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# Evaluation Of Smart Parking Applications Through –ITS

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## Abstract

This research focuses on the derivation of an assignment model that can be used for the evaluation of Smart Parking ITS applications. Behavioural research is conducted in order to gain understanding of the individuals' behaviour concerning parking, on three behavioural levels (Strategic, Operational and Tactical), and for two user classes (Familiar and Unfamiliar users). A Parking Decision Process model, which represent the decisions that individuals have to take when parking is suggested. A Stated Preference experiment is conducted –designed using efficient designs– for the investigation of decisions for familiar and unfamiliar users and discrete choice models are derived for familiar users. The outcome of the behavioural research (Parking Decision Process model & MNL Parking Discrete Choice model) is applied in the development of a Parking Assignment Model for simulation on the behavioural levels for both user classes. The components of the Parking Assignment Model are verified and the applicability of the model is examined. Finally, the Parking Assignment Model is applied for the evaluation of the Smart Parking application, developed for the Sensor City project in Assen. The results of the evaluation illustrate the positive impact of the Smart Parking application to the reduction of individuals' and total travel times

## 1. Introduction

Parking in urban areas is an issue of increasing importance, especially the last few years. There is voluminous literature concerning the problems consequential to the high parking demand, with researchers indicating that the average volume of the total traffic related to parking during peak hours in city centers can reach 30 to 50 percent of the total traffic (Shoup,2006; Arnott and Inci, 2006). As each trip ends to a parking spot, searching (*cruising*) for parking is a phenomenon widely met in the urban environment, and it is related to problems in terms of to name but a few: lost time, fuel consumption, traffic flow, safety and emissions (Kaplan and Bekhor, 2011). The main instrument for reducing the impact of parking is the development of parking-related policies. Those balance the demand and supply for parking with the most prominent to be parking pricing (Lam et al., 2006). However, as parking pricing policies reach their limits due to social and political reasons, the need to develop new systems to alleviate the parking impact has become imperative. Lately, Intelligent Transport Systems (*ITS* ), and more specifically Smart Parking applications are being designed and require evaluation before being implemented on a wide scale.

## Evaluation Approach

The evaluation of a Smart Parking application can be achieved by the evaluation of the situation without the application (reference case) and then, the evaluation of the situation –as predicted– with the application (proposed case). The evaluation on a real network and in a wide scale is most times impossible and for that reason *models* are being developed to represent the decisions and actions taken, in both the reference and the proposed case.

The parking process includes decisions and actions on how individuals cruise for parking, the parking destinations chosen and the routes taken to reach those destinations. The difference between the reference and the proposed case is found on the affect the Smart Parking appli- cation has on those decisions and actions. This directly suggests that the model definition of the parking

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process at the reference case and the effect Smart Parking application has on it are the two modelling modules required for the evaluation of a Smart Parking application (Figure 1.1).

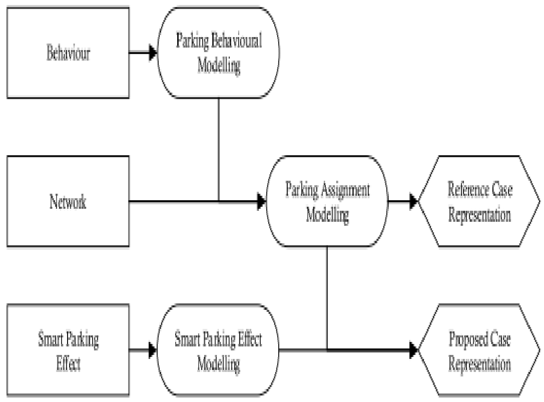


Figure 1.1: Components of the evaluation and evaluation approach

The starting point of the behavioral research is the investigation of the Parking Decision Process, which involves the decisions taken when travelers need to park at an urban en- vironment on defined behavioral levels (pre-trip and on-trip). The decisions should then be modeled as an assignment of individuals pre-trip and represents the reactions with the network on-trip. Modeling in various decision levels and for multiple user classes increases the complexity of the Parking Assignment Model. For this reason it is chosen to implement it in a simulation environment.

## Smart Parking

Smart Parking is a **parking reservation system** that can be described as it consists of mainly three entities: the user, the parking facility agent and the parking management agent (Figure 1.2). The user entity is connected to the system via a device able to communicate (GPRS-3G) and to track position (GPS/GNSS/Galileo). The parking facility entity that provide services (parking spaces) and information to users. The third entity is a control agent that gathers information from the user and the parking entities as well as from various other sources (traffic counts, road sensors) in real time and combines all pieces of information into a suggestion for reserving a specific parking space (Jonkers et al., 2011). The conceptual design of the system informs the driver about the closest - to the destination - available parking spots 15 minutes before arrival to the destination and encourages the driver to reserve a parking spot.

