Trafikverket

# Parking resistance in Sampers

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## Summary

In urban areas, access and cost of parking are factors that affect car travel. Parking resistance is captured in today's version of Sampers only in a simplified form for Gothenburg and Stockholm. This simplified form has drawbacks that make the method unsuitable to implement on a larger scale. As a result, Trafikverket has identified in this project the need to investigate how parking resistance is implemented in other regional and national traffic models around the world. The purpose of the project is to make academic and applied knowledge available in Swedish to provide a knowledge base for how parking resistance can be implemented in Sampers.

This report provides a literature review which examines worldwide transport modelling guidelines and academic research investigating 17 models from around the world which have implemented parking resistance modelling in some form. From the literature review two main approaches are identified. These are:

- An approximate treatment of parking
- Full treatment of parking

The approximate treatment involves the parking fee and most often also search time components as part of the model's calculation of travel cost. The treatment requires information about parking fee per area, geographical aggregation of areas to apply fees consistently and estimates of search time per area.

The full treatment of parking involves modelling the impact of the supply of parking and how decision making about parking location is impacted by the combined effects of price, location, and availability. For this to be modelled properly data on the supply of parking (number of car parks) is required.

Finally, this report outlines potential implementation steps for parking resistance in future versions of Sampers. These included further investigation into the data collection methods that could be used for parking prices, search times, and parking supply. As Trafikverket is keen to capture the impacts of parking supply/demand this implementation plan focuses on development of a full treatment of parking in Sampers. Two options were laid out for future more detailed focus. These were a matrix-based cost process and the network-based approach noted in some of the models reviewed in the literature review section. Future work should examine the feasibility and detail of these options from a level of detail at the Sampers scripting level.

## Contents

Parking resistance in Sampers
(PM/Rapport)

# 1. Introduction

## 1.1 About this study

Trafikverket has identified the need to understand how parking resistance is implemented in strategic transport models around the world. The aim of this is to build a knowledge base for the future implementation of parking resistance in the Sampers model.

| What is parking resistance? |
|---|
| 'Parking resistance' is the catch-all term we use in this report to describe the disutility of parking. This means, the costs faced by trip makers in parking during a modelled trip. These include:<br>• Out-of-pocket monetary costs<br>• Time searching for an available park. This is influenced by the availability (supply) of spare parks.<br>• Parking in a location further away from one's final destination<br>• Walking time between park location and destination<br>• Time restrictions on parking<br>• Insufficient supply of parking for a guaranteed carpark at ones' destination |

Parking is one factor which strongly influences car trips in urban environments. Currently, the practice of accounting for parking resistance in strategic transport models around Sweden is limited. In the Stockholm and Gothenburg city models the solution used is to model parking resistance using higher travel time costs for individuals making trips to selected zones by car. But modelling how parking resistance works in reality is more complex. In real life, trip makers are faced with an array of combinations and options for trips, combining decisions about price, location, duration and transport mode. The balance between the supply, price, and demand for parking is also complex, with feedback and interplay between user choices and decisions about parking and even parking policy.

## 1.2 The importance of parking

Including parking resistance in transport models is important because of the important role parking plays in car trips: i.e. vehicles must be parked before occupants can partake in their trip's purpose (Young, 2007). Not accounting for parking resistance in models can lead to an over-estimation of car trips to certain areas and an under-estimation of usage of other modes like public transport

(Department for Transport UK, 2014). In the box below, the influence of out-of-pocket costs of parking are shown using an example for a typical trip. The example shows that parking prices can make up an important part of the disutility of making a trip by car. But price alone is just one component of parking resistance.

Example 1: The typical car trip in Sweden

According to the Swedish national travel survey Resvanundersökning (RVU) for 2015-16, the average car trip time for all purposes was 43 minutes (Trafikanalys, 2016). Assuming for such a trip that 60 minutes paid parking was required at the trip's destination. Using the national standard perceived monetised value of travel time savings of 116 SEK per hour, it can be seen in Figure 1 that parking price increases to around 35% of total trip perceived cost (also called 'generalised cost', see Section 1.3) as parking prices rise to over 60 SEK per hour (a figure close to some per-hour rates in central Stockholm).

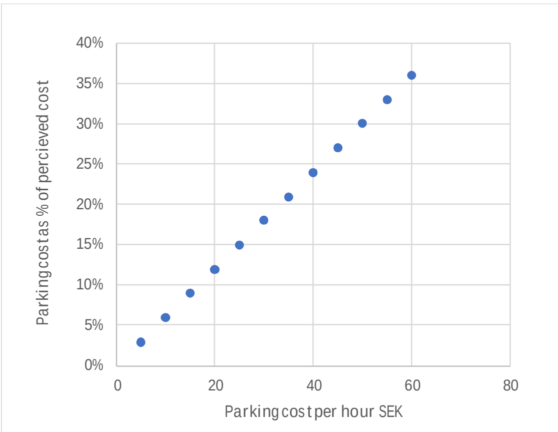


Figure 1: Example of parking costs as proportion of perceived trip cost (assuming a fixed value of time)

## 1.3 Key terms

There are several key terms used in this report which should be clarified early. These are outlined in this section.

'Parking resistance' is described above in Section 1.1.

'Generalised cost' in this report refers to the common use of the perceived cost of travel expressed in terms of generalised units (usually time in minutes) within transport models that the use random utility theory (see Ortúzar & Willumsen, 2009). Here the costs of travel for car trips includes not only travel time itself, but vehicle operating costs like fuel and servicing, but also road taxes and tolls and other out of pocket costs like parking.

When we refer to ‘modelling parking’ we refer to the attempt by planners to account for parking resistance in some form or other in transport models. This can range from very simple attempts like including out of pocket parking costs in car generalised cost functions, to fully modelling the supply and demand balance of car parks in a model of an urban area to achieve a stable equilibrium estimate on number of cars parked during specific time periods.

‘Trip-based’ models are transport models which use trips as a fundamental unit to model transport networks. A trip is a one-way movement from an origin (start location) to a destination (end location) in a transport model.

‘4-step model’ refers to transport models using the traditional or ‘classic’ four stage process: trip generation, trip distribution, mode choice, and assignment (see Ortúzar & Willumsen (2009)). These can be trip-based or tour-based.

‘Tour-based model’ refers to transport models which model ‘tours’, not just individual trips. A tour captures both the out and return trip legs associated with travel to perform some function or activity. These models can often also model chains of several trips. For example: a whole day’s transport from home to work, from work to the shops, and finally returning home. The advantage of these types of models are that more realistic ‘whole-day’ travel choices and behavior are modelled, instead of modelled decisions being conducted on isolated trips from a single origin to a single destination. Tour-based models still typically rely on random utility theory based mode choice concepts like generalised cost. ‘Activity based models’ are an advanced form of tour-based model which take activities conducted by individuals and households as the basic building block to begin to model transport decisions and trip-chains.

When other new terms are introduced for the first time in this report they are formatted in italic font and are defined in the text directly.

## 1.4 Sampers

Sampers is the Swedish national transport model currently. Its development began in 1998 and was completed around 2001. New versions of Sampers are released periodically. The current version is version 4. With the next version anticipated to be available in May 2020. Sampers is a 4-step transport model that calculates tours for home-based journeys which are later broken up into time-period modelled trips. Early versions of the model had attempted to model trip chains, but these components of the model were deactivated and are not used in the current official versions of Sampers due to their instability.

Sampers is a national model but is divided in to five regions and run separately for each of these. There is also a separate calculation model for long trips, however this report focuses on and is most relevant for the region-based Sampers. Figure 2 shows the five regions in the regional Sampers model. As an indication of the zonal detail in urban areas Figure 3 shows the zonal structure for the city of Malmo in the model.

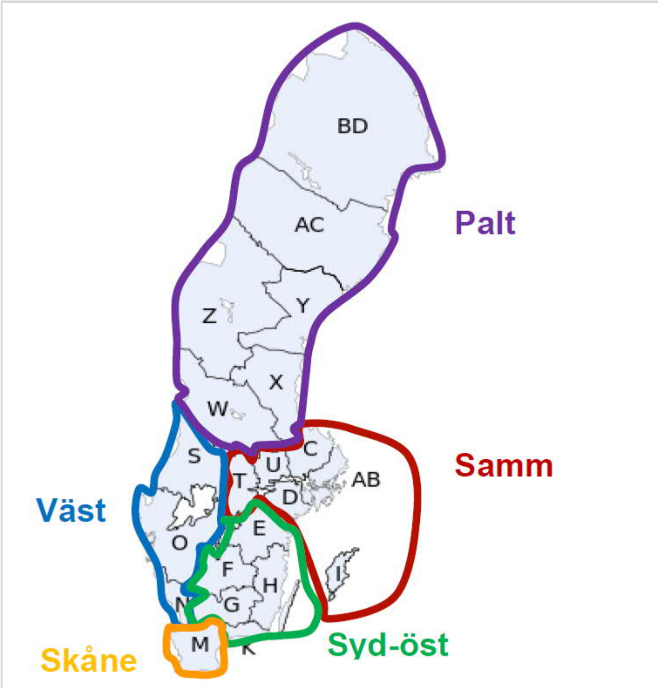


Figure 2: Sampers regions
Source: Kristoffersson et. al (2018)

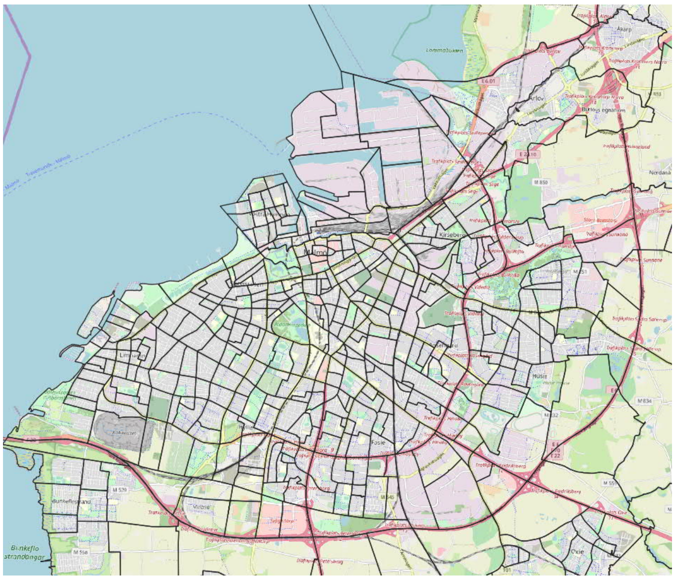

Figure 3: Malmo zonal detail in Sampers
Map: OpenStreetMap contributors (2019)

Sampers does not currently model parking, nor does it include parking resistance as a cost or time component. Instead, only for selected areas, it is indirectly proxied using a dummy variable in travel cost calculations. Introducing some form of resistance to car travel to urban centres to capture the impact of parking resistance is expected for future versions of Sampers. The main reason until now for not including parking in Sampers is due to the lack of data on parking supply at destinations (e.g. workplaces), and a concern about the lack of data on parking supply at origin ends of trips (i.e. home) and a good understanding of how this may influence car ownership (Kristoffersson et. al, 2018, p.127). Counterbalancing this there is a growing desire to include parking in Sampers, particularly in the Stockholm region. Sampers forecasts for that city show that for future years car trips into the central urban area increase significantly whilst parking supply is in reality expected to remain relatively constant at today's levels or may even decline.

## 1.5 'Park and ride' models

The literature review in this report has focused on modelling parking resistance for private vehicle trips in models (i.e. car trips). We chose not to outline how parking is modelled for public transport trips taking 'park-and-ride' (P&R) options (e.g. car to railway station). This is because the way parking is modelled for P&R trips is handled differently and P&R models are usually more common in transport models, so examples of implementation are easier to find. Often P&R parking models have a higher level of complexity than parking models for private car trips as they are less demanding to develop and are sometimes easier to collect necessary data for (parking supply at specific sites like railway stations, and their parking prices). P&R parking models are often seen implemented with capacity feedback loops as trips crowded-off parking spaces are shifted over to car modes.

# 2. Literature Review

## 2.1 Transport guidance and other literature

Young (2001) describes the different scales of modelling parking, which can be done at the macro-level (region, city or conurbation scale), meso-level (e.g. central area of a city), or at a micro-level (a car parking facility). These scales are represented visually in Figure 4. At the most micro-level, modelling parking enables the physical design of parking lots and their functional performance (circulation areas, gates, etc.). At the meso-scopic level, modelling can involve estimating or simulating the behavior of trip makers in choice of location to park, traffic assignment onto links, search times, and walking journeys between parking locations and destinations. At the macro-level, parking policies (e.g. parking prices) and the impact of parking capacity have impacts on mode shares, trip attractions, and even on the value and use of land for specific purposes. Young (2001) suggests that modelling parking properly often needs to address several levels at once, as the details at various levels influence each other.

