project is envisioned. The five phases would be carried out in sequence, not in parallel, although phases 2 and 3 could occur in parallel, and some other minor phase overlaps might occur. The phases are as follows:

1. Design. The design would develop specifications for the enhanced models, all of the software to be included in the integrated system, and each of the five types of needed data. The design would be detailed so that development of models, software and data could proceed in parallel with little risk of subsequent incompatibility.
2. Data. In the data phase all five categories of data would be collected and prepared for its intended use.

3. Software. While the data was being collected, the software implementation would occur. This would build upon the software basis established in the ACTUM project. It would result in a fully functioning operational model system, but the model utility functions and coefficients would lack the sound empirical basis provided by the data being collected.
4. Estimation. Once the data and software were in place, the structure and coefficients of all the models would be estimated and tested using the route choice, household diary and stated preference data.
5. Integration. After the estimation was complete, a short integration phase would be used to incorporate all of the estimation results into the software and get it running smoothly.
6. Validation. In the final phase, the model system would be tested in detail for base year conditions, and sensitivity tests would be conducted. This phase would naturally lead to software bug fixes and model improvements to address problems uncovered during the tests.

The detailed project plans might lead to a multi-project approach, in which lower priority objectives are deferred for later implementation.

Appendix 1—List of Persons Interviewed

The needs represented in this white paper, and the understanding of the current data situation, were derived primarily from a series of formal interviews with the following persons. The interviews were conducted without formal feedback mechanisms to assure that the author understood the remarks of those who were interviewed, or that those interviewed agreed with the author’s conclusions.

Christian Overgård Hansen, DTU

Katrín Halldórsdóttir, DTU

Andreas Røhl, City of Copenhagen (Københavns Kommune)

Erik Kjærgaard, Atkins

Søren Hasling Pedersen, DTU

Svend Jacob Senstius, DTU

Linda Christensen, DTU

Lars Moustgaard, Danish Road Directorate (Vejdirectoratet)

Henrik Gudmundsson, DTU

Henrik Nejst Jensen, Danish Road Directorate (Vejdirectoratet)

Niels Jensen, City of Copenhagen (Københavns Kommune)

Søren Elle, City of Copenhagen (Københavns Kommune)

Troels Andersen, City of Odense (Odense Kommune)

Pablo Celis, City of Aarhus (Aarhus Kommune)

Anne Marie Lautrup Nielsen, City of Aalborg (Aalborg Kommune)

Niels Thorup Andersen, City of Aalborg (Aalborg Kommune)

Lizzette Birk Petersen, Danish Road Directorate (Vejdirectoratet)

Appendix 2—Link Attributes of the Existing Copenhagen Bicycle Network Data

Table A2 lists attributes of the existing Copenhagen bicycle network data. A high priority for improving the modeling of bicycling is to correct inaccuracies of these data. For example, "bridges/tunnels across rail road tracks are missing, bicycle paths along roads are missing, and a large number of links (e.g. in forest) are not really bicycle paths and should be deleted from the network" (Nielsen, 2014).

Table A2

ID		Description/Values
FOT_kbh_ID		Project related reference
FEAT_ID		Original FOT-kort10 id
From_node		Unique node identification
To_node		
mm_Aktiv		Project related attribute, derived from "Type"
rc_Aktiv		
OpenFor		Driving directions
OpenBack		
Type	11	Road
	12	Road with striped bicycle lane
	13	Road with curb-separated bicycle track
	21	Bicycle path (off-road)
	22	Footpath
	23	Steps
	31	No bicycle access
	32	No access
Surface	1	Paved
	2	Paved, cobblestone
	3	Unpaved
	4	Unpaved, only mtb
LanduseRight		Low residential, High residential, Industry, Town center, Park, Forrest, Heath, Cemetery, Sport facilities, Sand, Technical facilities, Gravel pit ect, Coast, Lake, Wetland, Stream
LanduseLeft		
Cum_elev_gain		Sum of elevation gain/loss on all subparts of a link. gain and loss is relative to drawing direction of the link. (Meters)
Cum_elev_loss		
Cum_elev_gain_0_10		Sum of elevation gain/loss on all subparts of a link categorized in ‰. gain and loss is relative to drawing direction of the link. In other words: Percentage of link with gain per thousand in range of 0 to 10 meters (ie with slope up to 1%)
Cum_elev_gain_10_35		similar as above
Cum_elev_gain_35_50		similar as above
Cum_elev_gain_above_50		similar as above
Cum_elev_loss_0_10		similar as above
Cum_elev_loss_10_35		similar as above
Cum_elev_loss_35_50		similar as above
Cum_elev_loss_above_50		similar as above
FromIntersectionLegsAll		Count of legs in an intersection. Dead end links are excluded in the count.
ToIntersectionLegsAll		
FromIntersectionLegsRoad		Count of legs in an intersection. Dead end links and paths (type 21 and 22) are excluded in the count.
ToIntersectionLegsRoad		
FromIntersectionType	-1	Unknown
	0	No intersection (pseudo-nodes and path intersecting road)
	1	Giveaway junction (da: vigepligt)
	2	Roundabout
	3	Traffic Signal
ToIntersectionType		
MotorTrafficSpeedLimit		Based on NavTeq Streets. For paths with type 13 values refers to corresponding road.
MotorTrafficLanes		
MotorTrafficFunctionalClass	1	Used for roads with high volume, maximum speed traffic movement between and through major metropolitan areas.