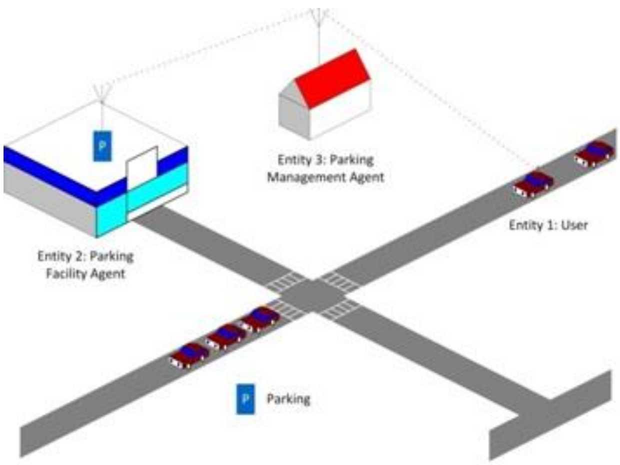


**Figure 1.2:** Smart p arking entities

## 2. Related work

One of the first papers for parking indicated that parking-related problems are the result of people wanting to park exactly outside the door of their destination (Behrendt, 1940). The increase of transportation demand changed the problem towards the difficulty of finding a vacant parking spot at all. Searching for a parking spot became a reality and solutions were proposed oriented towards increasing supply by building (usually) off-street parking. As this approach was found to create problems, the solutions were then oriented towards managing demand with policies or information applications.

The need to find solutions to the parking related problems arose the need for representing parking choices and derive models that would represent the parking dynamics. Starting from the very basics, a model is a “simplified representation of a part of reality ” used to investigate a part of the real world and what will happen in case of changing something (Bovy et al.,2006). In the beginning models were very simple. However, managing demand requires more detailed characteristics of demand, yet representing the way individuals behave in relation to parking, more sophisticated models arose.

Parking is a transport component causing high externalities such as congestion, space occupation, reduced safety and others (Feitelson and Rotem, 2004). There is extensive literature in which the problem is addressed and suggested solutions are provided. Chronologically, the literature started by addressing the parking problem a few years after the mass production of cars. Aspects such as the occupancy of public or private space for parking aesthetics, safety and vulnerable users mobility are some of the issues examined for parking (Smith, 1947; Ricker, 1948; Swanson, 1989; McCoy et al., 1990; Arnold and Gibbons, 1996; Akbari et al.,2003; Feitelson and Rotem, 2004; Shoup, 2006; Davis et al., 2010a) and are briefly presented here.

To begin with, the occupancy of public or private space for parking is addressed by several researchers (Davis et al., 2010a; Feitelson and Rotem, 2004; Arnold and Gibbons, 1996). It seems that parking occupies space especially in city centres. Akbari et al. (2003), as an example, found that for Sacramento parking can reach 57 per cent of commercial areas. The surface can be thought as closed areas that cannot be used for other uses –e.g. as recreation– affecting the urban development (Feitelson and Rotem, 2004).

The transport system can be defined as “a set of elements and interactions between them that produce demand for travel and the provision of transportation services to satisfy this demand” (Cascetta, 2009). The representation of this system is approached by modelling the components of the system that seem to have a clear influence to the outcome. In the context of evaluating an ITS application the two main components to be explored are the modelling of the behavioural characteristics using mainly discrete choice models and the traffic assignment modelling.

Young and Taylor (1991) hierarchies models based on their scale of the examination area (Fig- ure 2.2). Starting from microscopic and moving to macroscopic, 4 levels can be distinguished: The parking lot level, the parking zone level, the sub-region level and the urban level. Those models communicate using a model that represent the connections between different levels (Young, 2008).

Another important distinction by Young et al. (1991); Young (2008) is the categorization of models based on their objective. Generally, the parking models are distinguished in Parking Design models, Parking Al location models, Parking Search models, Parking Choice models and Parking Interaction models. Parking design models are used to design parking, calculate capacities, dimensions and generally understand the performance of the parking system.

## 3.Theoretical Parking Behavior

The understanding of the decisions taken in the parking process, and how individuals decide upon them are crucial for the representation of the parking process. The definition of the parking decision process model and the discrete choice models help towards this direction, with the investigation of the attributes which shape those decisions and the way individuals evaluate the available alternatives to be required. In order to fulfill those requirements there is a need to explicitly define and analyze the parking system (users, network), and the decisions behavioural levels. The behavioural research is going to be used as the basis for the parking assignment modeling framework.

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The decisions are explored on a decision process level starting with pre-trip decisions and moving towards the decisions taken while individuals interact with traffic (on-trip). In order to have a clear structure of the decision process it is chosen to categorize decisions on a three-layer behavioural model. Different users of the network imply the definition of users classes.

Towards this understanding, and for the estimation of the discrete choice model a Stated Preference experiment is conducted. The reasoning for conducting an experiment lays on two main reasons. First of all, parking regulations in the urban environment have changed since the latest experiments affecting the behaviour concerning parking. Second of all, it was believed that the attributes widely used in the literature, partially represent parking choices and that there might be a set of attributes which would describe the choice in a more representative way.

The focus of this research –on the impact of a new system to the existing traffic– implies the consideration of trips only made by car. A probable increase of traffic caused by the usage of the new system is not taken into account. The investigation of parking involves the definition of the strategy that people select when choosing for parking on a pre-trip level and the interaction with traffic when reaching the destination area (on-trip) for a defined network with fixed number of trips and fixed departure times concerning shopping.

## User Classes

Before continuing with any decision process specification, there is a need to investigate the users (also referred to as travel lers or individuals) of the system and try to aggregate them into groups (users' classes) characterized by the same decisions process. The results of inter- view, the nature of the motivation system and the conclusions of the literature study lead to distinction of two user's classes. The travellers which are **familiar** with the parking situation at the destination and those who are **unfamiliar** with that situation.

