Cumulative prospect Theory and High Occupancy Toll Lanes

Understanding and modeling drivers' choice behavior on High Occupancy Toll Lanes

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Preface

I wrote this research report about HOT lane modeling and the Prospect Theory for my bachelor thesis at the University of Twente, this marks the end of my bachelor in civil engineering in Enschede. I want to thank my supervisor from the University of Twente, Dr. Jing Bie and my supervisor from the University of Florida, Dr. Yafeng Yin for their support and advice before and during my research in Enschede and in Gainesville (Fl). I also want to thank Ellen van Oosterzee and Ines Aviles for making it possible to do my internship at the University of Florida, especially their help with the visa procedures. I also want to thank Bouke Vogelaar for his company during our internship and help with the arrange of everything we needed before and during our time in the United States.

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Summary

High Occupancy Toll (HOT) lanes are a relative new approach to attack congestion and a better use for often underutilized High Occupancy Vehicle (HOV) lanes. Just like HOV lanes HOT lanes lay next to the normal or General Purpose (GP) lanes. The I-95 near Miami is an example of a road with HOV lanes and a lot of congestion. The transformation to HOT lanes will give single occupancy vehicles an alternative for the congestion: if they pay a fee, they are allowed to ride on the carpool lanes, if they don't want to pay they can still ride for free on the GP lanes. The fee depends on the number of vehicles that ride on the HOT lanes, to prevent congestion on those lanes.

In the literature there are several studies that use or develop a model of HOT lanes. The goal is to find an optimal tolling strategy, finding or comparing parameter values or investigate the influence of different attributes. Almost all the models that are developed or used are based on the assumptions of the Utility Theory, namely that people are rational and try to find the optimal solution. In the 1970's Tversky and Kahneman developed the Prospect Theory. This theory is more descriptive than the Utility Theory. Instead of a cost benefit analysis, they separate gains and losses because of the loss aversion of people, losses are much higher valued than equal gains. Therefore the prospect theory should model actual behavior better than the utility theory. In 1992 Tversky and Kahneman came up with a further development of the prospect theory: the Cumulative Prospect Theory (CPT). The difference from the original version of prospect theory is that weighting is applied to the cumulative probability distribution function, rather than to the probabilities of individual outcomes.

Although HOT lanes choice is a form of route choice, there is a significant difference because there are two main factors: time and money. The choice is based on a combination of those two factors. The prospect theory is not often used in route choice models and even less with HOT lane models. Therefor a model is developed to model the choice process on HOT lanes with the Cumulative prospect theory, it is implemented in a general HOT lane model of the I-95.

The model is based on the CPT model from Tversky and Kahneman and the probability weighting function comes from Prelec(1998) and is used in more route choice models. This model has the following assumptions: the reference point of people is based on their previous experience with the general purpose lanes. With people's value of time, time and money are comparable. Losses are two times higher valued than gains.

The result is a practical and usable model. The outcomes of the original and calibrated utility theory model are roughly the same as for the new CPT model. However, the parameters are not calibrated for HOT lanes but come from other route choice models or the original CPT model. There is also more study needed to the suitability of the model for other HOT lane models.

Introduction

Implementations of the Utility Theory (UT) are commonly considered as the most useful concept for the description and modeling of human choice behavior, and the prediction of its outcomes in transportation literature. However, its descriptive-behavioral validity has been under discussion since the 1950s. Many experiments and surveys in several behavioral sciences have demonstrated violations of its principles. Drawing on these findings, Prospect Theory (PT) was proposed in the 1970s as an alternative behavioral-economic model of choice behavior. Though researchers in mainstream economics and transport sciences are well aware that many individuals and organizations violate UT's principles, PT and alternative behavioral concepts are only incidentally considered. Improvements to the structure and mathematical formulations, particularly of stochastic elements of discrete choice models, followed by calibration to empirical findings, are the dominant approach to coping with 'inconsistent' subjects. This led to the introduction of the Cumulative Prospect Theory (CPT) in 1992. The difference with PT is that weighting is applied to the cumulative probability distribution function, as in rank-dependent expected utility theory, rather than to the probabilities of individual outcomes.

Over the last years, CPT gets more attention in transportation literature; there are findings in route choice that prospect theory describe choice behavior better than the commonly used utility theory. The problem with the utility theory is that it assumes that people make rational choices that maximize their utility, when the information is more complicated, it is harder to make a perfect rational choice. The prospect theory describes behavior better than the more prescriptive utility theory.

An example of a more complicated choice are High Occupancy Toll (HOT) lanes. Drivers have to make a comparative assessment between travel time savings and money, while they don't know the time they will eventually save. Because not all the information is present and the possible outcomes are unknown it is harder to make a rational choice. This report will look at the modeling of HOT lanes or more specific: the modeling of the behavior of drivers on HOT lanes with the CPT. To develop a model, it must be clear what HOT lanes are, on what points they differ from normal lanes and how drivers react to them. Therefore, the following questions will be answered:

1. What are the differences between High Occupancy Toll Lanes and General Purpose Lanes?

2. Which models are used to describe drivers' behavior?

3. To what extent is the Cumulative Prospect Theory accurate to describe drivers' choice behavior?

4. How can the result of the cumulative prospect theory model be used in practice to optimize the circulation of traffic?

The contribution of this research to HOT lanes is that the simulation model will deliver a better tool to model the choices of motorists and analyze the travel demand for a HOT lane system. It also provides translated CPT model, that was originally developed to explain inconsistent gamble behavior but is now translated to a route choice model.

Chapter one looks at the first question: what are HOT lanes, what is the difference with normal lanes, where are they and why. Chapter two describes what is written in the literature about HOT lanes, what kind of models are used and with what purpose. In chapter three I will look at the Prospect theory, what is the difference with the utility theory and why is it a better theory to model choice behavior and to what extent. Chapter four looks at the factors that influence the choice of drivers for HOT lanes. In chapter five the general HOT lane model is introduced and in chapter six the choice process with CPT will be explained and how it fits into the general HOT lane model.

1. The differences between High Occupancy Toll lanes and General Purpose lanes

This part will describe what High Occupancy Toll lanes are, how they work and how they differ from general purpose lanes.

1.1 History

In the 1970s California experiments with a new tool to reduce auto traffic: High Occupancy Vehicle (HOV) Lanes. These were lanes parallel to the general purpose lanes, but only cars with two or more passengers were allowed to use them. This plan should reduce auto traffic but many lanes were underutilized while congestion did not decrease. The question was if the benefits of HOV lanes exceed their costs. To increase the traffic on those lanes, and decrease it on the general purpose lanes, cars that didn't have two or more passengers were allowed to use the HOV lanes if they paid a fee. The height of the fee depends on the density within the lanes to avoid congestion. The first project in which they were implemented was on the State Route 91 in Orange County in 1995, four new 10 mile long lanes, called value-priced lanes, were constructed in the median of the SR 91. These lanes are now called High Occupancy Toll (HOT) lanes before entering these HOT-lanes drivers must ride through a toll booth that displays the price that has to be paid for using the HOT-lanes.

1.2 Characteristics

High Occupancy Toll (HOT) lanes are lanes on a highway, parallel to general-purpose lanes. Drivers have to pay toll if they want to access the HOT-lanes, the toll rate is displayed on an electronic message sign and visible for drivers before they enter the HOT lane facility. Exceptions are made for carpoolers and busses they do not have to pay toll on HOT-lanes. Some HOT-lanes also allow motorcycles and hybrid vehicles to ride free of charge. The speed limit is usually the same on both HOT-lanes and general purpose lanes.