While Sampers is a national/regional transport model (a macroscopic model), in addition to modelling parking at the macro-level, implementing parking resistance in Sampers may also benefit from modelling parking at the meso-level to capture the parking resistance impacts of choice of location to park, search times, and whether trip makes choose to park further away from destinations and complete their trips on foot. The way this would work is explored in later sections of this report.

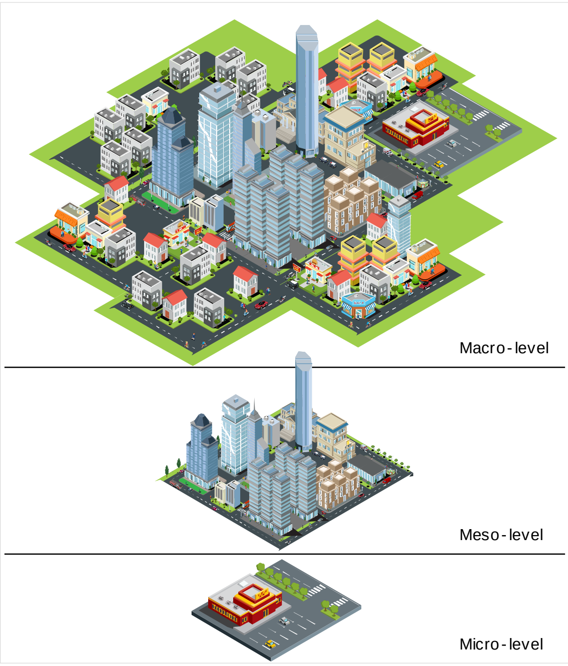


Figure 4: Scales of modelling parking

Image source: https://www.vecteezy.com/

The UK's WebTAG guidance M5.1 (2014) provides a comprehensive overview of the technical aspects of modelling parking in strategic transport models. The guidance advises that before an attempt to model parking is made there is a need to consider whether it is appropriate that parking is modelled at all for the aims and uses of the model in mind. If some consideration of parking resistance is needed the level of sophistication of the approach should be proportional to the context and circumstances of the model.

The guidance recommends that the most appropriate models to undertake detailed modelling of parking are for models of locations where parking demand is close to the supply for parking i.e. locations where parking is under capacity pressure. Models of urban centres relative to other locations are particularly appropriate, as trips to these locations are often strongly influenced by parking resistance and that if these constraints on parking are ignored, forecast numbers of car trips to these locations could be over-estimated. The guidance does not provide specific advice on the appropriateness or recommended level of complexity for including parking resistance in a national model like Sampers, however the authors are clear that parking resistance is an important factor in modelling car trips meriting inclusion in most models. Furthermore, that there are many options for level of detail in the implementation that can be appropriate for models of varying focus.

WebTAG outlines two different levels of parking modelling complexity: full treatment of parking and approximate treatment. According to the WebTAG guidance a full treatment of modelling parking involves:

- Segmented trip makers by trip purpose and income
- Tour-based linkages across time periods for given trips and parking duration and tour destination zones if different to chosen parking zones.
- Definitions of parking types (private, public), their fees and charges, zonal location and disaggregation within zone.
- Tracking of arrivals and departures from parking locations and capacity of park feeding back into parking choice and resistance considerations and recording the "history" of parking between time periods so that information on how full parking locations are is carried over into the next time period.
- Calculating walking times between parking location and destination, search times for available parking slot, additional inter and intra-zonal vehicle km associated with searching
- Choice modelling of the array of options available to trip makes encompassing the parking options available.

To conduct this full treatment a model which uses tours, not trips, as the main unit of modelling is recommended. The WebTAG guidance notes that for most model applications the use of trips is an acceptable simplification of the transport task, but that the outward and return legs of home-based journeys (which usually form the majority of transport undertakings) need to be linked for applications like modelling parking. The reason that the linkage is important is because travellers' responses to changes in parking conditions are modelled based on the total cost of travel for outward and return journeys combined. As an example, take the daily journey to work by car by a single traveller which involves driving from home to their workplace, parking their vehicle, time at work, then exiting the car park to return home. The specific duration that their vehicle is parked is a key consideration to the traveller especially if the parking place is priced according to time.

An approximate treatment of parking in models as outlined by WebTAG is to simplify the problem down to:

- Using trips instead of tours and use of independently modelled time periods.
- High level of aggregation of parking areas and types (e.g. using total parking places by type by zone).
    - WebTAG recommends as a minimum: private non-residential parking (e.g. company parking) and publicly-available parking types (e.g. kommun public parking sites, retail parking, privately-run public-usage parking).
    - Spatial aggregation can be set up with very low spatial detail, perhaps just two zones (inner and outer) in urban central areas.
- Exogenous parking charges with aggregated assumptions (cost of parking average per zone by type of parking).
- Ignoring 'border effects' between charged urban parking areas and periphery zones.

Care should be taken with this approach as it can overstate the impact/importance of parking prices in model results, relative to what is likely to occur in reality. This problem relates to how trip-based models work. Model results are likely to be exaggerated because of the numerous trade-offs that a traveller can in reality make in response to a change in parking resistance which aren't captured in trip-based models. In trip-based models decision-making is conducted per trip, mostly isolated from whole-day or multi-purpose/destination tour decision-making factors. A simple example of this problem is how a trip-based model would model the trip legs of the tour shown in Figure 5. Each trip leg would be modelled independently, without knowledge of the trip legs that are to occur later in the sequence. This is a problem for instance if, assuming a car was used for all trips initially, parking prices were doubled in the model at the trip maker's workplace. The model may then reassign the trip leg from home to work to public transport. However, if a car was in reality necessary for the shopping activity public transport for the first trip leg may not actually be an attractive alternative mode to real-life version of the trip maker. This example shows that decision making can be disconnected in trip-based models, and the impact of parking prices can overestimate changes to other modes. Tour-based models avoid this problem by forming links between trip-legs so that the cost of the entire day's "tour" is considered.

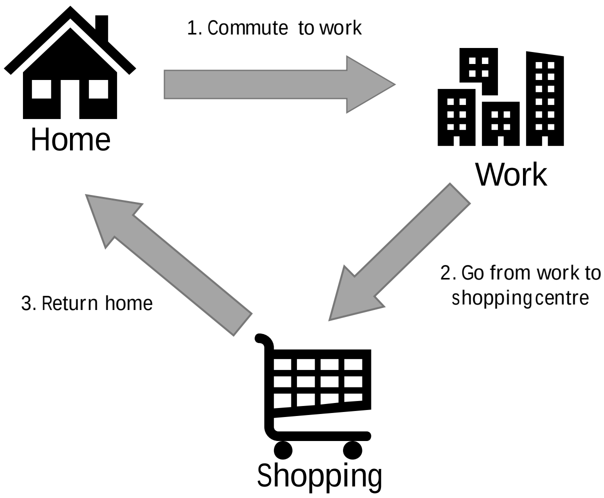


Figure 5: A whole-day tour made up of several trip legs

This problem is well outlined in the WebTAG guidance (2014). They state for example, that a simple change such as a 20% increase in all parking charges for the urban centre may not lead to in reality, a 20% increase in parking revenue or car drivers switching to other modes based on their relative price elasticities to this change in cost. Trip-makers may in reality react by moving to lower price car parks where the absolute increase is less or to free locations peripheral to the urban centre.

Johansson (2000) looked at how parking resistance could be modelled in an older version of the Sampers model for the Gothenburg area. Johansson focused on the dynamic modelling of parking demand by location in the model. Two versions of this approach were identified, network-based parking models and non-network-based models. Network-based models are described by Johansson as models that:

- Can be connected directly to assignment model stages in strategic models
- Route choice and parking location choice are modelled at the same time
- Involve the creation and use of special parking access links that connect to, and utilize capacity/flow relationships, to destination nodes.

The network-based approach is shown diagrammatically in Figure 6. This figure shows how the highway network (simulation links) is connected to travel zones via parking links and walking access links. These parking nodes and links are in turn connected to one another to allow reassignment between full parking and alternative parking locations with spare capacity.

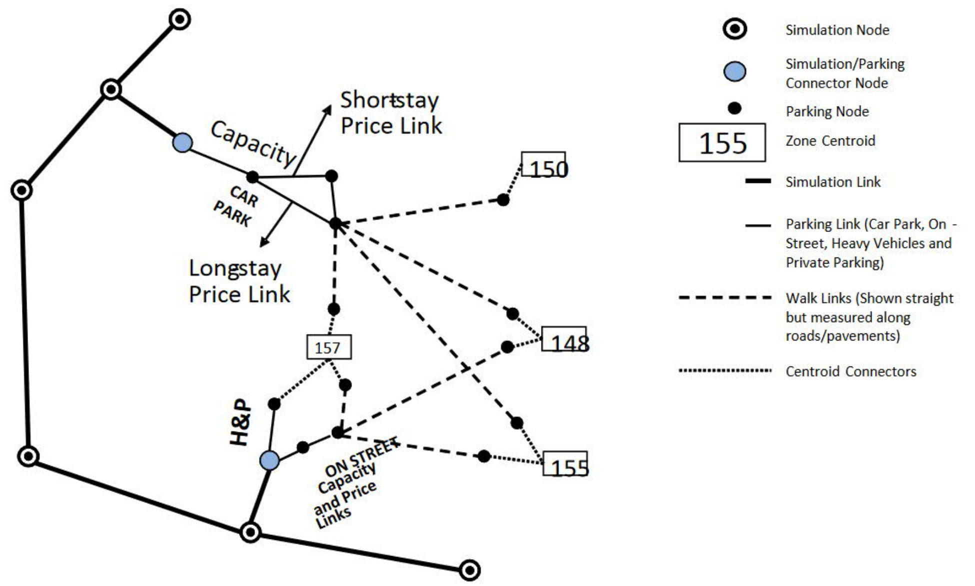


Figure 6: Parking choice and pedestrian movements in a road traffic assignment model

Source: Department for Transport UK (2014)

Non-network-based models according to Johansson are freestanding models that determine parking location choice after route assignment has already been calculated. Later in this report we identify a non-network-based approach which acts at a similar point in the model to the network-based approaches, but operates using matrix costs.

Johannson implemented a test model of parking in Gothenburg using a network-based approach and by splitting up Sampers matrices into smaller time segments. The model was able to satisfactorily model the demand for parking at a high level in Gothenburg. Since then others have attempted to implement some form of parking resistance in Sampers for testing purposes in Gothenburg as well as in Stockholm.

In a Sweco study (2018) the authors tested applying an additional time penalty to zone centroid connectors in central Stockholm in order to reduce the over-estimation of car trips to this area in the SAMMS Sampers model. Figure 7 shows which centroids were penalized (red centroids had the penalty applied in the base year model, and the blue links show the extension of the penalty application area in future year scenarios). They found that applying a 15-minute penalty in the base year reduced the over-estimation of car trips in the area and improved model validation.

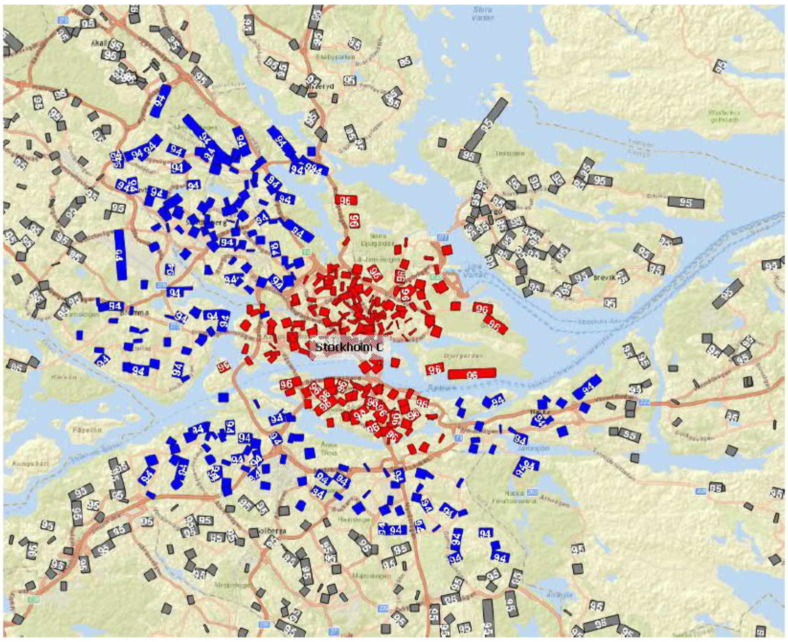


Figure 7: Sweco (2018) tested centroid connector parking penalties in Sampers

Other international transport guidance documentation as well as research/industry body publications support including parking in some form in strategic transport models (ATAP (2015), TRB (2013), Victoria Transport Policy Institute (2016)). These references mostly advise that just parking out of pocket costs are included, but parking provision is also cited as an important input into transport models on the transport network supply side.