In is clearly evidenced in the literature, that transport research usually focuses on travellers who are assumed to have knowledge of the system (see Bovy et al., 2006). This cannot always be the case – especially for parking. Travellers might be unfamiliar with the parking situation at areas of the cities they even dwell. It is logical that in case someone is unfamiliar with the parking situation cannot be treated as part of a group which assumes full knowledge. Unfamiliar users take different decisions, or even considers different levels of alternatives characteristics. However, there is nothing preventing unfamiliar users from becoming familiar, by acquiring knowledge of the transport system.

## Parking Behavioural Levels

Parking behavior is analyzed on three behavioural levels, with respect to the undergoing behavioural process of individuals: Strategic, Tactical and Operational. Those three levels apply for both the familiar and the unfamiliar users however, different decisions are involved in each user class.

In this research, the **strategic** level incorporates the strategy individuals' devise before trip, in order to park. The **tactical** level deals with the interaction between the individuals and the traffic and parking dynamics. This level includes decisions to proceed from one parking destination to another one, given the strategy mentioned above. Furthermore, this layer contains decisions which are related to the change of the initial strategy after interacting with the transport system. Finally, the **operational** level is related to link choice when cruising, or route choice decisions while it is intended to travel from one parking destinations to another.

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The definition of the behavioural levels indicate an order of decision to be followed (e.g. the strategic level defines the decisions on the tactical level). In this case, the strategic level is the first to appear in the decision process determining the decisions on the operational level. The tactical level defines the decisions of the operational level. Apart from the decision flow from the tactical to the operation level, decisions on the operational level might lead back to the tactical level, given the interaction of the individual with the transport system. On the other hand the strategic level is based on the perception of individuals concerning the parking system and take place before trip.

## Behavioural Concept

The interviews and the panel conducted showed that there is a distinct pattern of behaviour among familiar and unfamiliar users. For that reason the description of every model is based on that pattern.

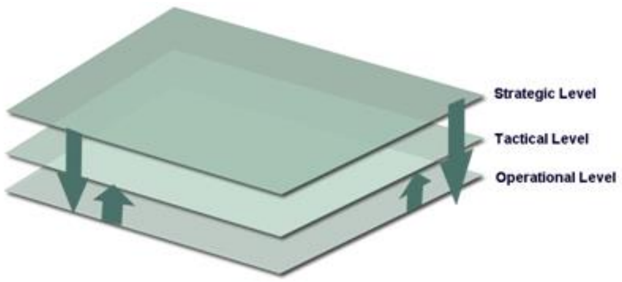


**Figure 3.3:** Parking Behavioural Levels

**Familiar** The discussion during the panel study and interviews illustrated an existence of a habitual pattern of people when choosing parking. The traffic situation at the destination as well as the state of the parking destinations available was found to be crucial in the decision process. However, it was also observed that people expect a certain amount of delay (cruising) when they want to park. In other words, people would visit a parking destination if they would expect to find a vacant parking spot in a "short" period of time but would not wait or search if this period becomes "long". This train of thought led to the following behavioural concept:

Individuals choose a parking destination based on their preferences concerning price of the parking destination, distance of the parking destination from destination, travel time to the parking destination's location, parking type as wel l as the probability of finding a vacant parking spot upon arrival and/or after a certain amount of time.

**Unfamiliar Users** Unfamiliar users have not been investigated to the best of the author's knowledge, indicating the need to cater for this user class in the experimental design. The idea is that there is a strategy on acquiring information for parking and that generally people would randomly search for parking.

## Parking Decision Process Model

There is a twofold reasoning behind the illustration of the decision process concerning park- ing: to set the guidelines based on which the survey experiment is designed, and to guide the parking assignment framework models derivation. More specifically, the decision process framework was employed to describe the decisions taken while choosing a parking destina- tion (Figure 3.4). As already mentioned it is a corollary of the literature review, individual interviews and panel interviews.

The random traveller (decision maker) who wants to travel to a city centre, **by car** can be described by a set of attributes describing the traveller (e.g. age, income, gender, age, area of living, network familiarity) and a set of preferences for the attributes which can characterize the parking alternatives. As described above, the main differentiation in the behavioural process is found based on familiarity with the parking situation at the destination.

From the already described clusters of attributes there is a decision on a parking search strategy. If travellers find an available parking spot at the

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destination they park and they are out of the system. However, if there is no vacant parking spot at the initial destination, they either continue searching or re-evaluating the alternatives each group have in mind.

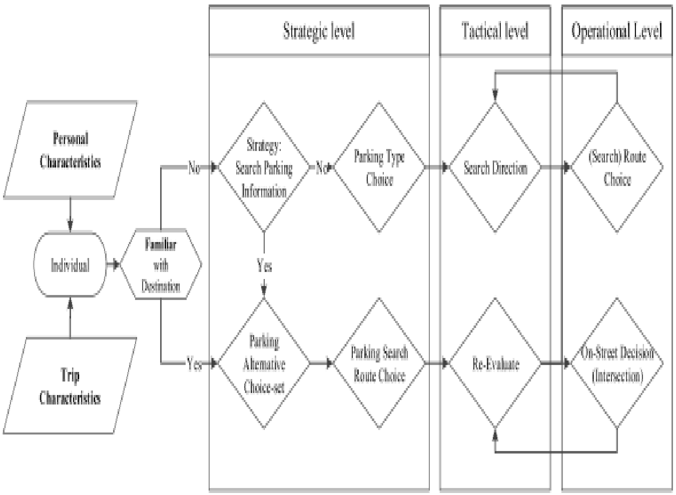


Figure 3.4: Decision Framework

The idea of the conceptual experimental design is to define a process that would guide the experimental design process away from possible complications that would risk the outcome of the survey. For that reason the experimental design was planned to follow a process with a two rounds pilot study based on efficient designs. The process defined goes through the design of a first survey to be used for the definition of an initial set of priors. Then the design of a second survey to be used for the definition of the priors for the final design (Figure 3.6).