Either HOT-lanes have a toll that is based on the time of the day or on the traffic that uses the HOT-lanes. If the toll is based on time, toll rates will be higher during rush hours and lower during the rest of the day, based on usual traffic situations. If the toll rates are based on traffic, toll rates will be higher when there is more traffic on the HOT-lanes. The HOT lanes have only a few entry and exit points to maintain the traffic flow, permanent HOT-lanes are separated from local traffic lanes by a barrier of flexible plastic poles. There are temporary HOT-lanes that are only operated during peak hours, the rest of the day they work as general purpose lanes or HOV-lanes; these lanes are mostly separated by a white line.

To pay the toll HOT-lanes drivers must have a transponder in their car when they want to use those lanes. The required fee will automatically be deducted from their prepaid account when they enter the HOT-lanes.

1.3 Differences

To find out which choices drivers make on HOT-lanes and when, it is important to make clear what the exact differences are between those lane types. For example some vehicles are not allowed on HOT lanes and because of the barrier not every exit ramp can be taken from the HOT lanes. Because not all HOT-lanes are exactly the same, the differences will be based on the HOT-lane project on the I-95 near Miami, Florida. For an overview image of the HOT lanes see appendix A.

These HOT-lanes are 20 miles long from the I-195 until the I-595 and are separated from the general purpose lanes by flexible plastic poles. All drivers who want to use the HOT-lanes must have a SunPass transponder, a SunPass transponder is an electronic device that is linked to a prepaid account from which the toll will be deducted. The SunPass can also be used on other toll roads in Florida, but they do not work on toll roads or HOT-lanes outside Florida.

For certain vehicle types toll exemptions are allowed:

Vehicle	Exemption
Carpool vehicles (3+)	Free after register the car and the passengers with South Florida Commuter Services (SFCS)
Buses	Free with valid US FMCSA and registration with SFCS
Vanpools	Free after the vehicle is registered to the vanpool program
Motorcycles	Free
Hybrid vehicles	Free after obtaining an HOV-decal and register with SFCS
Trucks(3+ axes)	Not allowed on HOT-lanes

Table 1-1: Vehicle regulations

Drivers with a SunPass transponder pay automatically when they enter the HOT-lanes, the toll is deducted from their transponder account. The toll rates are based on the density of traffic on the HOT-lanes, the more traffic on the lanes the higher the toll rate is. Variable toll pricing will be used to help achieve the goal of free-flow speeds of 45 miles per hour or greater in the HOT-lanes. General purpose lanes are always free of charge

There are only 3 or 4 entry and exit points for HOT lanes, and about 20 for general purpose lanes. This means that HOT-lanes can only be used for long distance trips.

Figure 1-1: Computer drawing from the I-95 HOT-lanes and GP lanes separated by a plastic pole barrier

2. HOT lane modeling

2.1 Introduction to HOT lane modeling

Most HOT-lanes are transformed HOV-lanes that were underutilized. These HOV-lanes did not reduce auto traffic or congestion nor increased the throughput of people or encourage carpooling. To make HOT-lanes more effective it is important to understand why drivers choose for HOT-lanes, how much are drivers willing to pay for HOT-lanes and how does that affect the GP-lanes.

This chapter contains a literature review of modeling HOT lanes. The purpose of research in literature is to find out where drivers make a choice for HOT lanes others tried to find an optimal toll rate for HOT lanes; or to uncover attributes or the value of those attributes from motorists on HOT lanes; or to look at the public opinion on congestion pricing and HOT lanes.

2.2 Choice process

Lane-changing models are an important component of microscopic traffic simulation tools. With the increasing popularity of these tools, a number of lane-changing models have been proposed and implemented in various simulators in recent years. Most of these models are based on the assumption that drivers evaluate the current and adjacent lanes and choose a direction of change (or not to change) based on the utilities of these lanes only. The lane choice set is therefore dictated by the current position of the vehicle, and in multi-lane facilities would be restricted to a subset of the available lanes. However, HOT-lanes are separated from GP lanes therefore the lane choice is practically a route choice between a toll road and a normal road with the same length. With lane choice a driver reacts to the actual situation and can switch when he wants to. On HOT lanes the choice can be made en-route but the choice is fixed, a driver can only choose based on his expectations of the traffic conditions, just like route choice where you can take a secondary road when you expect congestion on the main road.

The choice for a specific route by the driver can take place at three moments or levels (Van de Kaa, 2006):

There are strategic choices: It encompasses processes like residence location, employment issues or car ownership that may last from days to months, are mostly made at the household level.

Tactical choices: like commuters' home departure times. It is also considered to accommodate constructs like willingness-to-pay or value-of-travel-time derived from stated or revealed preference studies.

Operational choices: The mental process that precedes and governs concrete everyday actions; like departure time postponement, route change underway, or lane switching. Based on their perception of traffic condition and their desired arrival times, travelers will evaluate the travel costs associated with different departure times and made their choices accordingly.

Most studies focus on tactical choices or operational choices because strategic choices are made on a more abstract level and is hardly visible in the choice between HOT lanes and GP lanes. The strategic choices are seen as attributes of drivers that influence their choice but are not impressionable by toll rates or travel times.

There are roughly two main purposes in the literature on HOT lanes: to find ways to make HOT lanes more effective, for example by adjusting the toll rate; or to find out why drivers' choose HOT lanes and what affects their choice.

2.3 Optimal toll rate

An important purpose of HOT lane modeling is to find an optimal toll rate, to make the lanes more effective by preventing congestion on HOT lanes. A secondary goal can be to cover for the costs of building the HOT lane facility. The toll rate depends on either the traffic on the HOT lanes or the time of the day. Yin and Lou (2009) point out that there is little knowledge about the determining of dynamic prices on managed lanes so far. In the paper they look at two approaches: 1. Toll rate based on feedback control 2. Learn to know the willingness to pay

The purpose of their research is to deliver two approaches to determine an optimal toll rate for HOT-lanes that makes the HOT-lanes more effective. The ideal situation is when there is no congestion on the HOT-lane and maximum throughput on GP-lanes.

The feedback control approach is based on the idea of a loop detector downstream of the HOT-lanes entry to detect the amount of traffic on the HOT-lanes. The new toll rate will be based on those data and the toll rate at that times, so that the new toll rate $\beta(t+1)$ will be the old toll rate $\beta(t)$ plus a scaling factor(K) times the actual occupancy($o(t)$) minus the desired occupancy(o^*).

$$\beta(t+1) = \beta(t) + K * [o(t) - o*]$$

The self-learning approach is based on two loop detectors, upstream and downstream of the HOT-lane entry. With that data the motorists' willingness to pay can be learned.

The lane choice can be modeled with a logit model whose parameters are unknown. The logit model is the demand function of the managed lanes. With the current travel time, toll rate and flow rates on HOT-lanes, the parameters can be learned, and the willingness to pay can be estimated and the toll rate can adjusted on the willingness to pay and the current traffic.

In reaction to Yin & Lou (2009), Zhang et al. (2008) still sees problems in the toll optimization model. Due to insufficient theoretical basis, it is hard to quantitatively achieve the optimal system performance. First, there is the change in toll rate that can be too large and the change interval can be too small, this can cause unstable traffic fluctuations. On the other hand, the change in toll rate can be too small and the interval too large that the system cannot respond accurate on the traffic situation. They propose a model that is based on the feedback control theory and is able to accommodate traffic variations fast and stably.

Their lane choice model is based on a binary logit model with the HOT-lane and the GP-lane as two alternatives for drivers. The attributes are travel time and toll rate. The travel time can be measured with the traffic detection system, and then the toll rate can be backward computed, based on the travel time on both type of lanes and the approaching travel flow. The toll rate can then be modified to attain the optimal distribution. The change of the toll rate is based on the speed of traffic on the HOT lane.

Both Yin & Lou (2009) and Zhang et al. (2008) try to develop a model that can calculate the toll rate to optimize the HOT lane facility, the most important factors in the determination process are travel time and toll rate, and the drivers value of time or willingness to pay to convert the time to money. Important in de modeling of HOT lanes is the behavior of drivers, the toll rate is based on the choices that drivers make, Zhang et al. (2009) made a VISSIM (microscopic traffic flow simulation software)model based on the utility theory to model that behavior.