ID		Description/Values
	2	Used to channel traffic to MotorTrafficFunctionalClass = 1 roads.
	3	Roads which interconnect MotorTrafficFunctionalClass = 2 roads and provide a high volume of traffic movement at a lower level of mobility than these.
	4	Roads which provide for a high volume of traffic movement at moderate speeds between neighbourhoods.
	5	Roads with low volume and traffic movement. In addition, walkways, Parking lanes etc.
	-1	Non-navigable links
LTM_ID		Reference to LTM version 1.05 road network
LTM_LinkType		
LTM_WDT		LTM modelled average week day total traffic (C146)
LTM_TruckShare		Truck share of LTM_WDT
LTM_FreeSpeed		Uncongested speed used in LTM
AccidentsVejman08_12		Count of reported accidents 2008 to 2012
AccVejmann08_12_NoIntersect		Count of reported accidents not related to intersections
Dead_end		Value is 1 for dead end link, while links with values greater than 1 is dead ends, only if links with lower values are removed. Possibly to be used for limiting the number of links.
Serviceroad		Road of lesser importance.
Type_quality		Project related attributes.
Directions_quality		
Surface_quality		
Municipality		
GreaterCopenhagenArea		
Urban		Urban area is defined as place with more than 200 inhabitants and less than 200 meters between houses
FOT_Vejtype		Project related attributes
BicyclePathFactor		To be used for a comparable quantification of the length of bicycle paths. When multiplying with Shape_length each route with bicycle path will count only once regardless of whether the route appears with one, three or more parallel links.
Shape_Length		Length in meters
Darkness		Darkness, calculated by date and time of day of trip by looking up in a table of sunlight hours

Sources: (1) Katrín Halldórsdóttir, Søren Hasling Pedersen, Svend Jacob Senstius (2013). Bicycle Network for Greater Copenhagen Area. Unpublished data dictionary, Danish Technical University; (2) Private conversation with Katrín Halldórsdóttir, Danish Technical University.

Appendix 3—Recommended Additional Link Attributes for the Network Data

Table A3 lists additional link attributes that would enable improved bicycle route choice modeling. The following summary comments deserve to be highlighted:

1. In modeling route choice it is important to know the attributes in the direction of movement. In many cases the attributes are the same in both directions, but in some cases they are not. The following list explicitly identifies attributes by direction of movement. If it is not feasible to maintain network information in both directions for all links, then a fallback option would be to develop two-directional information only in known cases where it is important to distinguish attributes by direction, and in all other cases assume that the attributes are the same in both directions.
2. The following list includes attributes that could be derived using other link attributes and logic embedded in the network traversal algorithms. These include link attributes and intersection attributes. For intersection attributes, it may be better, for purposes of practical application, to collect and gather them into a separate data table along with intersection attributes that are already used for car route choice.
3. The table includes link and intersection traversal times, which carries the assumption that these are exogenous. As mentioned in the main body of the report, it would be better for the route choice model to account for link capacities that restrict flows and reduce speeds, depending on the level of demand. This would require speed-flow functions for links and intersections, which might be developed through rigorous empirical research. Such functions would then be used in conjunction with demand-supply iteration, instead of treating travel times as exogenous.
4. The currently active LTM route choice model development work may lead to an enhancement and refinement of this list.