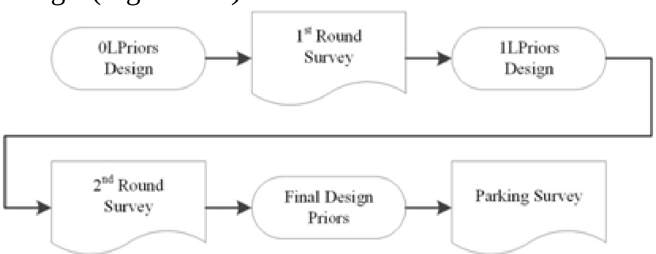


**Figure 3.6:** The survey design procedure

Both for familiar and unfamiliar users the main concept is that there are decisions revealing a strategy on approaching parking as well as operational and tactical characteristics that can be represented. Familiar user indicate a habitual pattern by developing parking search routes and unfamiliar users indicate preferences on their planning concerning parking.

Based on the Decision Process framework the conceptual experiment design was derived in such a way that it would result in the acquirement of more information about the estimators of the attributes examined. The attribute levels are conceptually defined and hypotheses are made concerning the expected outcome of the experiment. Finally the concept of the data collection process is described.

## 4. Experiment Design And Model Estimation

The design of a survey and the analysis of the acquired information are both very important components of behavioural research. As the system describing the behavioural responses of individuals is complex, its identification and the investigation of the experimental designs were rather limited to some basic concepts of efficient designs.

The literature suggests that the most usual design for Stated Preference research is the orthogonal design. However, as it is indicated by Rose et al. (2008) even in case there is only an indication of the *priors*[1], designing a survey with efficient design techniques yields more information. This information can be described by the Fisher Information Matrix[2] with the highest information to result in lower variance described by the Cramer Rao Inequality[3] (given that some conditions on the estimators properties are met). The experiment design process does not take into account the application (which in this case is the prediction) with the

## Experiment Design Process

The experimental design process for the familiar section (as conceptually designed in the previous chapter - Section 3.7) was initially implemented from data from the literature and compared to the orthogonal design. The comparison was made on the D-error estimator (the determinant of Variance Covariance Matrix). As expected, the orthogonal design was found to be ineffective with many scenarios to be governed by dominating alternatives. As such, the first round of the pilot study was introduced to have a clearer indication of the estimators. Afterwards, the design process continued with the derivation of the second round's design and was completed with the final design. All the experiment designs were produced using Ngene. The model structure chosen to use for the designs was the MNL model.

## Parking Choice Models Estimation

On of the reasons for the realization of the behavioural research is the derivation of models that would be able to represent individual's choices concerning parking. For that reason both for familiar and unfamiliar users it was attempted to derive choice models.

## Model Verification

Model verification is a tedious task in general. Although the models derived seem to behave as expected (with the costs to be negative and the utilities to be positive) and the estimation process did not resulted in general in little radius of fit or other negative diagnostics. Although the goodness of fit is presented for all models and is described by the likelihood ratio index (see Train, 2003, section 3.8), it was intended to further explore it, by comparing the predicted percentage of choosing one alternative to the actual percentage of people choosing the same alternative. It is important to keep in mind that as Train (2003) clearly indicates, this metric for the goodness of fit should not used due to the fact that it "misses the point of probabilities". In this case, a random choice situation was chosen, the utilities and the probabilities were calculated and compared to the actual choices of individuals. The resulted percentages are presented in Table 4.17 indicating a rather high goodness of fit.

It is important to mention at this point that a proper verification and to an extend validation would require further investigation. One of the ways this could be possibly done is by collecting again data and comparing the choice of individuals to the one initially derived. Another way would require the assignment of individuals given a network structure and the actual recording of the chosen parking destinations. Both approaches were found to be too costly to implement.

## 5. Parking Assignment Model

The discrete choice model on which the assignment models are practised is the Multinomial Logit model, derived in Section 4.5.2. The introduction of a more sophisticated model can take place rather easily although a simple model structure would allow for direct analysis of the results and verification. The parking assignment model takes into account both traffic interactions, and parking inter- actions. In a sense, it could be described as a Dynamic Traffic Model with Parking, however, for consistency with the terminology used in parking modelling it is referred to as Parking Assignment Model.

## Parking Decision Process Summary

Unfamiliar users have a strategy on searching or not information pre-trip as well as for the desired parking type. The operational level applies after reaching the destination (or when close to it) where a search direction is chosen. Afterwards, the route towards the direction chosen is defined on the tactical level and, in case of on-street parking the link on intersection level.