## 2.2 Transport models around the world that model parking

We conducted a review of several strategic transport models from around the world. In our review we looked at 17 different models across several continents. The list of the models we examined is shown in Table 1. A description of these models and how they account for parking follows in this section.

Table 1: Models and geographical locations reviewed in the literature review

| Region | Country | Model scope |
|---|---|---|
| Nordic | Norway | Regional model |
| | Denmark | National model |
| | | Copenhagen |
| | Finland | Helsinki |
| Europe | Germany | National model |
| | The Netherlands | National model |
| | Ireland | Regional model |
| | United Kingdom | National model |
| | | London |

| | | |
|---|---|---|
| | | Newcastle<br>Sheffield |
| North America | United States | Los Angeles<br>San Fransisco<br>Washington DC |
| Australasia | Australia | Brisbane<br>Melbourne<br>Sydney |

### 2.2.1 Norway

#### 2.2.1.1 Regional Persontransportmodell (RTM)

The RTM is Norway's multi-modal tour-based 4-step model for the whole country which is run separately for each of its five regions to model short to medium length trips. A national model exists for long distance trips the Nasjonal personmodell (NTM) The model has approximately 15 000 zones and is run in Citilabs Cube.

The RTM includes parking costs in car generalised cost functions which influence the trip distribution and mode choice steps of the model. A zonal lookup on average parking prices is used which includes parking price for two parking types: short-term one hour, and long term eight-hour parking (used for work trips only). For work trips a proportion of parking cost is assumed to be paid for by employers (derived from surveys) which reduces the user cost of parking for a proportion of these trips. For non-work trips a weight factor is multiplied by the out-of-pocket cost of parking. This weight is above 1,0 for leisure trips to estimate the inconvenience of finding a park, and the duration of parking itself. For personal trips the weight is below 1,0 in order to capture the higher assumed willingness to pay for these trips and the possible preference for parking for these types of trips (shopping, etc.). Parking supply/capacity is not modelled in the RTM.

### 2.2.2 Denmark

#### 2.2.2.1 Danish National Transport Model (LTM)

The LTM is the national model of Denmark which is a tour-based model of Denmark (excluding overseas territories). The model uses 907 zones and includes parking price costs in its generalised cost formulas for car trips within Copenhagen, Aarhus, and Aalborg. The model also includes an estimated parking search time cost component. These costs are added based on a zone lookup of parking prices per hour for daytime, evening and night. Prices can be charged per hour in the model because, as a tour-based model, travellers' durations at locations are modelled. These costs affect the mode choice and trip distribution components of the model. Despite being a tour-based model the LTM does not model parking supply effects. The reason for not including this is possibly due to the aggregate nature of this model, being at national level, in terms of suitability and appropriateness given the course level of model resolution.

##### 2.2.2.2 The Øresund Transport Model (OTM)

The OTM is a 4-step multi-model (car, public transport) transport model of the greater Copenhagen area (including Malmö). The model has around 953 zones, but a newer version under development is expected to have significantly more. The model is run in ESRI Traffic Analyst software. Parking monetary costs are included in the model at zonal level based on a zonal lookup and these are added as components to car generalised cost. An average parking search time is also added to generalised cost by zone to reflect this in car generalised cost.

#### 2.2.3 Finland

##### 2.2.3.1 Helsinki transport model (HELMET)

Helsinki's transport model is a multi-modal 4-step model hosted in EMME software. The model has a scale of about 2 000 zones. Parking prices are included in generalised cost functions for car travel depending on location (mostly urban destinations) with this influencing results on mode choice and trip distribution. Parking supply is not modelled in the current model version, but we were told that this has been tested in internal studies where availability of parking was included in the utility calculations for car. Detail on how this was conduction was not available.

#### 2.2.4 Germany

##### 2.2.4.1 National model (Deutchlandmodell - DEMO)

DEMO is Germany's national transport model. DEMO has around 6 500 zones and includes parking in car generalised cost. The model has a joint mode choice and trip distribution step, which means that parking costs affect both choice of mode and the destination choice of modelled destination at the same stage. i.e. trip destinations are not determined first, then mode options compared. These instead interact as one.

#### 2.2.5 Netherlands

##### 2.2.5.1 National model - Landelijk Model Systeem (LMS)

The Dutch national model, the LMS, has a long history. It was developed in the 1980s by the Dutch Ministry of Infrastructure and the Environment as was groundbreaking at the time for Europe. Since then the model is continuously updated. The LMS is a tour-based model for the whole of the Netherlands but contains the option to also model 5 sub-regions. The model has around 1 500 zones. Parking monetary prices are included in car generalised cost, but parking capacity is not.

#### 2.2.6 United Kingdom

##### 2.2.6.1 National model: National Transport Model (NTMv2)

The NTMv2 is the UK's national model. Unlike many of the other models in this report this model functions more as a 'sketch model'. It is a 4-step trip-based model but has only 17 zones and is used mainly to model productions and attractions between regions in the UK and mode shares. It models car and public transport. It includes parking charges (set to averages for each zone), and it also includes an average parking search time component to generalised cost but doesn't not model parking capacity. The model is hosted on in-house developed software.

##### 2.2.6.2 London: London Transportation Studies Model (LTS)

The LTS is London's 4-step model, which is the key demand model for greater London. Its forecasts inform several other models in London which have more mode-specific or land-use focus. The LTS has 6 000 zones and is a 4-step trip-based model in the Cube platform. The LTS models parking extensively. It includes parking prices (by zone and by type of parking from a zonal lookup table) in car generalised costs. It also models parking capacity in a very detailed way in separate module that connects to the Cube model. It does this by modelling parking in every zone in Greater London with encoded details on parking supply (number of bays) by zone and by type of parking (public off-street, public on-street, and workplace parking). Information on parking supply was derived from the London Parking Supply Survey (LPSS). The parking model initially assigns home-based trips to destination zones, then as parking fills up it reassigns trips to neighbouring zones based on a multi-nomial logit model, taking into account walking time and cost for these alternatives. Reassigned trips park in the neighbouring zone and trips are completed via walking links to the original destination zone.

##### 2.2.6.3 Newcastle: Transport Planning Model (TPM)

The TPM is Newcastle's strategic transport model which is soon to be replaced (a new model is currently under development). It is a 4-step trip-based model in Cube with approximately 1 000 zones. It is a variable demand model (VDM), which means that changes to the transport network impact also trip making rates. For example, if the cost of driving was significantly reduced, say through halving the price of fuel, then more trips occur in the model to reflect the reduced burden of travelling in the first place.

The TPM includes parking out-of-pocket costs in car generalised cost, and it also models parking capacity. It does this through a network-based approach (see Johannson, 2000) whereby special links are created in the transport network to connect to zone centroids for parking. These in turn are connected to one-another, to form a walking network. As highway trips to a zone fill up parking in that zone, a link flow capacity curve adds additional cost to accessing that link for all succeeding vehicles, making other zones for parking more attractive. Trips are diverted to these neighbouring zones on the highway network, and the final leg of the trip is made by walking to the original zone. Because the TPM is a variable demand model and also employs a network-based parking modeling approach, this means that parking impacts on all stages of the 4-step model. Trip generations via the variable demand impacts of changes in mode generalised cost, trip distributions as these costs also affect which zones are key attractors, mode choice – via how attractive car is relative to other modes, and also finally in highway assignment due to the diversion of trips to zones with available parking.

#### 2.2.6.4 Sheffield: South Yorkshire Strategic Transport Model (SYSTM+)

The SYSTM+ is a variable demand 4-step trip-based transport model. It runs on a combination of EMME and SATURN software and has around 500 zones. The standard model models parking out-of-pocket charges in generalised cost but does not model search times or parking capacity. For one study a team from SYSTRA developed a parking capacity model for central Sheffield in the SYSTM+ to look at how parking capacity in the future would impact on mode shares when the number of jobs in the central area increases significantly, but parking is capped at a lower level. The parking model was a network-based model. Data on parking capacity was sourced from time and resource intensive manual surveys of sites in the centre of Sheffield. The model satisfactorily was able to converge on a realistic model of existing and future conditions, despite increasing overall model run times by a factor of 2-3. The SYSTRA team noted that the value of the parking model was not really seen in this piece of work because parking was not actually under pressure in Sheffield in the current or future scenarios. This meant that for vastly longer model run times they did not ultimately need to model parking at the implemented level of sophistication.

### 2.2.7 Ireland

#### 2.2.7.1 National model: Regional Modelling System (RMS)

The National Transport Authority developed the RMS, which comprises the National Demand Forecasting Model (NDFM), five large-scale, detailed and multi-modal regional tour-based transport models and a suite of appraisal modules covering the entire national transport network of Ireland. The five regional models are focused on the travel-to-work areas of the major population centres: Dublin, Cork, Galway, Limerick, and Waterford.

The RMS includes parking out-of-pocket costs in car generalised cost, parking search times and also parking capacity modelling. The RMS has a separate module for work trips that models mode choice based on availability of workplace free parking. This module works by ‘crowding-out’ the free workplace parking once full, so that residual drivers are forced to then have to reconsider mode choice options with other modes alongside alternative paid parking options. Another module handles parking capacity for non-work locations. In this module, when parking is full in one zone, parkers are forced to consider neighbouring zones and walking to their final destination instead.

### 2.2.8 United States

#### 2.2.8.1 Los Angeles: Southern California Association of Governments (SCAG) Regional Travel Demand Model

The SCAG model is an activity-based multimodal transport model hosted in TransCAD. The model has around 12 000 zones. As an activity-based model the SCAG model simulates activities and tours throughout the day. Despite being of this form of model, the SCAG model does not model parking in a detailed way. It only includes parking out-of-pocket charges in car generalised costs.

#### 2.2.8.2 San Francisco: San Francisco County Travel Demand Forecasting Model (San Francisco Model)

The San Francisco Model is a full day activity-based model. As such it models tours instead of trips, modelling these as chains of individual linked trips for each individual in the population. The model has 766 zones and is run in TransCAD and Transport Planning plus (TP+) software. The model includes parking out-of-pocket costs in generalised cost but does not model parking in a detailed way. Parking search times and parking capacity are indirectly addressed using zone-based lookup of attributes like: type of parking provided (% free, % subsidised, % paid), % of trip makers paying, % of on-street and % of off-street parking, and a ‘parking availability index’. The last variable is an attribute that acts on generalised cost to reflect the difficulty in finding a car park in a zone. In other words, a form of parking search time / capacity catch-all parameter.

The model developers noted that they had difficulty estimating a parking cost coefficient (parameter that convers money cost units for parking into minutes) that led to logical results. They suggested that this is most likely due to the use of an average parking cost value for each zone, as opposed to the actual parking cost that the traveler paid or would have paid. Using average parking costs tends to obscure the sensitivity of individuals to this important variable because some travelers are provided parking for free, while others have partially subsidised parking paid for by their employers, and finally others pay full price, even within the same zone.

#### 2.2.8.3 Washington DC: Transportation Planning Board (TPB) Travel Demand Forecasting Model

The TPB Travel Demand Forecasting Model is Washington DC’s strategic model. It is a 4-step trip-based model run on the Cube platform with 3 722 zones. The model includes parking out-of-pocket costs in car generalised cost through a unique mechanism of estimating prices based on employment density each zone. Whereby more dense employment areas have a higher price (two pricing curves are used, one for day rates and another for hourly rates). Using this estimate avoided the need to collect data from the real world for each zone, rather the curves were estimated from samples of prices correlated to zone employment density. In addition to parking prices the model includes a parking search component. This too is based on employment density, but rather than taking the results from a curve it works using a lookup table with five bands of employment density. More employment dense zones have higher parking search times than less dense zones.

### 2.2.9 Australia

#### 2.2.9.1 Brisbane: Brisbane Strategic Transport Multi-Modal Model (BSTM)

The BSTM was developed from an older version of an existing model which did not have multi-model functionality. It is a 4-step trip-based model run in EMME software with 1 504 zones. The BSTM models parking out-of-pocket costs only and does not model parking search times or capacity. Parking prices are input as an average for a zone based on cost of parking at designated parking lots within each zone and are only applied to the central area of the city.