Table A3

ID		**Description/Values**	**Notes on new items and usage**
LanesForward		Number of motor vehicle lanes in the forward (For) direction	Needed in conjunction with traffic volumes to assess bicyclist exposure to danger from motor vehicles
LanesBackward		Number of motor vehicle lanes in the backwad (Back) direction	
OpenForwardBicycle		Link is open for bicycling in the forward direction	Need to know availability specifically for bicycles (e.g., contra-flow lane or permission)
OpenBackwardBicycle		Link is open for bicycling in the backward direction	
TypeForward		Type in the For direction	Need to know the quality of the bicycle facility in each direction, because it sometimes differs by direction
	11	Road	
	12	Road with striped bicycle lane	
	13	Road with curb-separated bicycle track	
	21	Bicycle path (off-road)	
	22	Footpath	
	23	Steps	
	31	No bicycle access	
	32	No access	
TypeBackward		Type in the Back direction	
	11	Road	
	12	Road with striped bicycle lane	
	13	Road with curb-separated bicycle track	
	21	Bicycle path (off-road)	

ID		Description/Values	Notes on new items and usage
	22	Footpath	
	23	Steps	
	31	No bicycle access	
	32	No access	
SurfaceForwardBicycle		Surface for bicycle in the forward direction	Need to know the surface quality in each direction for bicycle if cyclists have a different surface than cars
	1	Paved	
	2	Paved, cobblestone	
	3	Unpaved	
	4	Unpaved, only mtb	
SurfaceBackwardBicycle		Surface for bicycle in the backward direction	
	1	Paved	
	2	Paved, cobblestone	
	3	Unpaved	
	4	Unpaved, only mtb	
WidthForwardBicycle		Width, in meters or centimeters, of the bicycle lane, track or path in the forward direction	Need to know width of cycle lane, track or path. Greater width should be more attractive. Stated prefrence analysis using this attribute would be beneficial.
WidthBackwardBicycle		Width, in meters or centimeters, of the bicycle lane, track or path in the backward direction	
ParkingForward		Cars can park on street in the forward direction	Car parking makes Type 11 or 12 dangerous and unattractive for cycling. Stated preference analysis using this attribute would be beneficial, if there is a lot of on-street parking on type 11 and 12 facilities.
ParkingBackward		Cars can park on street in the backward direction	
GreenSignalForward		Signal ahead in forward direction is timed for and announced to bicyclists via green wave or signage	Presence of many green signals provides enhanced flow for bicyclists. This attribute identifies 'Green Wave' treatments. Stated preference analysis of this attribute, in the context of analysis of other intersection attributes, would be beneficial.
GreenSignalBackward		Signal ahead in backward direction is timed for and announced to bicyclists via green wave or signage	
LTM_WPHT		Modelled average weekday peak hour traffic	It is unattractive to bicycle unprotected on roads with high speed and/or volume. Motor vehicle speed and volume attributes can be interacted with bike facility type to identify the unattractive conditions. Technically speed and flow are endogenous, but could be treated as exogenous, using trend estimate, or base case result for forecast scenarios, or using free flow conditions or road class as proxies. If iterative bicycle assignment procedures were implemented, then it would become possible to use auto flows and speeds from prior iterations to explain bicycle route choices (and also use bicycle flows from prior iterations to explain auto route choices). Stated preference analysis to evaluate the sensitivity of bicycle route choices to the speed and flow of motor traffic would be beneficial.
LTM_TruckShare_H		Truck share of LTM_WPHT	
LTM_PeakSpeed		Peak hour speed from LTM	
IMPORTANT ITEMS DERIVED FROM OTHER ATTRIBUTES AND EXTERNAL INFORMATION			
Various turn and signal attributes		for example, number of unsignalized left turns, or number of left turn signals per km, or number of signals per km	Calculated from geography of the network. Some types of turns are time consuming and unattractive. High signal density is unattractive. Some coefficients can be borrowed from existing studies. However, a substantial amount of stated preference analysis would be beneficial, exploring the importance of various attributes related to intersections on the route.
Link, intersection approach and intersection traversal stress levels:		Interaction of bicycle facility type with number of traffic lanes, other geometric attributes, and levels of motor traffic and speed, during peak and offpeak periods.	A simple measure would be a binary variable for combinations of the variables that fail to meet accepted safety standards. An example of a dangerous combination would be Type 11 or 12 roads with high traffic per motorized lane and high speed. Another could be any type 11 road with one motorized lane, high traffic volume and on-street parking. A more complex measure could identify levels of stress, such as those developed by
Link traversal stress level			
Intersection approach stress level			
Intersection right turn traversal stress level			