## Conceptual Implementation Procedure

The Parking Assignment Model is proposed to be implemented in a simulation environment. The reasons are mainly practical but also

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methodological. On the practical side, the implementation of the components of the Parking Assignment Model, in a macroscopic Dynamic Stochastic User Equilibrium assignment, for both familiar and unfamiliar users and on all behavioural described is a tedious work that was considered to be out of the scope of this thesis. On the methodological side, it is generally acknowledged in the literature (see Section 2.3.2) that the exploration of ITS application and their impact magnitude is not captured by steady-state models, due to the dynamic character of traffic information and in this case of parking occupancies, departures and arrivals. This is widely evidenced in the verification of the familiar strategic level presented in Section 6.4.3, where the time interval of 15 minutes do not provide for understanding on re-routings that might take place.

Here, the Parking Assignment model is developed in order to be implemented in two phases: **Pre-trip** and **On-trip**. The pre-trip phase represents the strategic level of the parking decision process and it is developed for being the input of the simulation. The on-trip phase is completely developed for being implemented in a simulation environment.

### Strategic Level

Familiar users are assumed to follow a **habitual pattern** when it comes to parking. This assumption is supported by the behavioural research and more specifically, by the interviews conducted. The habitual pattern includes the devise of a strategy (**pre-trip**) consisting of visits to sequential parking destinations until a vacant parking spot is found (Figure 5.4). The basic assumption that shape familiar users assignment on a strategic level is:

**Assumption 5.1.** Familiar individuals plan a search route that passes from 3 sequential parking destination pre-trip. This route is referred to as **strategic parking search route** (*SPSR*).

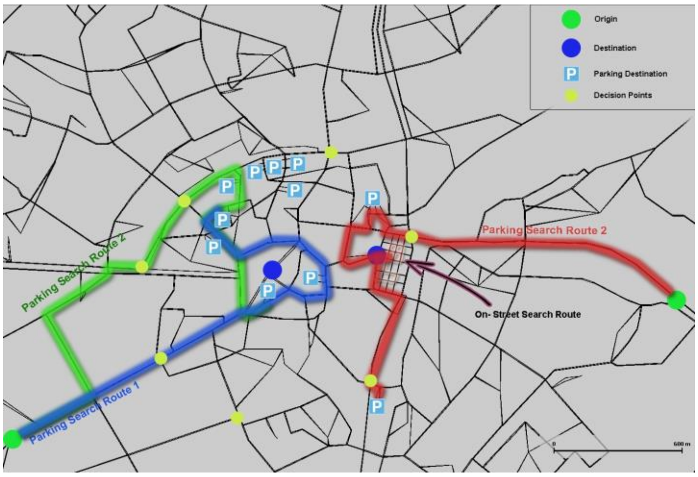


**Figure 5.4:** Strategic Parking Search Routes. Each coloured route represents a strategic parking search route that individuals have in mind before trip.

Familiar users are assumed to have knowledge of the system which falls among the definition of equilibrium assignments (see Cascetta, 2009, chapter 5). The general idea of equilibrium assignments is that travellers have information of the system in question and try to minimize the travel costs (or maximize the obtained utilities). This can be described as an equilibrium in which the utility of each traveller cannot be increased (Deterministic User Equilibrium). Another expression of the famous Wardrop's principle assumes individuals having imperfect information, but still acting in a way that would maximize the obtained utility leading to a partial equlibrium, where the perceived utilities cannot be increased (SUE). The same concept is **assumed** to apply for parking choice in a network structure:

**Assumption 5.2.** Familiar parking users can be represented –in an assignment context– by a Stochastic User Equilibrium for parking with the stochastic terms to be the travel time to the parking destination and the probability of finding a vacant parking spot.

As it is a Stochastic User Equilibrium assignment the duality gap is not expected to reach 0. However in case it does not converge properly, yet stabilize it is suggested to use the parking search route flow comparison as a convergence criterion.

## Tactical Level

The tactical level includes the interaction with other individuals **on-trip**. Individuals interacting with others, might result in a change of strategy, in the same manner as a route might have changed, due to congestion of the links initially thought to offer lower travel costs (higher utility) (Ben-Akiva et al., 1991). It is in-line with the literature on en-trip route choice models and hybrid route choice models where the route is evaluated respectively at every intersection or given some minimum improvement (Pel, 2011) and the bounded rationality concept that is also implemented in DYNASMART (Mahmassani, 2001b) where the route is evaluated at specific points.

Here, travellers re-evaluate their initial strategy based on changes concerning the perceived travel times or the perceived probability of finding a vacant parking spot which is described again in the context of utility maximization. In the utility derived for the SPSR (Equation 5.4 in Section 5.5.1), the only stochastic terms are the travel time and the probability of finding a vacant parking spot allowing the use of the utility for the description of changes. The decision of individual to re-evaluate the alternative strategy is based on a comparison of the *expected situation* and the *experienced situation* given an *improvement margin*. The expected situation is defined as the utility perceived by individuals before trip, while the experienced situation is defined as the utility perceived by travellers, given information received on-trip.

It is chosen to apply this particular behavioural level in certain nodes of the network where individuals would decide to change their strategy (**Strategy Evaluation**). Those points are named *decision nodes* and are located at the boundaries of the centre area (*entrance decision node*), when receiving information from PGIs (*PGI decision node*) and in case of arrival at a parking destination which is full (*P.D. decision node*).