#### 2.2.9.2 Melbourne: Victorian Integrated Transport Model (VITM)

The VITM is a model for the whole state of Victoria, Australia, but is typically just run for the Melbourne region as a cut-out model. The model is a 4-step trip-based model with 3 178 zones and is run in Cube software. Parking out-of-pocket costs are included in the model, based on zone lookups which assign an average parking price (based on infrequent market price surveys) to trips to these zones. Parking search times are not included, neither is more detailed modelling of capacity.

#### 2.2.9.3 Sydney: Sydney Strategic Travel Model (STM)

The Sydney STM is the strategic transport model for Sydney. It is a tour-based transport model with 1 500 zones in EMME. The model calculates tours, but these are converted to trips for the traffic assignment stage, similar to how Sampers works in this regard. Like the other Australian models described above, this model only models parking resistance via parking out-of-pocket costs through zone lookups. The model's documentation notes that it was chosen not to model parking in a detailed way because is 'parking is essentially associated with an individual, a particular trip and a particular time', and the model developers believed that the framework of the model was not able to accurately do justice to the complexities of these trip attributes to realistically model parking properly.

## 2.3 Summary of literature review findings

### 2.3.1 Overview

The first part of the literature review on parking resistance in models looked at international transport guidance and other literature. A large proportion of this section dealt with the detailed guidance from the UK's WebTAG. This guidance is an internationally respected source on modelling best-practice. It described how there are two main approaches to modelling parking resistance: full treatment and approximate treatment. According to this guidance implementation of the full treatment of parking is recommended when a model is tour-based in order to accurately capture the trade-offs and options an individual trip maker must make based on the circumstances of each journey. Approximate treatments do not require tour-based models but can have problems with over-exaggeration of the effect of parking resistance. Other guidance sources reviewed were less detailed in their advice on modelling parking, but they all supported the need to account for parking in models in some way due to the importance of parking in car mode choice. The first section of the literature review also described a paper from 2000 which tested detailed parking modelling in the Sampers model. The paper described network-based approaches to modelling parking – using special links to route and reroute trips through the network to reach an equilibrium between parking supply and demand. The paper noted that it was possible to implement this in the Sampers model in the Gothenburg area.

The next part of the literature review described how parking resistance is modelled in 17 international transport models. These were a mixture between national/regional models and urban area models. The models also varied between 4-step trip-based models to tour and activity-based models. A summary table of the key features of these models is shown in Table 2.

Based on the review of the 17 models several things are notable observations about how parking resistance is modelled:

- All the models reviewed included, at a minimum, parking out-of-pocket charges (prices/fees) in car generalised cost formulations.
- In all cases parking out-of-pocket costs impact on, at least, the trip distribution and mode choice steps in models.
- About half of the models included parking search times for car generalised cost.
- Only four models performed detailed parking modelling. Of these only one model was tour-based. The remaining models were 4-step trip-based models.

Table 2: Summary of models reviewed in the literature review and their parking resistance methodologies

| Model | Model type | Software | Number of zones | Parking included in car generalised cost? | Parking search-time incl. in car generalised cost? | Generalised cost impacts on which aspects of the model | Parking capacity modelled? |
|---|---|---|---|---|---|---|---|
| Norway | Regional 4-step | Cube Voyager | 15 000 divided into 5 regions | Yes | Yes | Trip distribution, mode choice | No |
| Helsinki | 4-step | EMME | Approx. 2000 | Yes | No | Trip distribution, mode choice | No |
| Denmark National | National tour-based | Unknown | 907 | Yes | No | Trip distribution, mode choice | No |
| Copenhagen | 4-step | ESRI Traffic Analyst | 953 | Yes | Yes | Trip distribution, mode choice | No |
| Germany | National 4-step | Unknown | 6 561 | Yes | No | Trip distribution, mode choice | No |
| Netherlands | National 4-step | Bespoke software | 1500 | Yes | No | Trip distribution, mode choice | No |
| Ireland | National tour-based | Cube | 18 488 | Yes | Yes | Trip distribution, mode choice, assignment | Yes |
| UK national | National 4-step | Bespoke software | 17 | Yes | Yes | Trip distribution, mode choice | No |

| Model | Model type | Software | Number of zones | Parking included in car generalised cost? | Parking search-time incl. in car generalised cost? | Generalised cost impacts on which aspects of the model | Parking capacity modelled? |
|---|---|---|---|---|---|---|---|
| London (LTS) | 4-step | Cube Voyager | 6 000 | Yes | Yes | All stages | Yes |
| Newcastle | 4-step | Cube Voyager | Approx. 1000 | Yes | Yes | All stages | Yes |
| Sheffield | 4-step | EMME/ SATURN | 500 | Yes | Yes | All stages | Yes |
| Los Angeles | Activity based | TransCAD | 12 000 | Yes | No | Trip distribution, mode choice | No |
| San Francisco | Activity Based | Bespoke software | 766 | Yes | Yes | Trip distribution, mode choice | No |
| Washington DC | 4-step | Cube | 3 722 | Yes | Yes | Trip distribution, mode choice | No |
| Brisbane | 4-step | Emme | 1 504 | Yes | No | Trip distribution, mode choice | No |
| Melbourne | 4-step | Cube | 3 164 | Yes | No | Trip distribution, mode choice | No |
| Sydney | Tour based | Emme | 1 500 | Yes | No | Trip distribution, mode choice | No |

### 2.3.2 Parking resistance modelling approaches

The literature review showed that there were various approaches and levels of complexity in modelling parking resistance. These can be summarised into the two general approaches described above in Section 2.1 referred to by the UK WebTAG guidance but slightly more generalised. Whilst presented here as two separate approaches, crossover between these two approaches is possible. The approaches are:

> Approximate treatment of parking: A complete picture of parking is not modelled, but some important aspects of parking resistance are modelled. This method describes techniques such as including parking price in generalised cost formulas to capture the out-of-pocket costs of parking and/or inclusion of some measure of parking search time and parking time limits.
>
> Full treatment of parking: A more complete picture of parking is modelled in this approach. This method includes the addition of the cost elements in the approximate treatment but also models the demand/supply equilibrium for parking. This requires record keeping across time periods of how many vehicles are parked at particular locations, a convergence process, and functionality that allows for the possibility of trips to be reassignment to neighbouring zones. Limiting the amount of possible parked cars using dynamic cost increases as parking fills to dissuade further car trips are the core of this approach's methodology.

# 3. Detailed assessment of the approximate and full treatment approaches to modelling parking

## 3.1 Overview

This section provides a detailed description of the two approach types described in the preceding section: the approximate and full approaches to modelling parking. This includes a detailed summary of each approach with examples from existing models, data requirements, and a review of the pros and cons of each approach.

## 3.2 Approximate treatment of parking

### 3.2.1 Detailed summary of the approach and examples

This approach attempts to capture the important aspects of parking resistance in a basic way. In the reviewed model examples in the literature review, it typically at a minimum involves including parking out-of-pocket costs in generalised cost for car trips and often also parking search times. More formally this looks like:

$$GC_{ij} = IVT_{ij} + PSearch_j + \beta_1 * (VOC_{ij} + PC_j) + ASC_{car} \qquad (1)^1$$

Where:

| | |
|---|---|
| $GC_{ij}$ | is the generalised cost of travel by car from i to j (usually in time units of minutes). |
| $IVT_{ij}$ | is the in-vehicle travel time in minutes from i to j. |
| $PSearch_j$ | is parking search time at destination j. This can have a higher weight than IVT. |
| $\beta_1$ | is the trip maker's (or group segment, e.g. income level of x) specific value of cost beta that converts money into time. Equivalent to 1/VOT, where VOT is value of time in money. |
| $VOC_{ij}$ | is the variable vehicle operating costs (fuel, servicing, etc.) for trip i to j. |
| $PC_j$ | is the parking out-of-pocket cost for destination j. |
| $ASC_{car}$ | is a constant which represents the specific attractiveness of car (can be signed negative or positive). |

Generalised cost is a key feature of trip distribution and mode choice stages of trip-based 4-step strategic models. Tour-based and activity-based models share some similarities to traditional 4-step models in this regard: after activities are generated, destinations for the activities are identified, and travel modes are determined so generalised cost comes into play in much the same way as trip-based models. The inclusion of parking costs into strategic models therefore affects where trips are attracted to and from in the distribution stage and impacts on the attractiveness of car as the preferred mode of transport for those trips. Figure 8 shows this visually.

[1] Road tolls can be included in (1) but have been left out for brevity. See Ortúzar & Willumsen (2009, p.165) and WebTAG M2 3.1.6 for other examples of car generalised cost functions.

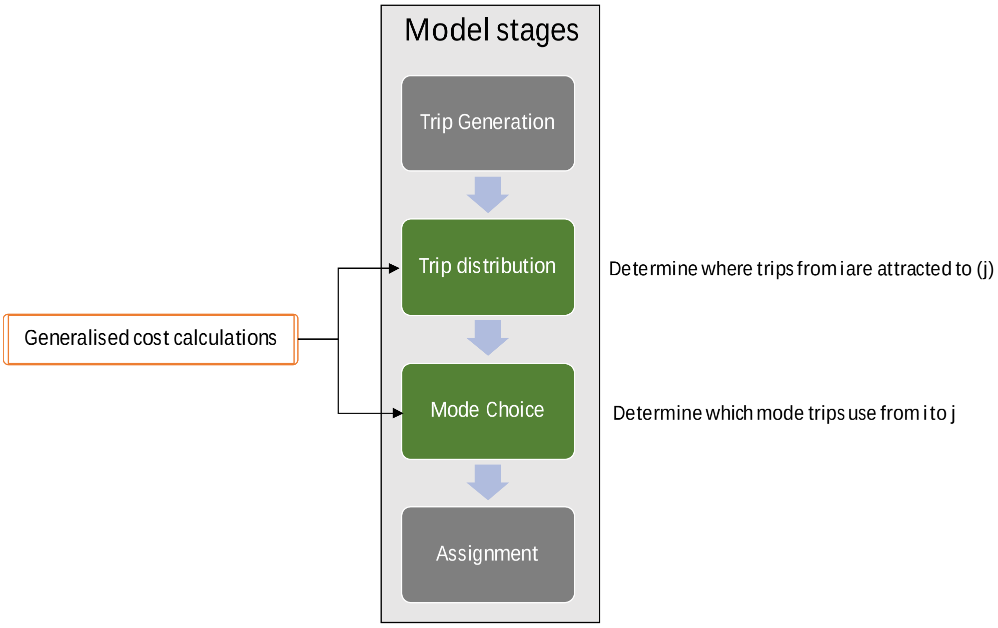


Figure 8 Influence of generalised cost calculations on trip distribution and mode choice in 4-step models[2]

Some important points to note about implementation of the above are:

- When modelling person trips, it is necessary to divide the out-of-pocket costs of parking by the vehicle occupancy rate for that trip type.
- For trip-based models without cost calculations capturing a whole day of trips for trip makers, it is necessary to also halve the cost of parking for specific trip types and time periods that involve long-stay parking, as these trips are actually half of a tour (i.e. the out and return trip combined) (Department for Transport UK, 2014).
- Income and trip purpose segmentation of trip makers are required in any model with parking charges to make modelled responses to price changes more realistic due to differences in willingness to pay for parking.

Modelling supply effects in the approximate approach were not noted in the international review of models. Supply effects refers to modelling the impact of the supply of car parks as an aspect of parking resistance and how this affects demand. Capping methods for trips to destinations and similar possible methods are described in the next section on the full treatment of parking approach.

### 3.2.2 Data requirements

[2] In models with ‘variable demand’ generalised cost influences trip generation as well. Variable demand is described briefly in Section 2.2.6.3.

The data requirements to include parking out-of-pocket costs in generalised cost are parking price data at zonal level, area definitions, information on the types of parking in each zone (private, public) and on which trip making groups and their proportions are provided free parking and estimates of parking search times. These are looked at in turn in the following sub-sections.

#### 3.2.2.1 Parking price

Collecting parking price information and then summarizing this up to zonal level is not straight forward. In the development of the Sydney model, the developers noted that "it is impossible to be precise in nominating the price of car parking in a zone because (a) it varies by site and (b) it varies by time of day and day of week" (NSW, 2001). In the Sydney model parking prices are set from surveyed zonal parking price per hour multiplied by the linear duration of average observed trip purpose types. For example, a home-based shopping trip has an observed average length of 1.5 hours (from travel surveys), a parking cost at a primary destination zone with a cost of $3 per hour would be calculated as $4.5.