The purpose of the HOT lane model is to optimize the system, risk-free and cost-effective. The choice model they use is a logit model to imitate this decision-making process. This simple model is used because of its applicability and simplicity although there are more sophisticated discrete choice models.

The model is based on the attractiveness of the alternatives, GP-lanes and HOT-lanes. The attractiveness is based on the total costs(TC): expressed in toll rate(TR) and travel time(TT). The utility of each of the lanes is 1 over the total costs of that lane.

$$U_{HOT} = \frac{1}{TC_{HOT}} = \frac{1}{\propto * \, TT_{HOT} + TR_{HOT}}$$

$$U_{GP} = \frac{1}{TC_{GP}} = \frac{1}{\propto * \, TT_{GP}}$$

Zhang et al. (2009) uses a binary logit model to calculate the probability of choosing the HOT-lane.

This simple model shows the most essential factors where drivers base their choice on: travel time and the toll rate. The utility theory is an commonly used theory to model route or mode choice in transportation literature.

2.4 Value of time

The perception of travel time and toll rate is not the same for each individual. If a driver has a tight schedule, his time is more worth than someone who goes shopping and does not care for a few minutes more or less. Both Small et al. (2005) and Brownstone & Small (2004) did research on drivers' preference for travel time and reliability.

The use of HOT-lanes is based on the variation in motorists' preferences for speedy and reliable traffic. This is observed by different value of time studies, but those studies only accounted for costs and travel time, not for reliability. Reliability can be an important factor because HOT-lanes have a more predictable travel time than GP-lanes, and that could be an argument to choose for HOT-lanes rather than GP-lanes.

To measure the values of those attributes, Small et al. (2005) use data from revealed and stated preference studies. The utility of the HOT-lane is based on toll difference, travel-time difference and (un)reliability difference between the two alternatives (HOT-lanes and GP-lanes). The probabilities of choosing the HOT-lane are calculated with a mixed logit model, to account for preference heterogeneity. Small et al. (2005) find a value of time median of $21.46/hour and a value of reliability of $19.56/hour. Brownstone & Small(2004) compared literature results and find values of around $20/hour, but the results are different for SP data and RP data.

2.5 Attributes and choices

Following research (Small et al. 2006) focuses on more than only lane choice namely: whether to have a transponder or not; whether to travel on a GP-lane or HOT-lane; and whether to travel with 1, 2, or 3 people in the vehicle. They use a linear utility function to find out how the attributes of toll rate, travel time, and reliability influence the choice that the motorists made. This has the same choice levels as van der Kaa (2006) identifies, namely: strategic choices such as the choice to buy a transponder; tactical or pre trip choice for example how many people travel with you; and operational or en-route choice that is the lane choice on the road. They use the same data as Small et al. (2005a)

They assembled a data set from surveys of travelers on the corridor, describing the lane choices they actually make and the choices they would hypothetically make in different circumstances. The difference to the previous study is that here are three simultaneous decisions by motorists modeled:

- Whether to acquire a transponder, which gives them the flexibility to use the express lanes whenever they desire;
- Whether to travel on the express or free lanes for the trip in question;
- How many people to travel within their vehicle.

Transponder acquisition is a separate choice because it is required to use the express lanes. They use the same model as Small(2005) and the values of time and reliability to compare different road pricing alternatives as toll roads HOV-, and HOT-lanes based on the impact of welfare. They find that accounting for heterogeneity is important for the model of HOT-lanes because without that no additional benefits would result from separating users based on their preferences.

In earlier research (Yan, Small, & Sullivan, 2002) they looked at the price elasticity of HOT lanes in order to see how people respond to toll changes in toll rate, and what the attributes of those drivers are. The elasticity is consistently estimated at 0.7 to 0.8. This represents the response to uniform percentage toll increases, and it arises almost entirely from route and occupancy changes. For more targeted toll increases – during just the one-hour "peak of the peak" – the price elasticity is between 0.9 and 1.0. These results demonstrate that there is plenty of scope for adjusting a toll schedule, even in as small as one-hour increments, in order to regulate traffic levels.

Kuhn et al. (2005) schematized the choice process and the information drivers want to know as seen in Figure 2-2

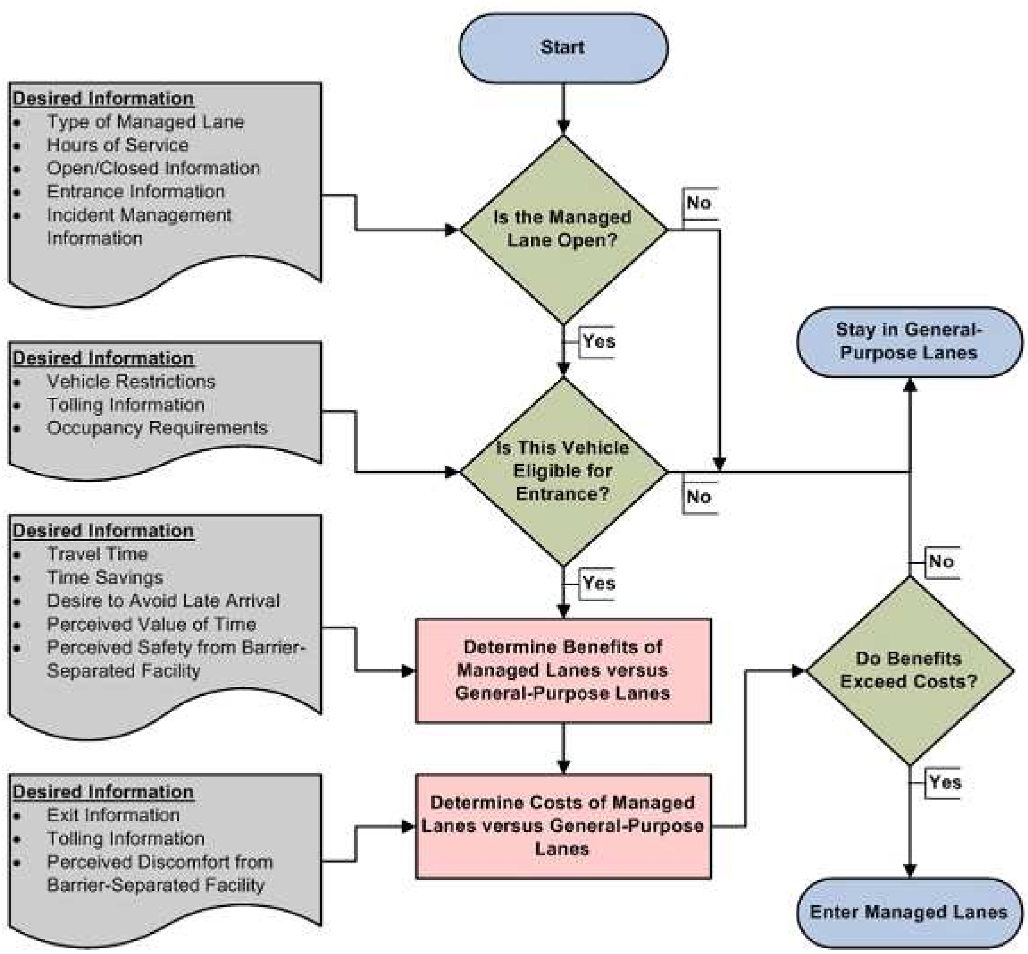

Figure 2-2: en-route choice process

2.6 Evaluation

The purpose of most HOT-lane models is to improve the efficiency by optimizing the toll rate. Important factors for an optimal toll rate are: travel time, value of time and the value of reliability that motorists have when they travel on the I-95. In order to make HOT-lanes more effective it is important to know why motorists choose to drive on HOT-lanes. To model this discrete choice, most studies used a utility function with the most important factors that affect the choice to calculate the utility of each alternative for the driver, and then a form of logit is used to calculate the probability of choosing an alternative.