## Operational Level

The operation level, as described initially, involves decisions concerning routes and search directions in case of on-street parking, **on-trip**.

Routes are derived by minimizing the travel time between one parking destination and another given congestion. In a sense it is assumed that individuals evaluate their options based on the perceived travel times (taking into account congestion).

The search process when referring to on-street parking is described as a decision at each intersection given again the utility maximization decision theory. For example, when a familiar individual stops at an intersection he/she has to peak a link to follow in order to find parking. If he/she believes that the at link ahead there is higher probability of finding a vacant parking spot, while all the other characteristics are perceived to be the same, he/she would choose to follow the link with higher probability.

## Parking Assignment Model for Unfamiliar Users

The unfamiliar users were treated in a rather different way compared to familiar users due their lack of information concerning the parking situation. Given this special attribute, unfamiliar users are modelled under a random adaptive context presented in the following sections. The general idea on how unfamiliar users are modelled is presented in Figure 5.6.

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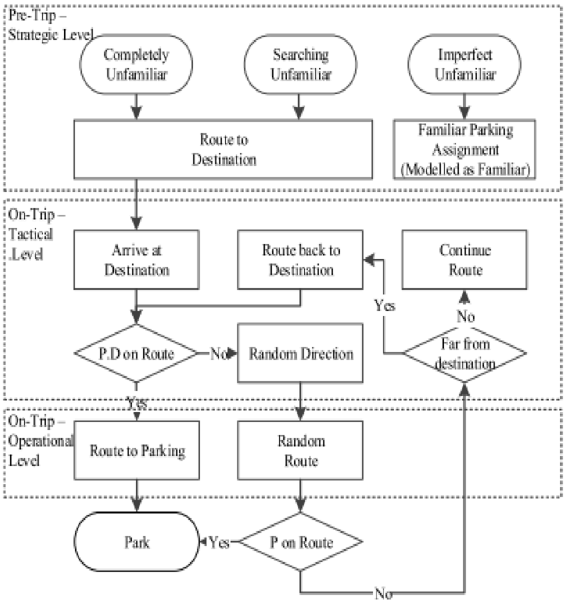


**Figure 5.6:** Unfamiliar Users modelling framework

## Strategic Level

It is accepted that unfamiliar users have a strategy, concerning parking with people either becoming familiar users (with imperfect information of the system) and drive directly towards the parking destinations chosen (36.6 % - *Imperfect Unfamiliar* ), or arrive at destination first and then start searching (50.1% - *Completely Unfamiliar* ), or start searching before arriving at the destination (13.4% - *Searching Unfamiliar* ) – see Section 4.4.3. Furthermore, travellers would mostly search for **off-street** parking destinations (78.6%). As it can be directly un- derstood the strategic level of decisions contain a route towards the parking destination or the actual destination (which due to unfamiliarity is assumed to be the shortest route) and the parking type.

While the *Completely Unfamiliar* and the *Searching Unfamiliar* only select the parking type on the strategic level, *Imperfect Unfamiliar* search for parking information before trip. It is **assumed** that individuals search information concerning the attributes that would be important for them and are included in the utility with the exception of the probability components. It is **assumed** *Imperfect Unfamiliar* individuals derive a choice set with their preferred parking destinations and create a search route given the utilities estimated by the individual. The assumptions made are summarized in the following:

**Assumption 5.3.** Unfamiliar users who search for information pre-trip are assumed to be treated as familiar users assigning utilities to parking search routes constituting a choice of parking search routes to consider. Finally, a parking search route similar to what familiar users follow is selected.

## Tactical Level

It is important to mention at this point that data collected concerning unfamiliar users was informative enough only for getting some preliminary insight in some aspects of the decisions involved. As already mentioned this happened due to the limited number of questions that could be accommodated.

The procedure of parking search for unfamiliar users is structured in different ways according to the strategy chosen to follow and the parking type chosen.

*Completely Unfamiliar*

Individuals arrive at the destination and, while on- route, collect information concerning parking. If they see any parking destination or any sign indicating one or more parking desti- nation they choose to drive to their destination and then re-route to the parking destination perceived to be the closest to their destination.

If individuals do not see any sign or parking destination they are **assumed** to pick a random direction (namely: north, south, west, east) and drive towards it look around for parking given their initial preference. If they have drive up to a distance away from their destination they peak a different route towards back to the destination completing one *search cycle*. This is followed until they find a parking destination or a sign containing information concerning parking. In case the chosen parking destination is full search is continued as described above.

The distance away from the destination people choose to re-route back depends on the net-work's structure and the size of the city centre.

*Searching Unfamiliar*

This user class is modelled in the same way as the *Completely Unfamiliar* with the exception that it is assumed they know where the destination is and they do not drive to it. They simply arrive at the area of the destination and search in the same manner as *Completely Unfamiliar* users do with the difference that they do not arrive at the destination but just at the area defined as closed to destination.

*Imperfect Unfamiliar*

The tactical level for this user class is modelled in the same way as the tactical level for familiar users with the information acquired at parking decision points (PGIs, Parking Destinations).