In the Norwegian regional model (RTM) parking prices were collected for 2001 and 2010 from a combination of the national travel survey (where the price paid, and location of parking was a question in the survey) and also desktop based manual data collection from municipal websites. For the manual collection, prices for urban areas were collected often from municipal websites. Where there were parking supply data (number of spaces), these were used in combination with the prices to weight the average prices for the area. For example, when it was found that 200 spaces were charged at 8 NOK per hour and 150 other spaces at 10, the weighted average price was equal to:

$$Price_{avg} = \frac{(200 * 8) + (150 * 10)}{200 + 150}$$

Different prices were collected and are included in the model for short-term (<8 hours) and long-term parking (8 hours). The latter being used exclusively for work trips.

The UK national model also uses national travel survey data to obtain parking prices. For each zone every trip purpose has a separate parking charge added to generalised cost. These were calculated by calculating average parking prices by purpose and destination groups from the survey data.

In the Washington DC model home-based work trips pay a daily parking charge which is estimated for each zone based on zone employment density. This curve was calculated using observed parking prices from surveys and floating employment density and is shown in Figure 9.

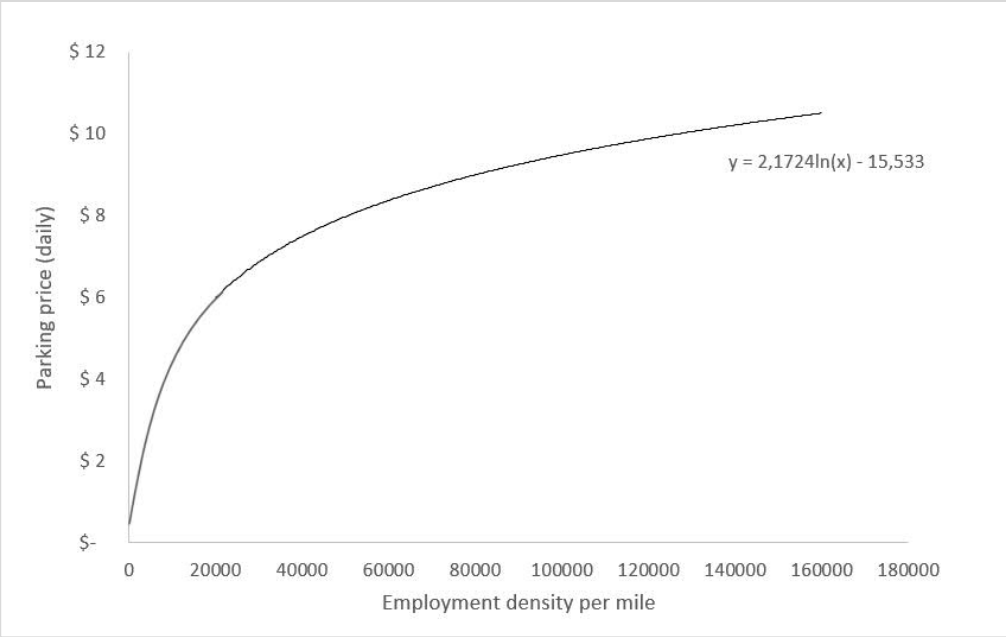


Figure 9: Washington DC model parking price function

In the Newcastle TPM, parking prices were obtained from using the average durations of stays for short-term and long-term parking and the average charge per hour derived for the local authority parking web sites for different areas. This was then weighted according to the number of spaces in each car park within each zone to account for scarcity price differences.

In the Danish LTM, parking prices are only added for trips to the largest Danish cities (Copenhagen, Aarhus, Odense, Aalborg and Hillerød). These are applied at different per hour rates for day, evening, and over-night.

#### 3.2.2.2 Parking area definitions

Defining the level of spatial detail of the parking zones is an important part of implementing this approach. Each model zone in turn can have its own specific parking price, but the overhead required in obtaining this information for all model zones is high. Another approach is to define aggregations of several or many zones based on their location. The UK's WebTAG (Department for Transport UK, 2013) suggests that aggregations can be very simple if desired, e.g. only two or three zones (inner, middle, outer), representing the urban central area (see Figure 10 showing the London model's parking area definitions). The drawback of having large aggregations is that the larger the aggregation's size, the more the detail in the real-life differences in pricing and types of parking are diluted to average values. In the Melbourne model (VITM), parking areas roughly correspond to the regional government's 'congestion levy' spatial areas. These are area definitions in the central area and surrounding neighbourhoods that are used to regulate minimum parking prices. With this approach the inner area (where parking demand is highest) is broken into several different pricing areas, but further out zones are defined under a single aggregation. Average prices are collected for these areas from surveys and government data.

In the Danish LTM Copenhagen has parking areas defined to match actual parking zones (see Figure 11). The other cities in the LTM that have parking resistance in the model have lower detail, with only one or two area aggregations in these cities.

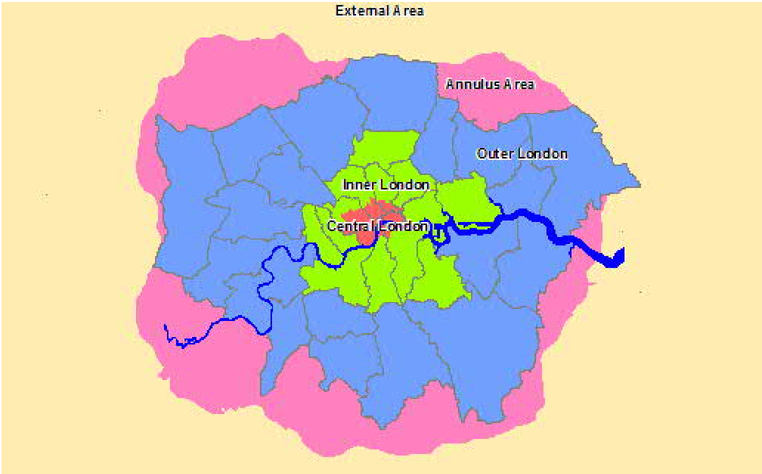


Figure 10: London model parking area definitions

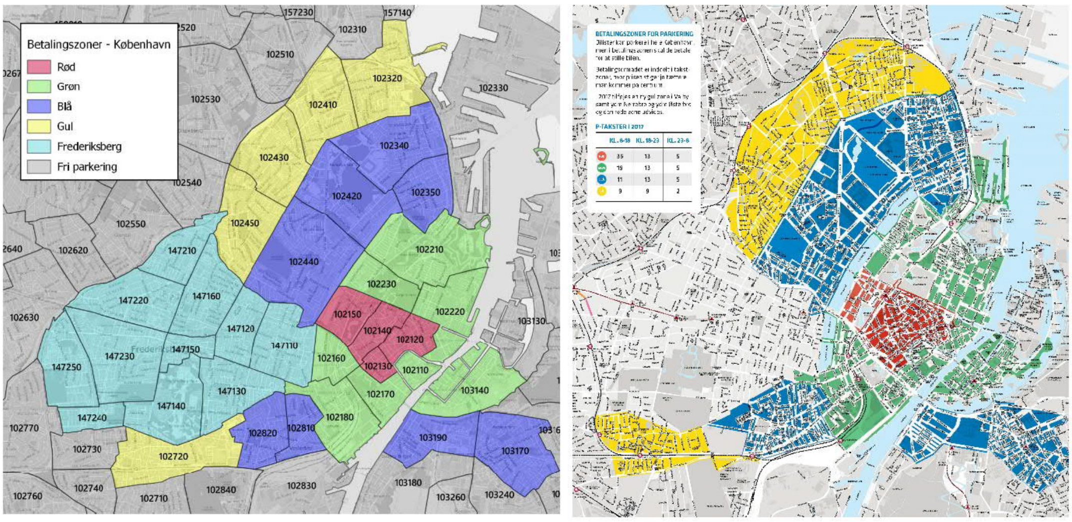


Figure 11: Danish National Model (LTM) Copenhagen parking zone definitions (left) and actual parking zones from 2017 (right)

3.2.2.3 Parking type and free parking provision

The Norwegian RTM only distinguishes between work parking and non-work parking. For home-based work trips (commute) by car a proportion (called a 'share-pay' factor) is defined from travel surveys for each zone to capture the proportion of car trips with free workplace parking. For these trips no parking out-of-pocket costs are added to generalised cost. For all remaining work trips as well as other trip purposes (employer's business, and personal business/shopping trips) parking costs are included in generalised cost using short-term parking costs Paid parking commute trips use long-term 8-hour parking costs.

The UK national model avoids defining parking types by instead using just zone location, trip purpose (of which there are eight in total), and proportion who paid to determine how much parking out-of-pocket cost should be added to generalised cost. A breakdown of parking costs for these definitions is shown in Figure 12. The data is obtained from the national travel survey by averaging how much parking cost for each trip purpose and zone multiplied by the proportion of trips that paid for parking. The Irish regional model places an assumption that for certain work commute trips 80% of parking available to this demand segment has access to free parking. The remaining 20% is charged a full parking fee.

| Area Type | Trip purpose | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | HBW | HBEB | HBEdu | HBPB | HBRec | HBHol | NHBEB | NHBOth |
| 1 Central London | 500 | 82.7 | 2 | 31.1 | 24.4 | 55.8 | 83.7 | 28 |
| 2 Inner London | 22.6 | 82.7 | 2 | 31.1 | 24.4 | 55.8 | 83.7 | 28 |
| 3 Outer London | 10.1 | 81.5 | 2.8 | 16.6 | 18.3 | 113.8 | 29.1 | 12.6 |
| 4 N&E Central Conurban | 19.3 | 86 | 5 | 25.6 | 15.5 | 187.6 | 39.5 | 15.6 |
| 5 West Central Conurban | 19.3 | 86 | 5 | 25.6 | 15.5 | 187.6 | 39.5 | 15.6 |
| 6 N&E Conurban surround | 8 | 31.2 | 2 | 9.8 | 4.3 | 85.4 | 11.6 | 7.9 |
| 7 West Conurban surround | 8 | 31.2 | 2 | 9.8 | 4.3 | 85.4 | 11.6 | 7.9 |
| 8 South Urban Big | 7 | 27.2 | 5.7 | 22.1 | 8.9 | 31.9 | 12.4 | 10.7 |
| 9 N&E Urban Big | 7 | 27.2 | 5.7 | 22.1 | 8.9 | 31.9 | 12.4 | 10.7 |
| 10 West Urban Big | 5.4 | 20.8 | 2.8 | 20.9 | 10.5 | 36.1 | 17.2 | 15.1 |
| 12 South Urban Large | 5.4 | 17.5 | 2.5 | 22.3 | 9.3 | 24.5 | 7.5 | 14.4 |
| 13 N&E Urban Large | 6 | 7.6 | 2 | 14.9 | 3.4 | 15 | 10 | 9.4 |
| 14 West Urban Large | 13 | 36.2 | 2.4 | 25.8 | 10.2 | 22.4 | 26.5 | 12.8 |
| 16 Urban Medium | 4.9 | 8.7 | 2.1 | 15.5 | 4.9 | 20.5 | 8.7 | 8.7 |
| 17 Urban Small & Rural | 2.1 | 4.2 | 0.4 | 5.2 | 3.5 | 30.9 | 4.2 | 6.4 |

Figure 12: UK National model parking costs by zone and trip purpose

3.2.2.4 Parking search times

The Norwegian regional model attempts to capture trip makers' perceived disutility in searching for parking and parking time limits by using a weight factor multiplied by the out-of-pocket cost of parking. For leisure trips this weight is greater than 1,0 (around 1,25). So, for example, when parking at destination zone j is 30 kr per hour, its value in the generalised cost function is actually 37,5 kr per hour. Interestingly the model allows the weight to be less than 1,0 for some trip types. Personal trips have this lower weight which is used to account for the preference for types of trips in this purpose category to prefer car (e.g. shopping). The assumption inherent in this is that parking price, search time, and parking duration are more tolerable expenses for these trip types relative to leisure trips.

The UK national model includes parking search times in generalised cost. During the model's development it was observed that car generalised costs for short distances were significantly lower (better) than for other modes. This feature was included to more accurately reflect the time accessing and egressing car, including time taken to park. It does this by using a lookup for aggregations of zones and is applied to all car trips in the model based on the destination areas shown in Table 3. The Danish OTM also includes parking search times as a fixed addition to generalised cost. These apply to both ends of trips for home-based trips and for non-home-based trips it is applied at the destination end only.