ID		Description/Values	Notes on new items and usage
Intersection straight ahead traversal stress level			Furth and Mekuria (2012). Estimation of coefficients could require customized stated preference data and associated econometric analysis.
Intersection left turn traversal stress level			
Link and intersection traversal times:			Link and intersection traversal times are sensitive to congestion. Given the presence of bicycle congestion in Copenhagen, it might be important to develop iterative procedures in which speed sensitive route choice is modeled, bicycle traffic is assigned according to route choice, and speeds are re-estimated based on assigned link and intersection volumes. This would require speed-flow functions for links and intersections, which might be based on empirical research using traffic counts, GPS data, and bicycle flow simulation tools. A significant issue with iterative bicycle assignment is that disaggregate route choice and assignment using an all-streets network would be very computationally intensive.
Link traversal time		Travel time required to traverse link	
Bicycle right turn intersection time		Wait and travel time required to traverse intersection when exiting the link without needing to cross traffic (usually a right turn)	
Bicycle straight ahead intersection time		Wait and travel time required to traverse intersection when exiting the link across stopped traffic (usually straight ahead)	
Bicycle left turn intersection time		Wait and travel time required to traverse intersection when exiting the link across moving traffic (usually left turn)	

Appendix 4—Recommended Parking Supply Attributes

Parking attributes are needed for including the effects of parking supply in the models. They are included as attributes of the microzones and the park-and-ride locations. They are used in the bicycle and auto mode-destination utility functions, as well as the PT access and egress choice utility functions. Table A4 provides a preliminary list of likely important attributes. To finalize the list and detailed definitions of attributes, further field work and discussions with transit officials should be undertaken, as well as a review of data already developed for LTM.

Table A4

Attribute	**Notes**
Number of public bicycle parking spaces, by type: --without designated spaces --exposed rack --covered rack --covered secured long term spaces --time-restricted short term spaces	
Median distance of parking spaces to principal transit access point (e.g. station entrance), by type: --without designated spaces --exposed rack --covered rack --covered secured long term spaces --time-restricted short term spaces	For bicycle park and ride locations only
Price of time-restricted short term spaces --peak hour --off-peak hour	
Time limit of time-restricted short term spaces	
Price of covered secured long term spaces --daily --monthly	
Number of public auto parking spaces	
Price of public auto parking --peak hour --offpeak hour --daily --monthly	

Appendix 5—Design Note on the Modeling of Bicycle Access to PT

Overview

This appendix describes how DaySim might handle bike and ride modes in the context of a consistent way of handling all journeys involving PT. The current DaySim approach is retained of modeling tour mode, then conditionally modeling trip mode as part of half tour construction on first half tour followed by second half tour. However, for tours and trips involving PT, the mode definition would be changed to carry information about access, parking and egress. For example, the mode called 'bike on PT' would use bike for access and egress, and the bike would be taken on board rather than parked at the access location. Given one of these modes, a PathType model selects (jointly) the access transfer node and egress transfer node, taking into consideration the separate attributes of the access, main and egress paths, as well as attributes of the transfer nodes themselves.

Since the tour modeling of Daly and Hess does not use modes defined by explicit access, main and egress modes and their separate attributes, their estimation results will need to be translated into the enhanced mode framework. For example, when the main mode is PT, the in-vehicle time and cost coefficients can be used for the main mode, and either the walk, bike or auto coefficients might be used for the access and egress legs of the journey. The details of this translation would need to be worked out.

PT tour and trip modes

The definition of mode for journeys involving PT is changed to refer not only to the main mode (PT), but also to the modes used for PT access and egress, and whether or not the access mode vehicle is parked at the access location. PT tours and trips can thus be conducted using the following modes:

Table A5.1. PT modes distinguished by access mode, parking and egress mode

Mode name	Access mode	Park at access location?	Egress mode
Car park and ride	SOV	Yes	Walk
Kiss and ride	HOV passenger	No	Walk
Bike on PT	Bike	No	Bike
Bike-park-ride-walk	Bike	Yes	Walk
Bike-park-ride-bike	Bike	Yes	Bike
Walk PT	Walk	No	Walk

The three modes that involve parking would be available as tour mode, but not as trip mode, based on the assumption that the vehicle must be picked up again and used for egress on the return half tour.