Utility is measured with a systematic (deterministic) part and a rondom error term. The systematic part includes vector variables, including attributes of the alternative and of the decision maker. The error term captures the unobserved attributes associated with the alternative. The probability that a person chooses an alternative above other alternatives can be determined by comparing the utility of that alternative with the other alternatives, this can be done with a logit model. The choice probability depends on the differences between the utility of the alternatives.

The models described in this review are based on the utility theory that implies that people make rational, deterministic choices that maximize their utility. Behavior studies however, point out that in practice people are not as rational as the theory implies, they do not always make a calculation to find out what option maximizes their utility because they do not always know all the effects of an alternative. For example, surveys conducted with SR 91 peak period travelers provide evidence that many commuters overestimate their true time savings when using the HOT-lanes. Actual time savings showed maximum time savings of 12-13 minutes per trip on normal traffic days. This compares to savings in excess of 20 minutes per trip reported by over a third of the survey respondents. In addition, some toll lane users choose to use the toll lanes under traffic conditions where the expected value of their time savings is clearly less than the tolls paid. Li (2007) finds that the perception of willingness to pay is different for the same people. A group believed that people tend to be willing to pay $1 for 5 min time savings more readily than $4 for 20 min (although both values are the same). Hence, people generally do not take the time to calculate how much time savings they get for what price, the more when they have to estimate the time they will save.

The causes of this non-rational behavior is that people cannot always make rational decisions: they are bounded rational. The necessary information to make a rational decision is not always known especially when a choice involves uncertainty. People cannot process all the complex information in their head, and there is often not enough time to process all the information. Because of these critics of the utility theory there are other theories developed that are more descriptive rather than the prescriptive utility theory.

3. Cumulative Prospect Theory

This chapter will describe the cumulative prospect theory and its predecessor the prospect theory. After the main characteristics of the theory and how the choice process is modeled, specific properties of the theory will be explained such as gains and losses, reference point and loss aversion. At the end, the relevance for travel or route choice is described.

3.1 Characteristics

Prospect theory (PT) is a theory that describes decisions between alternatives with uncertain outcomes (risk), where the probabilities are known. PT was developed as a descriptive-behavioral theory, it tries to describe how an individual makes choices in real life rather than how they should do it to optimize some 'objective' interests. Amos Tversky and Daniel Kahneman introduced the theory in 1979. It was developed because of the inaccuracy of the expected utility theory (EUT). In 1992, Kahneman and Tversky came up with an improved version of PT, the Cumulative Prospect Theory (CPT). The main difference with PT is that weighting is applied to the cumulative probability distribution function, rather than to the probabilities of individual outcomes.

Utility Maximization models determine for each alternative the probability that it is chosen by an individual, as a function of the utility derived from its attributes, including unobserved ones. The problem is that people are not utility maximizers, they are bounded rational, that means that they cannot calculate what option maximizes their utility, especially when the outcome is uncertain; instead they choose for the first option that meets an aspiration level (satisficing).

Van de Kaa(2006) describes the most important differences between CPT and UT:

Context-dependent preferences: an individual's preference order is dependent on the context of the choice situation and the way alternatives are presented and perceived.

Change-oriented framing: an individual frames alternatives in terms of the expected change in their assets rather than on the expected state of them.

Reference dependency: expected outcomes of choice decisions are valued relative to some reference state. An expected increase in satisfaction, utility or positive affect relative to the reference state is valued as a gain, a decrease as a loss.

Loss aversion: losses are valued much higher than gains of equivalent size, 'the (value) function is sharply kinked at the reference point, and loss averse – steeper for losses than for gains by a factor of about 2-2.5

Diminishing sensitivity: 'the marginal value of both gains and losses generally decreases with their magnitude'. Thus the value function is considered to be concave for gains and convex for losses.

Non-linear weighted probabilities or Certainty effect: an individual over-weights outcomes with low probabilities and under-weights outcomes with high probabilities relative to certain outcomes: 'Over-weighting of small probabilities contributes to the popularity of both lotteries and insurance. Under-weighting of high probabilities contributes both to the prevalence of risk aversion in choices between probable gains and sure things, and to the prevalence of risk seeking in choices between probable and sure losses'.

3.2 How do people choose?

The Prospect Theory subdivides the choice process of people into two phases: the editing phase and the evaluation phase. The choice process starts with an editing phase. In this phase, the decision-maker organizes and reformulates the available options to simplify the choice. The organization and reformulating contains the translation of possible outcomes to gains and losses, rounding off prospects and discard extremely unlikely outcomes. After the editing phase comes the evaluation phase, the decision-maker examines all the edited prospects and chooses the one with the highest value. The prospect contains two elements, the weighted chance and the subjective outcome. There is a weighted chance because people tend to overweight small probabilities and underweight high probabilities. The outcome is subjective because of the higher impact of losses and values that are further away from the reference point are much higher weighted than values close to the reference point, both for gains and for losses.

3.3 Bounded rationality

CPT assumes that the decision maker lacks knowledge about many feasible alternatives and corresponding consequences and has a limited capacity of the mind. Bounded rationality also postulates that a decision maker has an aspiration as to how good the outcome of an alternative should be. Instead of effortful striving for the outcome that maximizes utility, the decision maker now accepts the first satisficing outcome: as soon as he discovers an alternative that meets this aspiration level, he takes it and the search for alternatives is stopped. This aspiration level may relate to a threshold value for the compounded utility of an alternative, or to a set of thresholds for the values of all relevant attributes of the alternative.

3.4 Gains, Losses and the Reference Point

In contrast to Expected Utility Theory, CPT measures losses and gains, not absolute wealth. Gains and losses are values that depend on the reference point of the person. In gambling for example, it might be the wealth before the beginning of the game, it could also be based on experience and expectations if one expect to earn a certain amount his reference point will be higher, because anything that he will earn less than that he will see as a loss. Therefore, from his reference point, the gambler values the possible outcomes as gains and losses. This valuation is not linear, people tend to overreact to small probability events especially when outcomes are extreme (in case of insurance and gambling), but underreact to medium and large probabilities (in case of investments).

3.5 Loss aversion

Loss aversion refers to the behavior of people to prefer avoiding losses to acquiring gains and the risk seeking behavior in case of losses but risk adversity in case of gains. For example, if one has to choose between one of the two gambles, or prospects:

Gamble A: A 100% chance of losing $3000.
Gamble B: An 80% chance of losing $4000, and a 20% chance of losing nothing.

The next choice is between:
Gamble C: A 100% chance of receiving $3000.
Gamble D: An 80% chance of receiving $4000, and a 20% chance of receiving nothing.

Kahnemann and Tversky found that 20% of people chose D, while 92% chose B. A similar pattern held for varying positive and negative prizes, and probabilities. This led them to conclude that when decision problems involve possible losses, people's preferences over negative prospects are not a mirror image of their preferences over positive prospects. Thus, people are risk-averse over prospects involving gains but become risk-loving over prospects involving losses.

Compared to Expected Utility Theory, PT and the other non-Expected Utility models showed a better match with the survey results of public transport passengers. Though we definitely have not had the last word about the best way to cope with choice heterogeneity, the different assumptions of PT can apparently be modeled smoothly within a discrete choice framework. (Van de Kaa, 2006)

The most fundamental difference is that UT assumes that each individual follows the same choice behavior strategy in all contexts, while PT allows for context-dependent intrapersonal and interpersonal differences in the framing of alternatives.