## Operational Level

On the operational level concerning unfamiliar users it is assumed that the *Completely Unfamiliar* and *Searching Unfamiliar* individuals pick randomly their (unfamiliar) parking search route given the direction selected on the tactical level. In case of straying far away from the destination without finding a vacant parking spot, they are assumed to pick a different route back to the initial destination. The choice of the route is done on a random way by excluding route that have been used before and, in case there is non left to be excluded, picking a same route. This is again in line with the myopic search and tumble behaviour described by Kaplan and Bekhor (2011). In case of on-street parking they randomly select a link at intersections.

It is very important to mention, that some features of this modelling framework, concerning unfamiliar users, apply in limited networks as there are usually signs at central spots, which intend to guide visitors to parking destinations. The reason for presenting such a rather extended representation lies on the need to provide a simulation environment, where even the worst case scenario can be handled by a model that can completely represent the unfamiliar user class.

## Parking Probability Model

In the conceptual behavioural design, it was introduced that a set of attributes to be investi-gated refer to the probabilities of finding a vacant parking spot (either upon arrival or after some minutes). The problem that directly arises is how probability is defined and how it is connected to characteristics of the parking destinations that can be observed. The goal in other words is to "translate" the probability of finding a vacant parking spot to measurable parking-related characteristics.

The probability of finding a vacant parking spot is related to the following parking-related characteristics:

1. The capacity of the parking destination
2. The number of occupied parking spots
3. The number of arriving vehicles
4. The number of departures

The characteristics should be included in an mathematical expression that represents the probability. This is a rather tedious task because the above mentioned characteristics are random variables with some being interdependent (e.g. arrivals and departures). Although several attempts were made to try to describe the probability in an analytic way (such as: renewal process, Markov Chains, steady state solutions) the results were not satisfactory, due to assumptions' violations. For that reason it was decided to create a event-based simulation that would be allow for the definition of a model to **approximate** the probability encountered by individuals. The input of the simulation is a *variable arrival process*, the *distribution of the duration of parking*, a distribution of the *maximum search times* and the parking destination *capacity*.

The simulation is repeated several times and the output is the probabilities of finding a vacant parking spot upon arrival and after some minutes by counting the number of parked vehicles given their arrival time and dividing them by the total number of vehicles searching for parking at that time.

The general concept is that its driver arrives at a specific parking location and if there is a vacant parking spot he/she parks immediately and a parking duration (and as a consequence a departure time) is assigned to him/her. If there is no vacant parking spot upon arrival the driver enters a queue which works either on the First In First Out (FIFO) principle (Figure 5.7a) for off-street parking (for which people are not allowed to enter if it is full) or on a random base for on-street parking (Figure 5.7b) .

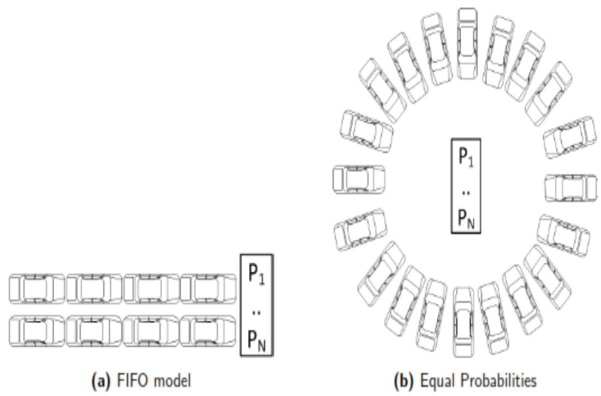


Figure 5.7: The two models used for car queues

An example is presented in order to investigate the workability of the model:

**Example 5.1. Saturday shopping:**

An interesting case is presented for Saturday shopping day when people park for a rather small period of time (around 150 minutes). Due to the low duration there a high turnover rate as different vehicles park and several times in a day at a parking location. Such an illustrative case, was simulated with the arrival rate presented in Table 5.2 (Poisson Process) and for a parking destination with capacity of 250 parking spot, with variable duration of parking and variable variation of of the parking duration (again extreme value distributed). The maximum search time was assumed to be 10 minutes.

For having a more realistic parking demand in this illustrative example, the parking occupancies were recorded (from 10:00 to 14:00 - 20 minutes intervals) for three concentrative Saturdays in the centre of Delft using the website of the Delft municipality. Those parking occupancies were used to derive the arrival rates assuming that during an recording interval there were either only arrivals or only departures.

As it is presented in 5.8 the probabilities change based on the time of arrival and as well based on the search time an individual is willing to search for parking. In the beginning of the examined period the probability is 1 as every vehicle arriving can park. Afterwards the probability drop with the increased number of arrivals to increase again if travellers wait, as there are many departures (around 200 to 300 minutes).

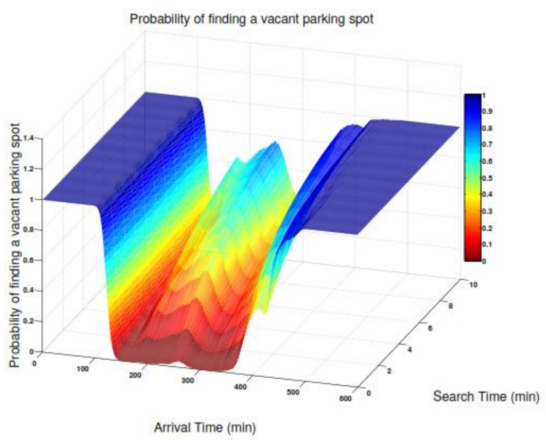


Figure 5.8: Saturday Shopping, 3000 iterations

The definition of a model that would describe the probabilities of finding a vacant parking spot comes into the field of model identification and as mentioned before out of the scope of this study. However an expression is derived that was tested against the results of the simulations that took place and was found to approximate those probabilities.