DaySim Spatial Classes

DaySim currently uses spatial data classes called Microzones, Zones, StopAreas and ParkAndRideNodes in dealing with park and ride mode and PT walk mode. These would be used and augmented to handle the additional PT modes:

Microzones are the basic spatial units, serving as the origins and destinations of trips.

Zones, which are larger than microzones, can be used as the OD basis for impedance of any mode.

StopAreas are special "zones" that consist of one or more closely related PT network stops. For modeling bike access and egress explicitly, StopAreas should be used instead of Zones as the OD basis for PT impedance, because they can provide a more precise network-based measurement that excludes access and egress, also allowing access and egress impedance to be measured precisely. Each StopArea is associated with a specific Microzone so that trip ends at a StopArea can be tabulated by Microzone as well as by StopArea.

WalkableStopAreas is a list of the best StopAreas within walking distance of each Microzone, along with the associated on-street distance. Similarly, BikeableStopAreas is a list of the best StopAreas within biking distance of each Microzone, along with the associated on-street distance (or route choice logsum converted to generalized PT time). These comprise the available access and egress locations for walk and bike access and egress when parking is not involved. The BikeableStopAreas also represent a reasonable set of access locations to be used for Kiss and ride mode. Otherwise, a third set of stop areas—KissAndRideStopAreas—would be needed.

ParkAndRideNodes are zones of a special type, which must be used for park and ride access by bicycle or car. Each ParkAndRideNode has attributes identifying parking capacity (which can be zero) and price information for both car and bicycle, and the IDs of the associated PT StopArea and Zone, which are used to model the choice of access location.

PathTypeModel

Given a tour or trip designated as one of the PT modes, the DaySim PathTypeModel selects locations where the access and egress occur, taking into consideration the attributes of the entire journey. To do this it loops on all available access and egress node pairs, calculates the utility of each one, and simulates the choice of one of them. For each available access and egress node pair, the level of service (impedance) information needed to construct the pair's utility function is retrieved from the skim roster separately for access mode, main mode and egress mode, using the skim attributes of the applicable mode.

For the bike-and-ride and kiss-and-ride modes, the number of available access and egress node pairs might be so large that it becomes necessary to implement alternative sampling of the node pairs for the sake of computational efficiency.

Several attributes are especially important for determining the utility of a PT journey by one of the PT modes. These include : (a) parking supply at the ParkAndRideNode, as described in Appendix 3; (b) route choice logsum (or distance) for the access and egress modes, calculated between microzones, and transformed into equivalent PT in-vehicle travel minutes; (c) PT stop-area-to-stop-area impedance variables that exclude impedance associated with access and egress; (d) for the Bike on PT mode, a special PT StopArea-to-StopArea impedance variable that indicates whether bikes are allowed on board for a specific origin, destination and time of day. If not allowed, then the utility of Bike on PT is severely reduced (but not eliminated to allow for folding bikes).

The following table lays out key aspects of the workings of PathType model for the various PT modes. It also notes that the initial implementation in DaySim might prohibit intermediate stops after PT egress on tours involving bicycle or car park and ride.

Table A5.2. Aspects of PathType modeling for the PT modes

Mode	**To model choice of access location, loop on…**	**Access impedance based on**	**To model choice of egress location, loop on…**	**Egress impedance based on**	**Egress Intermediate stops allowed?**
Car park and ride	ParkAndRideNodes	SOV zone-to-zone IVT	Walkable StopAreas	Microzone-to-StopArea distance	No
Kiss and ride	Bikeable StopAreas	Microzone-to-StopArea distance	Walkable StopAreas	Microzone-to-StopArea distance	Yes
Bike on PT	Bikeable StopAreas	Microzone-to-StopArea route choice logsum	Bikeable StopAreas	Microzone-to-StopArea route choice logsum	Yes
Bike-park-ride-walk	ParkAndRideNodes	Microzone-to-StopArea route choice logsum	Walkable StopAreas	Microzone-to-StopArea distance	No
Bike-park-ride-bike	ParkAndRideNodes	Microzone-to-StopArea route choice logsum	ParkAndRideNodes	Microzone-to-StopArea route choice logsum	No
Walk PT	Walkable StopAreas	Microzone-to-StopArea distance	Walkable StopAreas	Microzone-to-StopArea distance	Yes