3.6 Accuracy for HOT lane Modeling

The advantages of the Cumulative Prospect Theory are that it is a more descriptive theory than the Utility Theory; CPT describes how people make a choice instead of how people should choose when risk is involved. Therefore the CPT assumes that people have a reference point to value gains and losses. A disadvantage is that the CPT was not developed for route choice, it might not fit properly because of differences between gamble experiments and route choice. CPT does also not exactly models the fact that people are more satisficers[1] than maximizers, because people still choose the alternative with the highest value. The theory assumes that people try to be rational but because people can't think perfectly rational the theory applies weighting functions and loss aversion parameters to model the bounded rationality. Also the attributes are valued in a commensurable medium, such as money or time. There is no qualitative aspect, while people can think in a qualitative way. It is by far the most used model to translate the decisions of people into a cost benefit analysis, usually expressed in money. However, the media and friends and family

[1] **Satisficing** is a decision-making strategy that attempts to meet criteria for adequacy, rather than to identify an optimal solution.

can influence an opinion; for example there was and still is aversion against the concept of HOT lanes because the idea is that poor people can't afford to pay the toll, so the opinion was that HOT lanes are mainly used by rich people while poor people are stuck in the GP lanes. This is also why HOT lanes are sometimes called Lexus lanes. It is hard to model such irrational behavior and with the Prospect theory it can't be modeled directly. Indirect it can model some of these arguments, like the fact that old people usually are less flexible to try new concepts and are therefore less likely to choose for HOT lanes. So to find out why people choose for HOT lanes it is important what arguments and motives they have to do so.

4. Attributes of HOT-lane choice

CPT is a descriptive theory and it is important to know what motives and arguments people use for their choice, because that is what the theory attempts to model instead of the best economical choice. This chapter describes what influences the choice of drivers, their own motives and their perception on HOT lanes.

4.1 Attributes of Transport

- Toll Rate

The Toll rate is obviously one of the most important factors why people choose to ride on the HOT-lanes. It is also the most important instrument for the road manager to distribute the traffic between GP-lanes and HOT-lanes.

- Travel Time/reliability

Drivers (want to) choose to use the HOT-lane based on the time that they save by using it. This is not always possible because drivers cannot see the traffic situation they face when they use either of the lanes. Therefore, drivers have to make an assumption how bad the traffic is on the GP-lanes and how much time they will save when they use the HOT-lanes. According to Gosh(2000) some commuters are using the toll rate as a signal for congestion. The commuters cannot observe the level of congestion but they can observe the toll before the HOT-lane entry. Since the toll varies according to the level of congestion, and this is common knowledge, commuters tend to use the HOT lane if the toll rises above its expected value. Also Bonsall et al. (2007) find that some people assume that high tolls indicate congestion on the GP-lanes and choose HOT-lanes when the toll is high, although the toll rate is based on the traffic on the HOT-lanes to prevent congestion on those lanes.

A solution for that problem and to provide drivers information about travel times, road manager can display the estimated travel times on matrix boards above the road.

Drivers do not respond the same, given the toll rate and the travel time they could save. It depends on their value of time if they are willing to use HOT-lanes. The exact value of time of each individual driver is hard to find, people do not calculate exactly the benefits of HOT-lanes for them, with the given toll rate and travel time. A way to find the value is to ask drivers about the choices they make and try to find the factors that had influence on that decision. Studies described the factors that could influence drivers' based on an OD-survey from the SR-91 Li(2001), Sullivan (1998) evaluated the impacts of HOT-lanes on the SR-91 and used observation data and surveys, including an OD-survey about travelers characteristics and their revealed travel behavior.

4.2 Attributes of Traveler

- Value of Time

The value of time is an important factor, it depends on this factor or someone is willing to pay the toll to save time, it is hard to give an exact value and it has a strong correlation with the purpose of the trip. Besides that, there is also the variability in time. According to Ghosh(2000) people hate variability in time and are willing to pay to prevent it. Small (2005) finds that travel time and its predictability are highly valued by motorists, and that there is significant heterogeneity in these values, and that models that count for values of time and reliability produce greater efficiency gains than other models.

- Gender

Sullivan(1998) finds that 42%of female respondents were frequently HOT-lane users compared to 28% of male respondents. Li(2001) however finds no statistical evidence that female commuters are more likely to use HOT-lanes, and doubts the results of Sullivan(1998). Small (2005) uses sex as an influence on lane choice and finds that women are more likely to use HOT-lanes

- Age

The youngest and oldest age groups are less likely to be frequent express lane users than commuters in intermediate age categories (Sullivan, 1998). Li(2001) finds that compared with those in their 20s (the reference category), travelers in the older age groups are more likely to use HOT lanes; travelers in the 50s are nearly 6.5 times as likely as those in their 20s to be HOT lane users, and commuters in their 40s are about 3.6 times as likely as those in the 20s to do so.

- Frequent user

The data from the panel origin-destination(O-D) survey on SR91 lends no support to the hypothesis that frequency of travel is positively associated with the use of HOT lanes. (Li, 2001)

- Occupancy

High occupancy vehicles are much more likely to use HOT-lanes because of the decal they get, and even if they are not a registered carpool vehicle, the occupants can split the toll costs in the case of carpooling.

- Income

However results show that drivers at all income levels use HOT-lanes, Li(2001) finds that people with an high household income are 18% more likely to use HOT-lanes than people with a low household income. Sullivan(1998) finds that highway users in the high income groups (> $40.000) are about twice as likely as users in the low income group (<40.000) to be frequent toll lane users, furthermore is the part of the high income groups from the non-users half of the non-users from the low income group. Hence income is a significant factor is for the choice to use HOT-lanes.

- Household properties

The results suggest that household size and household type probably do not make much difference in the use of HOT lanes. (Li, 2001)

4.3 Attributes of trip

- Trip purpose

Trips from home to recreation or leisure sites are about 88% less likely to use the HOT lanes. Similarly, home-to-shop trips, personal trips, and other trips are, respectively, about 60%, 67%, and 86% less likely to use HOT lanes than home-to-work trips. Nonetheless, the odds ratio for work-to-home suggests that people who drive home from work are 1.8 times as likely to use HOT lanes as those who drive to work from home. (Li, 2001)

- Trip length

The result lends no support to the hypothesis that frequency of travel is positively associated with the use of HOT lanes. (Li, 2001)

There is another factor, the HOT-lanes does not have the same entry and exit points as the general purpose lanes. HOT-lanes are therefore not always an alternative for people who make short trips.

5. Model

This chapter will describe the simulation of HOT lanes with the learning model. The results from this model will be compared to the model without the Cumulative Prospect Theory part.

5.1 Learning Model

The model to simulate HOT-lanes with CPT is based on the learning model developed by Wu-Di. The framework of the model has two main components:

1. The learning process, a driver's previous experience with the HOT lanes provides his choice the next time. The more recent the experience the more influence it has on the choice, both positive and negative.
2. Route choice, the choice between GP lanes and HOT lanes, there are two moments where drivers make a choice, the pre-trip choice before leaving and the en-route choice before the HOT lane entrance when the exact toll rate is known.