Table 3: UK national model parking search time component

| Destination Area | Search time (minutes) |
|---|---|
| Zone 1 - Central London | 15 |
| Zone 2 - Inner London | 5 |
| Zone 3 - Outer London | 4 |
| Zone 4 & 5 - Inner Conurbations | 6 |
| Zone 6 to 17 - All other areas | 4 |

In the Washington DC model parking search times are referred to as 'highway terminal times' (i.e. time added at the end termini of trips for access between vehicle and destination). These are added in addition to out-of-pocket costs to generalised cost based on the employment density of the destination zone. These are shown in Table 4.

Table 4: Washington DC model highway terminal time and employment density

| Employment density range (Emp/Sq. Mi.) | Highway terminal time (minutes) |
|---|---|
| 0 - 4,617 | 1 |
| 4,618 - 6,631 | 2 |
| 6,632 - 11,562 | 4 |
| 11,563 - 32,985 | 6 |
| 32,986 + | 8 |

Referred to in the Irish RMS documentation (NTA, 2018), parking search times are estimated in that model using a function defined in a study conducted in Leeds, UK. This is shown in equation (2):

$$STime = Min[S_{max}, \alpha * e^{\beta * 100 * OCC/CAP}] \qquad (2)$$

Where:

$OCC$ is the occupancy of a site

| | |
|---|---|
| $CAP$ | is the number of spaces |
| $\alpha$ | is the minimum search time found to be 0.9 minutes |
| $\beta$ | is a parameter found to be 0.0146; and |
| $S_{max}$ | is a maximum value for search time (user defined but in the RMS 15 minutes was used) |

In the Danish LTM, parking search times for Copenhagen are sourced from an external matrix of parking search times from the Copenhagen OTM model. For the other major cities in Denmark where parking costs are included in the model, parking search times are approximated by looking up similar zones in the Copenhagen matrix.

### 3.2.3 Pros and cons of this approach

#### 3.2.3.1 Pros

In general, this approach is simple to implement in existing models as it entails small changes to the generalised cost functions for car linked to specific data by zone. Furthermore, there are many examples of different ways to either obtain real data on parking prices from observation and survey or to synthesize estimates of these inputs. Some of which have been outlined above. If implementing in an existing model, the burden of recalibration is likely to be small as changes are relatively minor. Model runtimes are also likely to be unaffected or only marginally lengthened by this approach.

#### 3.2.3.2 Cons

Whilst in principle this approach is simple to implement, several aspects if done satisfactory require untrivial amounts time and effort, these are:

- Collection of pricing data. This can be done through desktop review of parking prices by area, manual on-site surveys, existing travel surveys (if conducted and if they include questions on parking), or synthesizing estimated prices using various sources.
- Definition of parking areas and aggregations.
- Gathering data on the proportions of free parking available to estimate what proportion of car trip makers pay for parking or get it for free.
- Using appropriate parking search times. These may vary across a model's area yet estimating or collecting real data on this for different locations could be expensive. Setting appropriate estimates or sets of estimates by different area aggregations (e.g. central urban area, middle, peripheral areas) is more feasible, but still requires analysis.

Care should be taken to also understand the limitations of this approach in terms of accuracy. As outlined in Section 2.1, this approach can exaggerate the impact of changes to parking prices, as there are numerous trade-offs that travelers can make in response to changes in parking resistance that require more detailed approaches to estimate than this approach.

## 3.3 Full treatment of parking

### 3.3.1 Detailed summary of the approach and examples

As described in Section 2.1 this approach involves the development methods to model the demand to supply equilibrium of parking and is more complex than the approximate treatment approach.

In the UK there are several examples of attempts at the full treatment of parking using trip-based models. The London LTS model is one such example. Aside from including parking prices and search times in car generalised costs it also models parking demand equilibria in a very detailed way. It does this by modelling parking in every zone in Greater London with encoded details on parking supply (number of bays) by zone and by type of parking (public off-street, public on-street, and workplace parking). Information on parking supply was derived from the London Parking Supply Survey (LPSS). The parking model initially assigns home-based trips to destination zones, then as parking fills up it reassigns trips to neighbouring zones based on a multi-nomial logit model, taking into account walking time and cost for these alternatives. Reassigned trips park in the neighbouring zone and trips are completed via walking links to the original destination zone.

The LTS parking model process is shown schematically in Figure 13. Starting from diagram 1 in the figure, consider a set of neigbouring zones, with three (A, B, and C) selected for focus in this example. Diagram 2 indicates trips to these zones. In diagram 3 parking capacity is shown by the numbers in each zone. The number of trips to A B and C exceeds the parking capacity available in these zones, so trips are forced to neighbouring zones. Diagram 4 shows which zones these reassigned trips are sent to. Where ‘full zones’ force trips outside to neighbouring zones which are also subject to reassigned trips from other full zones, these zones take in both zones’ reassigned trips (diagram 5). When the capacity of neighbouring zones that take in trips is full, the net is cast slightly wider to a defined set of wider-area zones with trips divided up and spread to available capacity in this set.

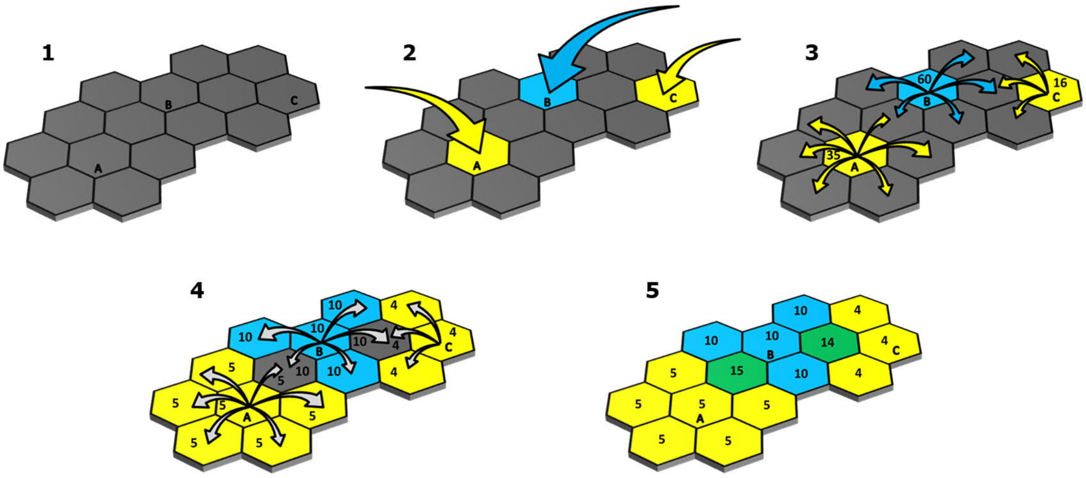


Figure 13: London LTS parking model schematic example

Source: MVA Consultancy (2010)

In the London model the parking model is included in the 4-step process after the distribution and mode choice step. This is because the parking model needs to know how many car trips in each iteration are bound for each destination zone, in order to then reassign these to neighboring zones. The parking model therefore needs to run several times within each main loop of the model in order to iteratively recalculate parking supply related cost changes. Multiple runs also allow excess demand to be reduced each iteration to a given convergence tolerance before the final matrices are assigned to the highway network.

Both Sheffield (SYSTM+) and Newcastle (TPM) have had full parking treatment implemented in their transport models. Both follow the network-based approach to modelling parking. In these models, as highway trips to a zone fill up parking in that zone, the parking link connecting the highway network and the zone (see Figure 6) registers a higher cost from its parking-specific delay capacity curve (shown in Figure 14). This additional cost to accessing that link for all succeeding vehicles causes neighbouring parking zones with lower cost to become more attractive for each marginal trip maker. Trips are diverted to these neighbouring zones on the highway network, and the final leg of the trip is made by walking along walk connector links connected to the original destination zone. In the Newcaste TPM, walk lines were set with a fixed walking speed of 4,0 km/h, and a weight applied to travel times of 2,0 (Jacobs Consultancy, 2008).

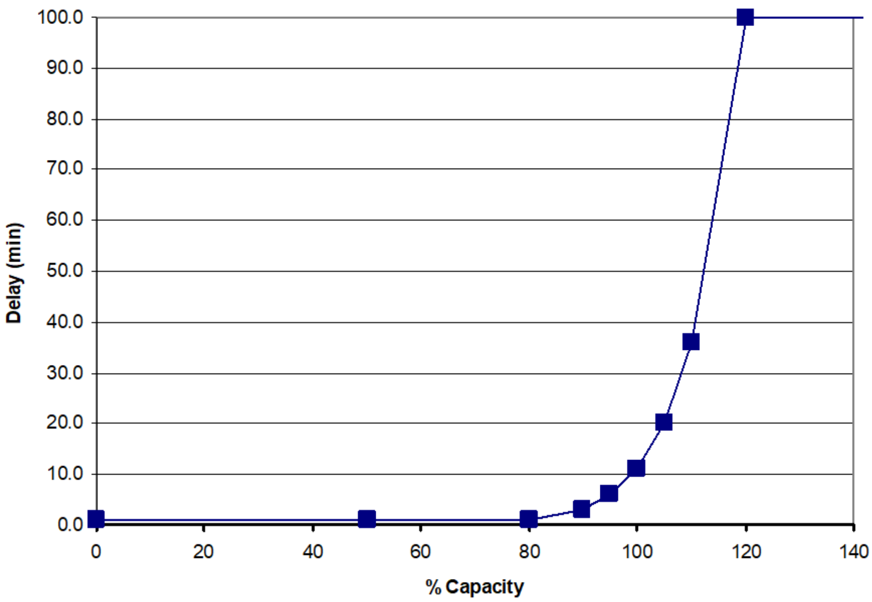


Figure 14: Newcastle TPM parking link delay/% capacity curve

Because both the Sheffield and Newcastle models are variable demand models, this approach to modelling parking impacts on all four stages of these models. Trip generations are impacted via the variable demand impacts of changes in mode generalised cost, trip distributions are impacted as these costs also affect which zones are key attractors, mode choice is influenced via how attractive car is relative to other modes, and finally the diversion of trips to zones with available parking affects the highway assignment stage.

So far, the three UK examples of the full treatment of parking involve the use of 4-step trip-based models. As discussed in Section 2.1, the full treatment of parking is not wholly recommended in trip-based models, as the complexities of parking choice are not appropriately captured by these models. Tour-based models are preferred as they can account for these factors much better.

The Irish RMS is a tour-based model which also includes full treatment of parking. There are several components to how this parking treatment is conducted. For workplace commute trips, there is a separate step to estimate the impact of free parking on mode choice. This process follows the steps shown below in Figure 15.

Box 1 shows the car mode share for workplace trips (left to right on the x-axis from 0% to 100%), and the proportion of access to free parking (top to bottom from 0% to 100%) when there is 100% access to free parking. Area A represents car trips, and area B trips by other modes. Box 2 shows the impact of a less than 100% access to free parking (i.e. capacity of the free parking is exceeded by willing demand), Area C trips must reconsider mode choice and other parking options. In Box 3, Area C is now comprised of Area D, who are trip makers that now pay for parking, and Area E, which represents trip makers that shift to other modes (e.g. public transport). Total car trips in the final box are represented therefore by the addition of areas A and D.

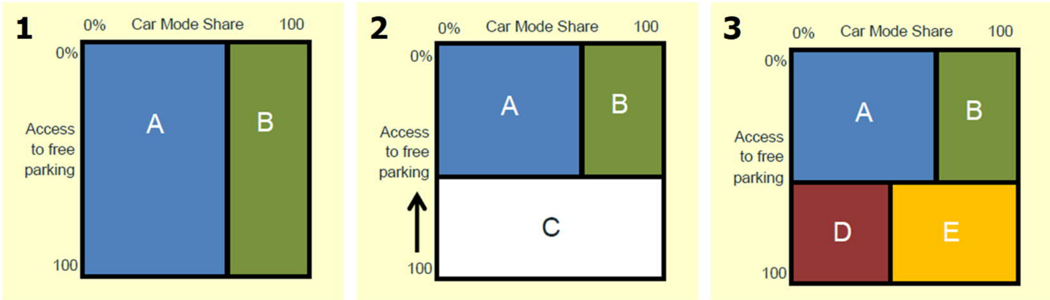


Figure 15: RMS free parking module schematic steps

Source: NTA, (2018)

The main parking distribution loop in the RMS conducts the reassignment of highway trips to alternative parking locations when the capacity of the primary destination zones' parking is reached. The model allows for some zones to be left out of this process (for example, non-inner urban zones) using a 0 or 1 flag for each zone in the model. This process follows the network-based approach described above (see Figure 6 in Section 2.1).