Park and ride capacity constraints

For car park and ride and bike park and ride, the access locations (ParkAndRideNodes) have parking capacity constraints. After car park and ride or bike park and ride is selected and the ParkAndRideNode is determined, the node's fill level is updated. It is also updated when the tour returns to the access transfer node and the car or bike is removed. In any given run of DaySim it is possible to exceed a ParkAndRideNode's capacity for any specific time of the day. To prevent the model from allowing unacceptably overfilled transfer nodes a shadow pricing mechanism is used: Shadow prices are used in the PathType utility function to reduce the attractiveness of overfilled nodes. DaySim is run iteratively, adjusting the shadow prices after each iteration until the fill levels are deemed acceptable. DaySim's current park and ride shadow pricing mechanisms need to be adapted to support shadow pricing for bike park and ride.

Trip outputs

In generating output, each trip by the newly defined modes should be split into three separate trips or trip legs, so that each leg can be assigned separately with other trips of the same mode. For example, a bike on PT trip would be split into two bicycle trips and one PT trip, and a car park and ride trip would be split into one car trip, one PT trip and one walk trip. The bicycle, PT and car trips would all be assigned separately. There is currently no provision for walk trip assignment.

Trip mode availability restrictions

Given a tour mode, restrictions exist on the availability of trip modes, as follows:

Table A5.3. Trip mode availability restrictions

Tour mode name	Restrictions
Car park and ride	--both half tours must include tour mode on exactly one trip --the SOV access microzone (park and ride node) on both half tours must be the same, based on the assumption that the rider picks up the car on the return half tour --trips on tour destination end of trip via tour mode can be walk PT, walk or HOV passenger --trips on tour origin end of trip via tour mode must be SOV
Kiss and ride	--at least one half tour must include tour mode on exactly one trip --trips on tour destination end of trip via tour mode can be walk PT, walk, or HOV passenger --trips on tour origin end of trip via tour mode must be auto passenger --trips on non-kiss and ride half tour can be walk PT, walk or HOV passenger
Bike on PT	--at least one half tour must include tour mode on at least one trip --trips on tour destination end of first modeled trip via tour mode can be bike or walk --trips on tour origin end of last modeled trip via tour mode can be bike or walk --trips on the tour between first and last trips modeled via tour mode can be bike or tour mode --for trips using tour mode, bike-allowed-on-board is not a firm requirement for the boarding and alighting PT nodes, because it is possible for person to carry a folding bike on board or have another bicycle at the alighting node; however, bike-not-allowed-on-board should strongly reduce the likelihood of a node pair.
Bike park-ride-walk	--both half tours must include the tour mode on exactly one trip --the bike access ParkAndRideNode on both half tours must be the same, based on the assumption that the rider picks up the bike on the return half tour --trips on tour destination end of the tour mode trip can be walk PT, walk or HOV passenger --trips on tour origin end of the tour mode trip must be bike
Bike park-ride-bike	--both half tours must include the tour mode on exactly one trip --the bike access ParkAndRideNode on both half tours must be the same, based on the assumption that the rider picks up the bike on the return half tour --trips on tour origin and destination ends of the tour mode trip must be bike
Walk PT	--at least one half tour must include tour mode on at least one trip --trips on tour destination end of first modeled trip via tour mode can be walk or HOV passenger --trips on tour origin end of last modeled trip via tour mode must be walk --trips between first and last modeled trip via tour mode can be walk or HOV passenger or tour mode Trips on non-tour-mode half tour can be walk or HOV passenger

Needed empirical analysis

The TU and ACTUM TU data need to be analyzed in several ways to verify or serve as a basis for enhancing the designs described above:

1. Analyze the occurrence and frequency of the three bike and ride modes, as well as the occurrence of cases that don't fit neatly into those categories, such as bike on PT that doesn't return to pick up the bike on the return half tour.
2. Analyze the distribution of the bike and ride modes by purpose, to determine whether they are both needed for all purposes.
3. Analyze the occurrence of trip mode combinations on tours and half tours, and the frequency and mode of trips before the access transfer and after the egress transfer, to test the stated trip mode availability assumptions.

The existing program that prepares the ACTUM TU data for model estimation might be used in this empirical analysis. Whether or not it is used for that purpose, once the design is finalized, it needs to be modified to accommodate the design changes. In particular, it needs to identify the mode of each tour and trip according to the new definitions.

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