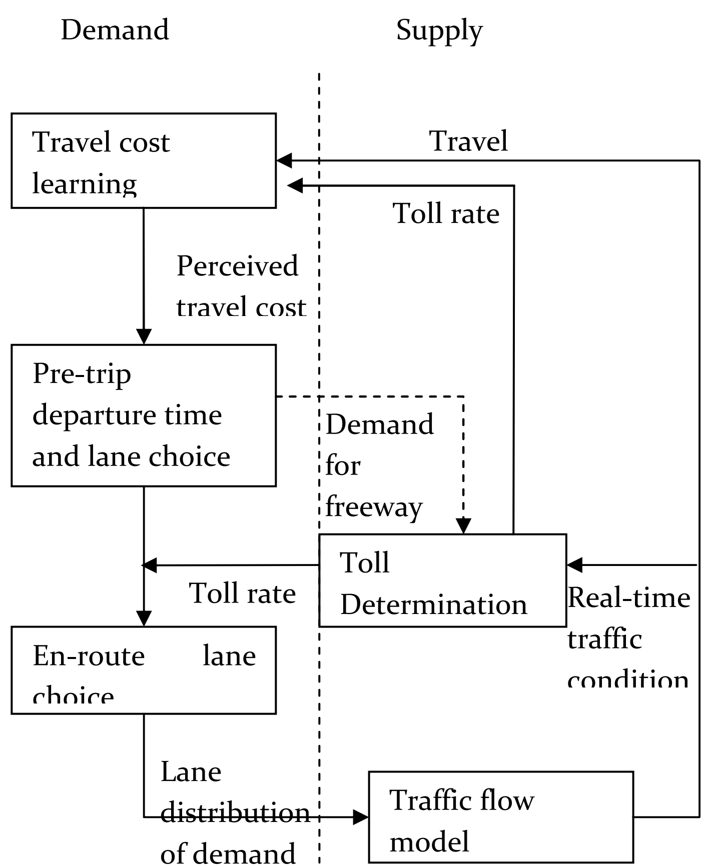

Figure 5- 3: Framework of the simulation model

Every driver in the model has his own value of time, preferred arrival time, and aversion of being late or early, these values are generated in the beginning of the simulation and remain the same during the simulation. The values are randomly generated and follow a normal distribution. For the determination of the values see appendix B: The HOT lane model.

Learning process: Given that road users are not able to foresee the outcome (travel time and toll charge etc.) of their trips, they make their travel decisions based on their own understanding of the traffic condition and the associated cost, which may be obtained from their own travel experience or other information sources through a learning process. It is modeled with a weighted average approach. That means that drivers remember previous travel times and toll rates; a factor is applied to that data, the more recent the data the higher the factor, the perception of the driver is an average of that weighted data.

Pre-trip route choice: Based on their perception of traffic condition and their desired arrival times, travelers will evaluate the travel costs associated with different departure times and made their choices accordingly. For GP lanes the costs become the travel time (in hours) multiplied by the drivers value of time(VOT) in $:

$C_{GP} = t_{travel} * VOT$

For the HOT lanes the toll rate is added to the costs of travel time so the total costs become:

$C_{HOT} = t_{travel} * VOT + c_{toll}$

Both the travel time and the toll rate are only based on previous experience, because the choice is made before the trip begins. These costs are in fact a negative utility or disutility.

En-route lane choice: The pre-trip departure time and lane choice is made by a traveler with previous information. However, the traveler will be able to revisit his or her lane choice once en-routes. Given that the toll rate is displayed ahead of the entrance of the freeway segment, the traveler will decide whether to pay to use the HOT lane. The preferred lane may not be the one pre-selected by the traveler at the time of departure. The costs en-route become:

$$C_{GP} = t_{travel} * VOT - f_{early} * VOT * \min(t_{delay}, 0) + f_{late} * VOT * \max(t_{delay}, 0)$$

$$C_{HOT} = t_{travel} * VOT + c_{toll} - f_{early} * VOT * \min(t_{delay}, 0) + f_{late} * VOT * \max(t_{delay}, 0)$$

The driver compares the costs, or the utility of GP lanes with HOT lanes and chooses the one with the least costs or least disutility.

5.2 CPT in the learning model

CPT is used for the on-route lane choice; the pre-trip lane choice is not modeled with CPT because the determination has a different aspect. The pre-trip lane choice depends on the departure time, previous experience, vehicle type and the number of passengers you are traveling with to get a toll exempt. En route lane choice is based on the current toll rate end the current travel conditions.

According to the prospect theory, all possible results are valued as gains or losses; the neutral point is the reference point of the driver. In this situation with HOT lanes there are several possible reference points based on experience with GP lanes, with HOT lanes, and expectations of travel time (savings). Because the GP lane is seen as the main road and the HOT lane as an alternative for congestion, the reference point is the previous experience on GP lanes. Drivers compare the total costs of the HOT lane, in time and money, to the expected time of the GP lanes.

5.3 Choice process

The CPT model focus on the en-route choice, important aspects that are involved with that choice are toll rate and the (perceived) travel time. Other factors are how tight the schedule of a driver is, his value of time and previous experience. Based on his experience and expectations a driver has an estimated travel time, this is his reference point. When he drives to the HOT-lane facility, he sees the toll rate and makes a decision to take the HOT lane or the GP lane. When a driver is late, the HOT lane is more attractive because there is almost no chance of congestion. When a driver is early, the GP lane is more attractive because time is less important.

The factors that play a role in the decision process are:

1. Perceived travel time (based on previous experience)
2. Current toll rate
3. Late factor (if a driver is late he is more likely to pay a fee to avoid obstruction)
4. Early factor (if a driver is early, obstruction is not a big issue)

5.4 Difference with UT model

The main differences between the CPT model and the UT model are the distinction of gains and losses separated by the reference point where the UT model calculates which alternative is the best, based on the factors that play a role in the decision process; a loss aversion factor to describe the fear of losses.

6. CPT route choice model

This chapter will describe and explain the cumulative prospect theory model that is used to model the route choice of drivers on HOT-lane roads in Matlab. The model is implemented in a drivers' learning behavior model described in chapter five.

6.1 CPT model

The differences with the utility theory model is that drivers value possible outcomes, in this case travel costs to a reference point, this reference point is based on their previous experience and actual toll rate. The uncertain part in the calculation of costs for the driver is the travel time. Travel times that are lower than a driver expects from his experience are positive and seen as a gain. Travel times that are higher than expected are negative and seen as a loss. Every possible travel time on the HOT lanes has a chance to occur but because of the bounded rationality of people drivers don't calculate that. The outcomes are framed, chances become perceived likelihood of occurrence for the driver, and losses are multiplied by a loss aversion factor because people prefer avoiding losses to acquiring gains; after these transformations the driver knows what he is likely to gain or lose by taking the HOT lanes. He does the same for the GP lanes and chooses for the lane on which he will gain the most, or lose the least.

To calculate the perceived value of each alternative, in this case either HOT-lanes or GP-lanes, the following formula is used as proposed by Tversky & Kahneman in 1992:

$$V = V^{-} + V^{+} \tag{1}$$

Where V is the perceived value; V^{-} the perceived value of outcomes below a reference point; and V^{+} the perceived value of outcomes above a reference point. Hence, V^{-} describes the perceived losses and V^{+} the perceived gains.

Each of the two perceived values contains two elements: a value function that describes the payoff level experienced by the driver for each possible outcome and is different for gains and losses.

Gains:

$$g(u) = (u - u_0)^{\propto} \tag{2}$$

Where u is the value of a positive outcome(a value higher than the reference point); u_0 is the value of the reference point. This means that g(u), the gain, is the value above the reference point, if one expects to save 6 minutes of travel time, his reference point, but in fact he saves 10 minutes his gain is 10 – 6=4 minutes[2]. α is a parameter between 0 and 1 that gives the concavity for gains. It also gives the level of diminishing sensitivity away from the reference point, this means that the further the distance from the reference point, the smaller the impact of a change.

[2] When travel time or toll costs are taken instead of time savings both the values of the utility (u) as the reference point are negative.

Losses[3]:

$$g(u) = -\lambda(-u + u_0)^{\beta} \quad (3)$$

Where λ is the degree of loss aversion with λ>1 describes the event that people prefer avoiding losses to acquiring gains; u is the value of a negative outcome (a value below the reference point); u_0 the value of the reference point; and β is a parameter between 0 and 1 that gives the convexity for losses. It also gives the level of diminishing sensitivity away from the reference point like α.