Not encountered or described in any of the reviewed models or literature was an attempt to model the impact of parking capacity limits on car access using some form of matrix-based cost calculation or even a simple capping system. For these types of approach to work a zone lookup for total destination zone parking capacity would be required (but this could be set up to have effectively infinite capacity in non-central areas). These methods would work by either capping the total allowable trips to the relevant destination zones then causing a hard shift of these trips to other modes or, by iteratively recalculating the destination-based cost of car trips over successive iterations as capacity fills up, increasing this cost exponentially as demand nears capacity. With an iterative cost-based approach trip distribution and mode choice would be directly affected. With a fixed capping matrix, only mode choice would be affected. For this reason, the iterative destination-based cost method may be more favourable than the hard trip-shifting method of trips to other modes. The disadvantage of this alternative over the more established network-based full treatment approach is that parking reassignment effects are not modelled. i.e. when drivers in the model park in other parking facilities instead of the first choice (which might be full) and complete their trip on the walking network.

### 3.3.2 Data requirements

The data requirements for a full treatment of parking includes the data required to conduct the approximate treatment of parking approach (i.e. parking price, search time estimates, see Section 3.2.2). These requirements are therefore not detailed in this section again. For the full treatment of parking a measure of the capacity of parking in each zone is the critical requirement (i.e. the number of car parks).

#### 3.3.2.1 Parking capacity

Parking capacity in the London LTS was obtained from the London Parking Supply Survey (LPSS). The LPSS was a dataset compiled over two years 1999/2000 and 2004/2005. The data was not a census of parking in Greater London, rather a survey of parking in randomly selected grids throughout the metropolis which was scaled up to estimate total parking spaces using a combination of land-use type and location (MVA Consultancy, 2005). For the Sheffield model, on-site surveys were commissioned to estimate total parking capacity by type of parking. The area surveyed was limited to the central core of the city to limit the scope of the survey. This survey was more closely like a census of parking spaces, but due to a limited budget for surveys the study relied on estimation of capacity for most sites. In the Newcastle model capacity for parking was calculated based on using base year modelled demand and an assumed uplift factor based on the knowledge that parking demand was not quite at capacity yet in most locations. The logic behind using a demand driven 'baseline capacity' was that trips to the city by car that have a destination in the city must be parking there, so the very minimum parking supply must be equal to this demand. In the model's documentation it is not clear on the specific uplift factors, but these are said to vary by area. How the Irish RMS model obtained parking capacity input data is not outlined in the model's documentation.

#### 3.3.2.2 Walking access to car parks

Because full treatment of parking methods that use the network-based approach require trip makers to use walking links to complete reassigned journeys, some level of accuracy is desired in the inputs regarding these journey legs. Use of the road network links in a model for these final walking components of trips is not generally desirable, as it is necessary to have direct walking link connections between neighbouring parking locations to ensure model connectivity and to feasibly model the transitions between highway and walk link legs of journeys. The UK WebTAG guidance (Department for Transport UK, 2014) recommends straight connector walking links coded with pavement/footpath distances measured off street maps. Average walking speeds are also necessary and should be set globally for a model implementing this approach.

### 3.3.3 Pros and cons of this approach

#### 3.3.3.1 Pros

A full treatment approach to modelling parking has the potential to provide the most detailed results and to yield the most realistic modelling of how parking works in real life. For models of locations where parking is known to be at or near capacity, then modelling parking using the full treatment could be valuable tool in testing parking policy and other related scenarios. Only with this more detailed approach is it possible to look at the impacts of changing the various aspects of parking and parking policy. Is it possible to model the varied and competing impacts of things like price, supply, availability, etc. by capturing the complex decision-making choices that trip makers make based on the combinations of these attributes.

Whilst the transport guidance reviewed in this report is specific about what are the recommended attributes of a model before a full approach is considered there is undoubtably room for customisation and the development of a bespoke approach for each model.

#### 3.3.3.2 Cons

According to the literature, to reliably undertake the full treatment of parking in a transport model it is recommended that the model under consideration meets the criteria set out in Section 2.1. That is, in the first instance, that the model is tour-based and has segmented user-classes and purposes. If these criteria are satisfied, another consideration is that a judgement is made about whether modelling parking in a detailed way is appropriate and required. This includes answering the following questions:

- If the model is a national or regional model, is modelling parking in urban centres appropriate if the detail in the model in terms of network and zonal structure are accordingly course?
- If the model is of an urban area, is parking policy a key driver of car mode choice? Is it likely to be in the future?

The data inputs required for the full treatment are also non-trivial. Significant and high-quality data is required and recommended on:

- Parking prices per zone
- Types of parking available
- Parking supply (number of car parks)
- Locations of parking

None of the models reviewed in this report that implement the full treatment of parking currently have an absolute high degree of quality in these inputs. Most of the models reviewed estimate or approximate these inputs.

A full treatment of parking will also require significant development cost and recalibration time for existing models. It may also be difficult to validate the performance of the parking module, as this may require having data on parking utilization over the modelled time periods for instance. High-level checks on road link flows and mode share proportions may be the only validation metrics available for reviewing the performance of the parking module in most cases.

RAMBOLL

# 4. Suitability of the approaches to implementation in Sampers

## 4.1 Appropriateness for Sampers

The UK WebTAG's guidance notes that it is important to make an assessment on whether modelling parking is appropriate for the model under consideration. This is especially relevant if the full implementation of parking is considered for implementation as this option is harder to implement and is more detailed than the approximate approach. At this juncture it is worth commenting on whether we consider modelling parking appropriate for Sampers.

The literature review showed that across the board parking resistance is accounted for in many national and regional models at the very least by the approximate treatment. It is therefore fairly safe ground to argue that for a model of Sampers' scale it is appropriate to implement at the minimum some form of approximate treatment.

The full treatment is harder to motivate given its uncommon implementation in national/regional models. Only the Irish RMS regional model was found to have a form of full implementation in our literature review. The appropriateness of this treatment in such a strategic level model is valid to question. Strategic model that model regional/national transport are not expected to contain detailed modelling of all aspects of transport. Not only would run times for these models be further lengthened if this was so but also because of their low-network detail, high detail in some areas of the model's calculation and not others can lead to spurious results and unbalanced performance.

That said, we believe that the full implementation approach can itself be applied in varying forms, from high to low detail and could be applied only in certain geographic locations in the model. Later in the report we will outline a lower-detail variant of the full implementation approach which is more appropriate for Sampers. It balances the need to model the impact of supply of parking with the requirement that such an implementation is lower-detail than what would be appropriate in a city macro or meso-model.

## 4.2 Key points

The previous section outlined the approximate and full treatment approaches to modelling parking. It outlined a detailed summary of each approach as well as providing information on the data requirements and the pros and cons of each. This section outlines the suitability of these two main approaches for implementation in Sampers and provides recommendations for further research.

An important note at the outset is that Sampers 4 is a tour-based model. It calculates trip generations, distributions and mode choice using tours as its unit of travel for all home-based trips, but work-based trips (trips starting and ending at work for work purposes, sometimes called “employers' business” trips) are calculated separately in a special module. Because Sampers 4 is a tour-based model it could be fitted out with a variant of the full treatment approach to parking in future versions. However, for a national/regional model like Sampers, the relatively low detail in the zonal system could be a barrier to implementing very detailed parking modelling. This is because higher detailed zonal networks provide enough detail to pick up different trip attraction types to parking destination zones, price areas, and reassignment effects to alternative parking zones. That said, as Figure 16 and Figure 17 shows Sampers has a relatively similar zonal detail to the Irish RMS model which employs a full treatment of parking. The figures show the zonal detail for the town of Limerick and Dublin compared to Sampers' zonal detail for Lund and Gothenburg at approximately the same magnification (zones in the maps are represented by the black polygons).


Figure 16: Irish RMS zonal detail in Limerick (left) and Sampers zonal detail in Lund (right) compared with the same geographic scale

Source: NTA 2016 (1), and OpenStreetMap contributors 2019

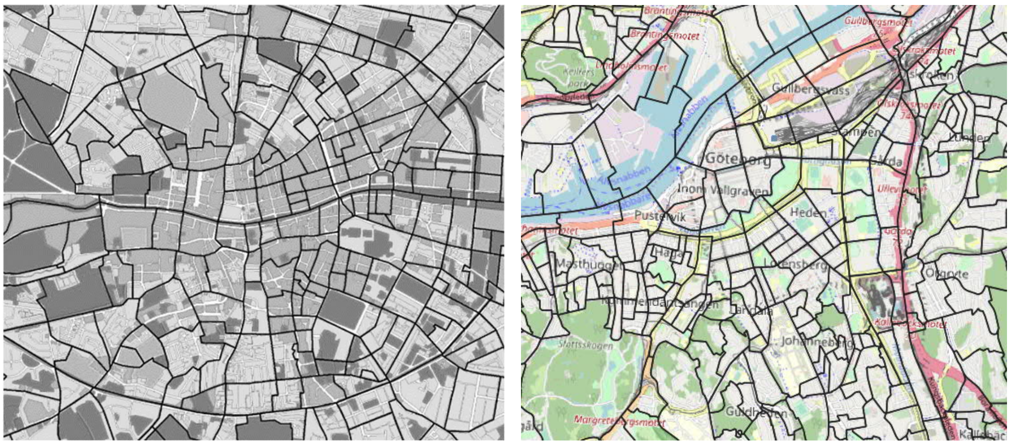


Figure 17: Irish RMS zonal detail in Dublin (left) and Sampers zonal detail in Gothenburg (right) compared with the same geographic scale

Source: NTA 2016 (2), and OpenStreetMap contributors 2019

Data collection methods for parking prices, access, parking types, and parking supply in cities in Sweden is a challenge. Improvement of primary data collection methods on parking could be improved in the future. This could, for instance include including parking location and price in regional and national travel surveys and implementation of parking supply monitoring and reporting in conurbations over a certain population.

As an alternative, or complimentary source, exploring existing and emerging big-data approaches (see Section 5.1) is another option. Work should be done to establish the quality and coverage of big-data options available. This could be done for a conurbation in Sweden which has relatively good existing data available (e.g. Gothenburg).

One alternative option described in Section 3.3.1 which would impact only central areas of the large Swedish cities (Stockholm, Gothenburg, and Malmo) would be a matrix cost calculation process at or just after the trip distribution / mode choice stage. This would work by iteratively recalculating generalised cost for car trips to specific destination zones (i.e. central core zones). As car trips increase to match parking supply in each iteration so increase also cost, up until the point that marginal extra trips to these zones taper off. Such a process may do a sufficiently reasonable job at modelling the impact of supply limits on parking.

It would have the advantage that as part of the distribution/mode choice stage or just after, trips can both shift to other modes as well as redistribute to other zones (if iterated though several times). However, this approach has not been observed in any models researched or encountered as part of this report's literature study, so such an approach may be experimental. This method should be preferred over a harder 'capping-off' and shifting method of trips to other modes as it achieves a similar outcome but via use of the more traditional 4-step framework. Its main disadvantage compared to the more established 'network-based' full treatment of parking is that it cannot model reassignment effects for trip makers forced to park in alternative parking locations if their first choice is full.

# 5. Further research directions

## 5.1 Parking prices and supply

Obtaining accurate pricing data for urban locations around Sweden could be a resource intensive exercise if done manually with site surveys. Examples of how parking prices were obtained using more efficient methods for models around the world can offer alternative approaches. The approach used to obtain parking price information for the Norwegian RTM model offers one template for how this could be done in Sweden.

For the Norwegian RTM, prices were collected from municipal websites, weighted (when available) by the supply of parking spaces by price (see description in Section 3.2.2.1). Short-term per-hour parking rates and long-term (per day) rates were collected, with long-term rates used for work trips and short-term rates used for other trip purposes. The RTM also used national travel survey information to inform parking price estimates for work trips. The survey asks respondents to say how much they pay for parking at their place of employment, whether they pay the full amount or whether they receive a cheaper rate or have parking costs paid through their wage via a payment plan.

In Sweden several cities have databases of parking prices by location, see for example, Figure 18 showing Gothenburg's database. Collecting these data and aggregating and averaging by zone using a similar process to the Norwegian RTM approach may be possible. The Norwegian and Swedish travel surveys contain similar parking price paid questions. Therefore, it may be possible to use the responses to these questions to obtain estimates on average prices for long-term parking for work trips, and whether employees or employers pay for parking costs.