Let i be the random individual arriving at moment $t_i$ at the parking destination $\pi$ willing to wait $x_i$ minutes. On the parking characteristics, let $K_\pi$ be the capacity of parking destination $\pi$, $P_\pi(t_i - dt)$ be the number of parked vehicles just the moment before the arrival of individual i $D_\pi(x)$ be the number of departures during $x_i$, $A_\pi(x)$ be the number of arrivals during x and $Q(t_i)$ be the number of vehicles waiting/searching for parking at the moment of arrival of individual i.

The probability of finding a vacant parking spot is defined:

$$P = \begin{cases} \dfrac{K - E[P_\pi(t_i - dt)] + E[D_\pi(x_i)]}{E[A_\pi(x_i)] + E[Q(t_i)]}, & K - E[P_\pi(t_i - dt)] + E[D_\pi(x_i)] \le E[A_\pi(x_i)] + E[Q(t_i)] \\ 1, & K - E[P_\pi(t_i - dt)] + E[D_\pi(x_i)] > E[A_\pi(x_i)] + E[Q(t_i)] \end{cases} \tag{5.14}$$

with $E[\cdot]$, denoting the expected value.

.

## 6.Conclusion:

This thesis presented the development of a simulation-based parking assignment model for the evaluation of Smart Parking applications.

Behavioural research was conducted, proposing a decision process model, that describes the choice for two user classes (familiar and unfamiliar parking users), on three behavioural levels (strategic, tactical and operations). A survey was conducted with 397 complete/stratified responses for the investigation of those decisions and several model structures were examined to derive the model that can best represent parking choices. The attribute set used in the experiment was based on those found in the literature, yet different, by combining the proba- bility of finding a vacant parking spot and the search time, into the newly introduced attribute of the probability after some minutes of searching/waiting. All attributes investigated were found to be significant in the model structures examined, supporting this inclusion.

The two probabilities investigated (upon arrival and after some minutes of searching) allow for the connection of the parking system with the choice of individuals as they were defined using parking related stochastic characteristics such as the arrival rate and duration. For that reason, a novel probability model based on simulation is introduced to approximate the true probability experienced by individuals.

The parking decision process model and the MNL parking choice model are used for the parking assignment model concerning familiar users. The decisions are represented in all behavioural models and the modelling methodology is suggested. This methodology differs to the methodologies presented in the literature, as it is solely based on the utility function of the MNL model. A habitual pattern is assumed on the strategic level, and a novel parking search route consisting of sequential parking destinations to be visited is suggested. On the tactical level, the re-evaluation of the strategy is introduced, for the first time for parking, given an improvement margin. Finally, on the operational level, decisions concerning route and on-street search decisions are included. The verification of the novel strategic search route show a realistic approach, in line with the theory related to them. A second user class, the unfamiliar users are introduced for the first time in parking modelling. They were modelled to have a diverse behaviour with some to search for information, and some drive to the destination and then start searching on the strategic level. On the tactical level for those without information concerning parking, a search process was defined in a random pattern of choosing direction and a random search, assumed to represent the lack of information.

The assignment framework was introduced in ITS modeller by coding the components for the evaluation of the Smart Parking reservation system developed in the Sensor City project and scenarios were investigated. The application of the framework shows the potential of using the Parking Assignment Model. It is found that it can be implemented in a simulation environment and is capable of representing the situation in a realistic way. On the other hand, is is found that the results for the scenarios developed indicate that the reservation system can improve the traffic conditions and offer lower travel times for its users.

Both the reference cases and the scenario cases are found to yield realistic results concerning travel times and parking choices. Even the case of unfamiliar users (who were found to have increased travel time) seems to be realistic, taking into account the lack of parking related signs in the implementation. The improvements of average travel times (both total and individual-based) were found to be of rather small magnitude, which is expected, as it is in line with the magnitude of many ITS applications.

## Recommendations & Future Work

In general, it is believed that the parking assignment framework is capable of evaluating parking related ITS applications and that the results of the implementation on the Smart Parking application are promising. In this section, recommendations are made in three direc- tions (Behavioural Research, Assignment Framework, Implementation & Smart Parking case). Those recommendations are considered as further steps for improving the components of this thesis with a strong focus on the further development of the parking assignment modelling framework for ITS applications.

**Behavioural Research:** In the behavioural research, the suggestions mainly lay on the ex-perimental design, the examination of other model structures validation and the investigation of unfamiliar users. Starting with the **experimental design**, it is important to mention that it was attempted to collect information for a rather large number of decisions and two user classes. This was done due to the limited resources available. It is suggested to limit the scope of future experiments, on this subject and conduct more specialised experiments with focus on components of the decision process and its development.

On the **model structures**, one strongly suggested to be further investigated is prospect theory. The probability of finding a vacant parking spot after some minutes can be perceived as a risk by individuals. A possible suggestion what was attempted to be investigated in this research (not possible due to software problems) would be to use as a reference point the probability of finding a vacant parking spot after 8 minutes set to one (1).

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