The second element of the perceived value is the probability weighting function; it transforms the probability scale into the perceived likelihood of occurrence. Prelec(1998) derived the following probability weight function, that Connors(2009) uses in his route choice experiment:

$$w(p) = \mathrm{e}^{-(-\log(p))^{\gamma}} \quad (4)$$

The prospect theory applied the weight function to the probabilities, the CPT however applies the weight function to the cumulative distribution function. If f(u) describes the cumulative probabilities then the perceived value can be calculated with:

$$V^{-} = \int_{-\infty}^{u_0} g(u) \frac{d}{du}(w(F(u)))du \quad (5)$$

$$V^{+} = \int_{u_0}^{\infty} g(u) \frac{d}{du}(-w(1 - F(u)))du \quad (6)$$

6.2 Parameter values:

Tversky and Kahneman proposed certain values for the parameters used in equations 1-3; Both Avineri (2008) and Connors (2009) used these values for route choice modeling. However Tversky and Kahneman calibrated their values from gambling experiments and not from transportation experiments, but both Avineri(2008) as Connors(2009) conclude that other studies confirmed, or found values that were close to, the parameter values obtained these parameter calibrations. Some studies tried to estimate the parameters for traffic and route choice problems as well. Chow(2009) calibrated the parameters for route choice problems and Van de Kaa (2006) summarized some loss aversion parameters found in literature.

[3] Note that g(u), both for gains and losses, is positive, when the weighting function is applied gains become positive and losses negative.

Table 6-1: Parameter values

Parameter	Value	Study
α=β	0,88	Tversky & Kahneman (1979)
	0,52	Connors (2009)
λ	2,25	Tversky & Kahneman (1979)
	2,0	Van de Kaa (2006)
	1,62*	Avineri(2008)
	3,26	Chow (2010)
γ	0,74	Connors (2009)

* This value is calibrated for the afternoon peak

6.3 HOT-lanes

In most route choice experiments the value of a route is measured in time, the faster the route the more attractive it is. In the case of HOT-lanes the toll rate is also a factor. To fit the toll rate into the CPT model there are roughly two options. Both time and toll can be measured in money through the value of time (VOT) of drivers. The reference point becomes an amount of money that can be a combination of travel time and toll rate. The other option is that the toll stays separated from travel time. The reference point is measured in time and toll is seen as a sure loss because it is out of pocket money that one does not have to pay on an average day. The reference point is still based on travel time that is experienced in the past and expected to be an average travel time for the driver. The model of the last option is the same as eq. 1,5 & 6 for the perceived travel time and for the toll eq. 3 can be add to eq.1. The weighting function is not necessary since toll is a sure loss, that means a chance of 1, and w(1)=1. Because the learning model transforms all the factors to money with the value of time, that approach is used for the CPT model.

The perceived travel time follows normal distribution with mu=experience from last time and sigma=0,1*mu, the travel time cannot be lower than the free flow travel time.

6.4 Results

The simulation model has the following input data: it simulates the afternoon peak traffic (4pm – 6 pm) with 25.000 vehicles, including 2.000 registered toll exempt vehicles on the I-95 along the 7 mile HOT lane facility. The road segment has 2 HOT lanes and 4 GP lanes, each lane has a capacity of 2400 vehicles. The free flow speed is 70 miles per hour. The model simulates the afternoon peaks of 10 days. Below are the results of the CPT model compared to the results of the UT model and the measured data from the I-95 HOT lane facility by the Florida Department of Transportation. More detailed results are in Appendix C.

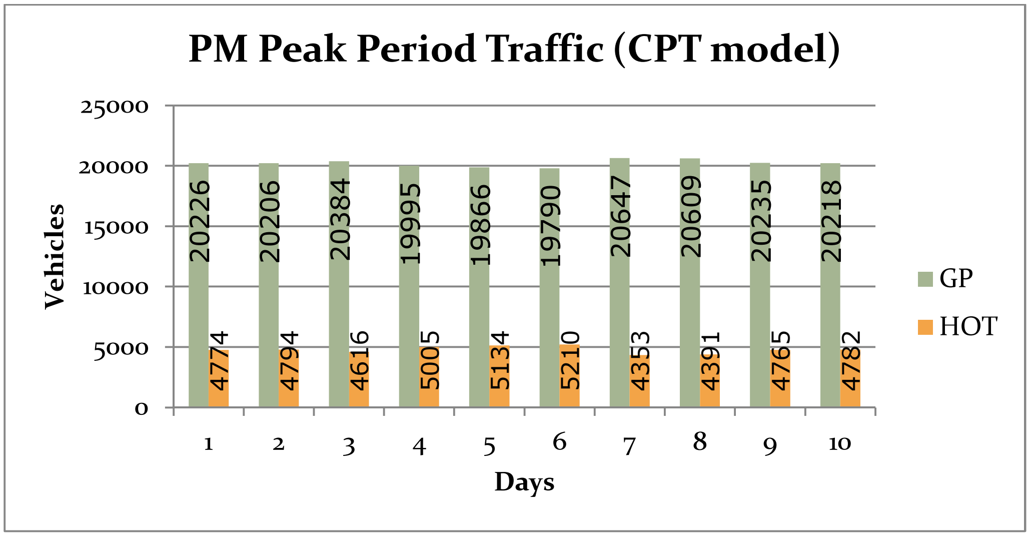

Figure 6-1: Distribution of Traffic in the CPT model

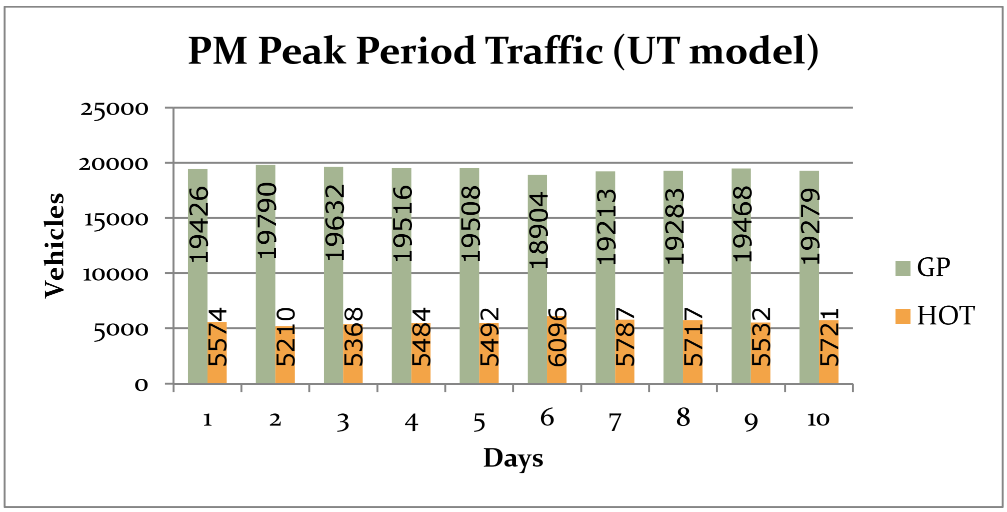

Figure 6-2: Distribution of Traffic in the UT model

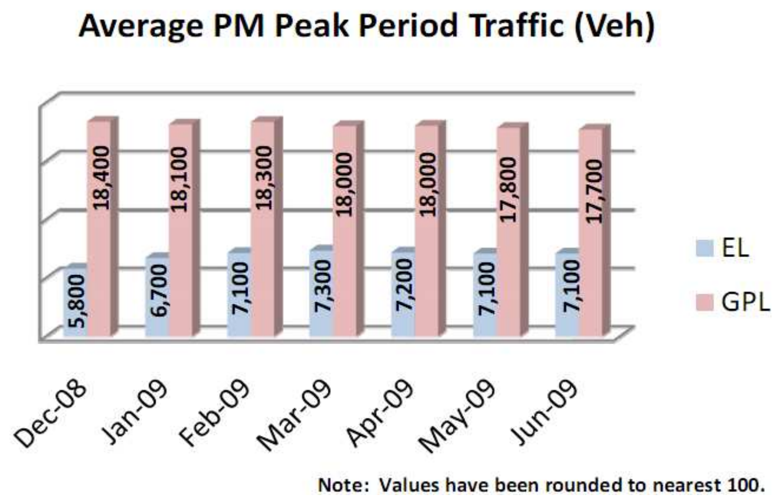

Figure 6-3: Observed data from the I-95 HOT lane Facility

Figure 6-1 shows the distribution of traffic, from the 25000 vehicles, with the new CPT model. The differences compared to the UT-model (figure 6-2) are small, but in the CPT model, slightly more drivers take the GP lanes instead of the HOT lanes. Compared to the measured data from the I-95 both models have less traffic on HOT lanes, it can be explained by the experience that drivers have, more drivers are familiar with HOT lanes, figure 6-3 shows a rising popularity over the months. Maybe the models experience attribute is not calibrated for the more experienced drivers.