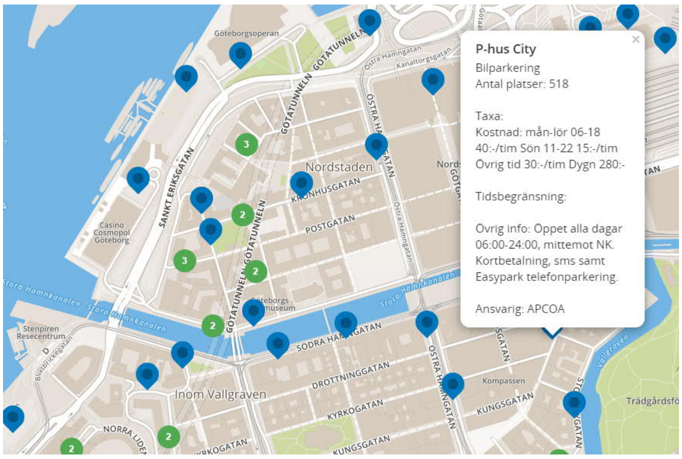


Figure 18: Göteborg Städ parking price database

Like parking prices, obtaining accurate numbers on parking supply (number of parking spaces) for a given area is a challenge. One option is to look to emerging technology options to obtain information on parking prices. 'Big data' providers (companies that collect and/or resell disaggregated data from mobile phones and GPS devices for analysis), like Inrix and Flowbird offer parking datasets for Sweden which list information on types of parking, number of spaces, prices, occupancies, and location information at highly disaggregated and aggregated levels across time. These sources could be used to calculate averages for zones or aggregations of zones by location for the Sampers model, potentially for the whole country. The benefits of this option are consistency of approach nationwide and lower data processing cost. An example of Inrix parking data for both on-street and off-street parking datasets is shown below in Figure 19. This type of data can be obtained from data-providers like Inrix via an application programming interface (API), so large datasets can be downloaded in single batches.

Off street

| Name | Operator | Spaces | Parking_allowed | Hourly_rate | Coordinates |
|---|---|---|---|---|---|
| Verkstadsgatan 2 Parking | City of Gothenburg | 122 | Yes | 21 | 11.9567397, 57.7047288 |
| Kungstorget 1 Parking | City of Gothenburg | 70 | Yes | 30 | 11.9684476, 57.7029632 |
| Kungsgaraget | APCOA | 250 | Yes | 40 | 11.9608574, 57.704389 |
| Verkstadsgatan 1 Parking | City of Gothenburg | 168 | Yes | 21 | 11.956016, 57.7041888 |
| Magasinsgatan | Q-Park | 15 | Yes | 30 | 11.9625723, 57.7029862 |
| P-hus City | APCOA | 315 | Yes | 40 | 11.9712153, 57.7060019 |

On-street

| Name | Operator | Spaces | Parking_allowed | Hourly_rate | Coordinates |
|---|---|---|---|---|---|
| Kungsportsavenyen | City of Gothenburg | 5 | Yes | 0 | 11.97062, 57.70333 |
| Stora Nygatan | City of Gothenburg | 11 | Yes | 30 | 11.97205, 57.70411 |
| Kungstorget | City of Gothenburg | 4 | Yes | 30 | 11.96839, 57.7038 |
| Lilla Kungsgatan | City of Gothenburg | 5 | Yes | 0 | 11.97137, 57.70539 |
| Stora Nygatan | City of Gothenburg | 1 | Yes | 30 | 11.97077, 57.70406 |
| Stora Nygatan | City of Gothenburg | 2 | Yes | 30 | 11.97253, 57.70442 |
| Östra Hamngatan | City of Gothenburg | 3 | Yes | 20 | 11.96889, 57.70537 |
| Östra Hamngatan | City of Gothenburg | 7 | Yes | 20 | 11.96842, 57.70584 |
| Östra Larmgatan | City of Gothenburg | 7 | Yes | 0 | 11.97184, 57.70699 |
| Lasarettsgatan | City of Gothenburg | 3 | Yes | 30 | 11.95711, 57.70372 |
| Surbrunnsgatan | City of Gothenburg | 2 | Yes | 0 | 11.95502, 57.70325 |
| Lasarettsgatan | City of Gothenburg | 10 | Yes | 30 | 11.95773, 57.7033 |
| Västra Hamngatan | City of Gothenburg | 3 | Yes | 0 | 11.96365, 57.70456 |
| Västra Hamngatan | City of Gothenburg | 3 | Yes | 20 | 11.96455, 57.70288 |

Figure 19: Inrix Parking data

It is recommended that parking data sources are investigated and reviewed for accuracy as part of research going forward.

## 5.2 Parking search time

As noted in Section 4.1, estimates on parking search times could be obtained through case studies at selected sites then methodology developed to apply these to aggregate zones, like for example, the methodology used in the UK National Model. Or through establishing relationships between variables, like the Washington DC model's correlation between parking search times and employment density. Limited on-ground data collection could be supplemented by leveraging big-data sources, like those mentioned above, to develop national datasets more easily. Using data from these sources on occupancy and capacity by time-period and location could allow development of different parking search times by modelled time-period as well as location. This rough methodology is shown in Figure 20. This could be supplemented with estimates from theoretical relationships developed in other locations like equation (2) used in the Irish RMS model to estimate parking search times.

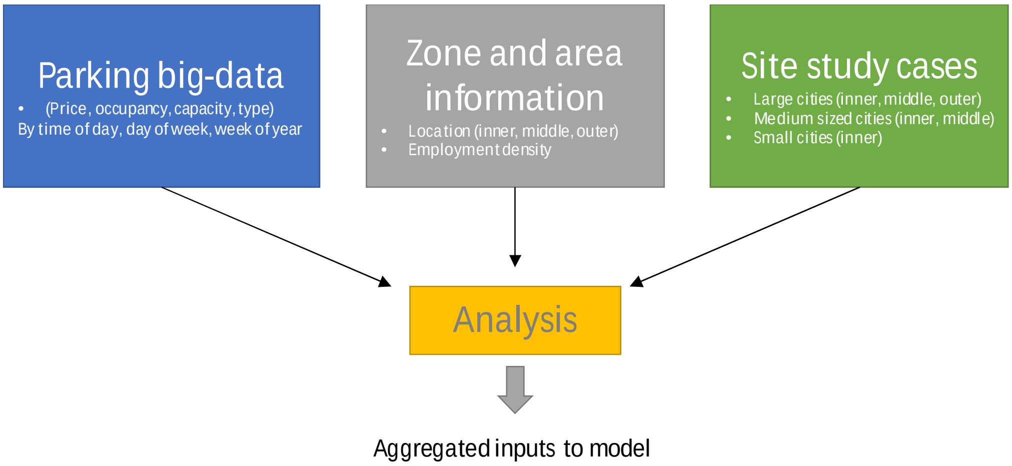


Figure 20: Parking search time possible methodology

## 5.3 Parking supply cost function

If a matrix-based cost process is included in future Sampers versions which simulates how saturation of parking limits car trips, then exactly how this cost function is specified would require research and testing. In the first instance an exponential cost function like that used in the Newcastle model for link-based cost increases could be tested (see Figure 14). Ultimately it may be within the model itself through calibration and validation to known car trips based on key link flows that may yield the most suitable parameters.

# 6. Potential implementation plan for parking resistance in Sampers

## 6.1 Overview

This section outlies the authors' opinion on the broad steps required to implement parking in Sampers. These are only a guide to the required steps in addition to further research on data required. A more detailed and technical study should be conducted at a later stage on Trafikverket's preferred approaches with more focus on Sampers coding detail. A key focus from Trafikverket on the impact of the supply/demand of parking as the key area of need means that this section focuses on implementation of at a minimum some form of the full treatment approach to modelling parking.

## 6.2 Implementation

We see that there are two possible options for implementation of a full treatment. The first is a matrix-cost based method in the trip distribution/mode choice component of the model. The second option is to implement a more network-based parking model like those described in the model examples reviewed in the literature. Both options should include elements of the approximate treatment of parking (inclusion of parking price and parking search times in generalised cost).

The following points are the broad steps to implement the matrix-based cost method within Sampers:

- Outside of Sampers
    - Decide on which urban areas should have the parking module applied to. In the first instance this should focus on Stockholm, but eventually should be applied in the other large cities.
    - A lookup of aggregations of zones should be done to define parking areas. These could be based on municipal parking price areas or by aggregating zones together with similar average parking prices.
    - Total parking supply (number of parking spaces) and average prices for the aggregate areas should be calculated and a lookup table created that matches to the aggregated zones.
- Inside Sampers
    - Within the mode-choice/distribution step of the model a new function needs to be structured, like the one presented in figure 14. The main purpose of the function is to add parking's contribution to generalized cost based on the on the number of trips distributed to the parking aggregation areas and the supply how this changes the supply cost function. It should also add in the other parking cost components (price etc.)
    - An important part of the function is the way it should 'record' the history of how many vehicles are parked at the end of each time

period modelled so that this is passed onto the next time period as the starting point form for the cost function based on parking demand. In Sampers there are only two time periods; morning peak hour and traffic between 9 and 15. The morning peak hour involves work trips and trips during the other time period involve other trips. A possible strategy in this case is to assume that work trips always have access to a parking space, but the access for other trips depends on how many vacant parking spaces are available at 09.00 when the work trip-makers parked.
    - A process of testing and calibration would be required, with likely changes required to other areas of the model as the impact on trip making could be significant – particularly in highly congested areas or future scenarios with higher travel demand. Testing and calibration using a single Sampers regional model to understand recalibration requirements is justified before the module is included in all regions.

To implement a full treatment like that described in several models in the literature review which relies on network links, the following broad steps would be required:

- Outside of Sampers
    - Decide on which urban areas should have the parking module applied to. In the first instance this should focus on Stockholm, but eventually should be applied in the other large cities.
    - Determine zonal aggregations. It may be possible to use large aggregations of zones for how the module works, however in the reviewed models parking prices are typically applied at aggregated levels but trips are distributed at the zonal level.
- Inside Sampers
    - Create the parking nodes and design the walking connections in the network connecting these nodes to model zones. Design also the parking links which connect to the highway network and which are the links that apply the parking supply cost function.
    - Create a parking supply lookup table which defines how many parking spaces each parking node has. This may need to be a link attribute for the parking links instead of a value stored in the parking node itself.
    - Within the mode-choice/distribution step of the model a new looping process needs to be structured. This could be like the parking module like the London model, which is located after the distribution/mode choice step.
    - Like the matrix-cost based option, a full treatment using the network approach should ‘record’ the history of parking so that the total number of parked cars at the end of one time period is passed to the next time period as the starting occupancy of the car parking in that time period.

- Loop convergence criteria to define when the parking module is ‘finished’ will need to be defined.
- Testing and calibration stage

## 6.3 Special note on the recalibration effort

Trailing and testing of an implementation of parking resistance in Sampers should be done early on to determine the model’s sensitivity to changes in car generalised cost and the likely recalibration efforts required. In the currently calibrated Sampers model, parking resistance effects are inherently accounted for in the other terms in the car generalised cost functions. In other words, as the model has been calibrated to observed traffic flows and mode shares, these observable realities are mirrored in the model by compensating with the other components of car generalised cost. By including parking resistance the other elements of the model’s cost calculations will no longer play a role in ‘approximating’ parking resistance. This means that recalibration of these other parameters may be necessary.

# 7. Conclusion

This report's aims were to provide an outline on how parking resistance is implemented in strategic transport models around the world and to provide a knowledge base for how parking resistance could be implemented in the Sampers model.

This report provided a literature review which examined worldwide transport modelling guidelines and academic research and looked at 17 models from around the world which have implemented parking resistance modelling in some form.

From the literature review two main approaches were identified. These were:

- An approximate treatment of parking
- Full treatment of parking

The approximate treatment of parking involves including out-of-pocket parking costs and often also parking search time components into a model's transport cost calculations. It requires information on parking prices by area, development of geographical aggregations to apply prices consistently, and estimates on parking search times by area (if included). The full treatment of parking involves modelling the impact of the supply of parking and how decision making about parking location is impacted by the combined effects of price, location, and availability. For this to be modelled properly data on the supply of parking (number of car parks) is required.

This report outlined some areas for further research needed. These included further investigation into the data collection methods that could be used for parking prices, search times, and parking supply.

Finally, this report outlined potential implementation steps for parking resistance in future versions of Sampers. As Trafikverket is keen to capture the impacts of parking supply/demand this implementation plan focused on development of a full treatment of parking in Sampers. Two options were laid out for future more detailed focus. These were a matrix-based cost process and the network-based approach noted in some of the models reviewed in the literature review section. Future work should examine the feasibility and detail of these options from a level of detail at the Sampers scripting level.

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