Table 6-2 shows the average distribution of a 30 days simulation with the UT model and with the CPT model. One can see that about 3% of the daily traffic takes the GP-lanes instead of the HOT lanes with the CPT model compared to the UT model but in the CPT model the HOT lane fraction 10% lower than the observed data from the I-95.

Table 6-2: Average distribution of traffic during the PM peak on GP lanes and HOT lanes

	UT model		CPT model		Observed Data	
Total traffic	25.000	100%	25.000	100%	25.200	100%
GP lanes	19.508	78%	20.277	81%	18.000	71%
HOT lanes	5.492	22%	4.723	19%	7.200	29%

The literature provides other values for CPT parameters see table 6-1, the loss aversion factor is the one with the most influence because α, β and γ transform some extreme chances. The reference point could also be a factor that has significant influence on route choice.

Appendix C shows also results of the vehicle types on both lanes. In the measured data, around 20.000 SOV and HOV2 vehicles in the facility take the GP lanes and around 5500 choose for HOT lanes, but from the 2500 HOV 3+ only 171 vehicles choose for HOT lanes.

In CPT model from the 23.000 SOV and HOV2 vehicles chooses 4200 for HOT lanes that is less than the measured data from the lanes, and also the UT model has with 4600 SOV and HOV2 vehicles less traffic on HOT lanes than with the measured data.

For the HOV3+ vehicles, the CPT model seems to model it better than the UT model but the behavior in the measured data is strange; because they have a toll exempt, more HOV3+ vehicles are expected on HOT lanes. An explanation is the more complicated registration process for carpool vehicles on HOT lanes compared to the old HOV lanes.

Average speed on HOT lanes: In the CPT model the speed is 50 mph, which is lower than in practice, where it is 56 mph. The UT model is a little closer to the measured data with an average speed of 52 mph, this seems not logical because in CPT model there is less traffic on HOT lanes. This could mean that at the peak of the peak hour when the GP lanes are congested, more people go HOT lanes in the CPT model than in the UT model or than with the measured data. However the GP lane speed is also too high in both models compared to the measured data, an explanation for that is that there are no incidents "programmed" in the models while they do happen in real life, and show up in the measured data.

The toll revenues: Measured is $11.500, in the CPT model it is $10.000 and in the UT model $15.000. the revenues at the UT model are much higher than the measured data and the CPT model and it seems unrealistic. The CPT revenues are somewhat lower than the measured data, but than can be because there is less traffic on HOT lanes in the CPT model than with the measured data, thus the relationship between traffic and revenue seems to be right. The average daily toll is $1,86 that is equal to a good month in the measured data and seems to prove that the relationship between traffic and revenue is the same.

6.5 Sensitivity Analysis

The sensitivity analysis shows that the en–route choice is not really sensitive to the parameters, with different parameter changes the results do not change with more than 10%. The reference point is more interesting, because at the beginning of the simulation the drivers have no experience, while in fact the rising popularity of the HOT lanes (figure 6-3) could be explained by the (positive) experience that drivers have about HOT-lanes. Because of that positive experience, drivers value the normal GP lanes as worse because of unreliability or because a bad experience with GP lanes is valued worse because they know there is an alternative. Those experience factors can be modeled by a higher loss aversion or a higher reference point.

When we look at that the value of the reference point, that is now the expectation of the GP lanes that is based on their learned experience. Drivers could value that experience lower because of the good experience with HOT lanes. Therefor a congestion on GP lanes is valued worse because they know there is an alternative. To model that, the reference point is multiplied by 1,1 and 1,2. The results of that analysis is in Appendix D. That shows that now 23% take the HOT lanes instead of 19%. When we look at a higher loss aversion (with the higher reference point) table 6-3 shows that with a loss aversion of 4,0, 27% of the drivers take the HOT lanes.

Table 6-3: CPT model, loss aversion calibration

	Loss aversion: 2,25		Loss aversion: 3,0		Loss aversion: 4,0	
Total traffic	25.000	100%	25.000	100%	25.200	100%
GP lanes	20.277	81%	18.813	75%	18.292	73%
HOT lanes	4.723	19%	6.187	25%	6.708	27%

6.6 Discussion

The fact that there are differences between the two models is not unlikely; the parameters used for the CPT model are not calibrated for motorists on HOT lanes, the parameters found in the literature came from other route choice experiments or the original theory. The differences compared to the observed data can be caused by the experience, the electronic tolling on the I-95 was launched in December 2008. It takes time to find out how much it costs every month and how much time it will save to take the lanes. To model that drivers got a higher reference point and a higher loss aversion. The results came closer to the measured data, but not exactly right. But there are other factors than the en-route choice that could explain the difference. The old UT-model does also not provide the exact data that is measured in 2009, however it is closer to the first data from 2008, this could mean that experience is not modeled good enough but there are more moments than only en-route where that could influence drivers. For example the pre trip route choice or maybe even the drivers VOT. Also the traffic could be changed. Maybe more HOV vehicles drive on the I-95 which gives more traffic on HOT lanes because they do not have to pay toll. That new data is not modeled yet and could give a better result.

Conclusion

HOT lanes become a more attractive solution for underutilized HOV lanes. The effectiveness of HOT lanes depends on a good toll strategy, to make them more popular than HOV lanes but also to prevent congestion on HOT lanes. The strategies are not the same everywhere; there are differences in toll exempt vehicles and in the determination of the toll rate. HOT lanes seems to be more used than HOV lanes, and there are conclusions that it is a good way to attack congestion but there is no agree yet.

There are several studies on the determination of an optimal toll rate, based on the traffic on HOT lanes. Other studies focused on the values of parameters that influence the choice of drivers. Almost every model and parameter study used the utility theory to make a model or to find parameter values.

An alternative theory is the Cumulative Prospect Theory, it was developed because the general utility theory does not model choice behavior, but what from a rational view the best choice is. The new approach, with more attention to the actual behavior of people, gets more attention in transportation literature, especially in the field of route choice. Several studies explored the Prospect Theory for route choice models. The properties of CPT are better for the actual modeling of human behavior on route choice and especially HOT lanes because of bounded rationality and uncertain costs. The whole concept ov gains losses and loss aversion is based on human behavior and motives. The Utility theory may be easier to implement but the underlying assumption that people are rational and can make all the calculations to find an optimum is not what people do. However CPT is still a based on rational choice and it is hard to model the qualitative arguments and motives.

The result of the implementation of CPT on HOT lane choice is a practical model based on the assumptions of the Prospect theory. It is a first combination of HOT lanes and the cumulative prospect theory. The results with the CPT model are similar to the results with the UT model as shown in figure 6-1 - 6-3 and table 6-2 but lower than the measured data. The original UT model is calibrated for the I-95 HOT lanes, the CPT model is based on the same assumptions of the I-95. The new model is not complete, the parameters come from other route choice experiments or from the original theory, there is more study needed to optimize those parameters. The first step is made which come up with a higher loss aversion and a first calibration of a reference point. But for the underlying assumptions that are used in this model, such as the reference point and the probability weighting function are other approaches possible. What exactly the reference point is is hard to find out, what do people expect, why and when does that change need is a research topic on its own. There is also no knowledge about de applicability on other HOT lanes. And because the popularity of HOT lanes rises on the I-95 without changes to the HOT lane pricing scheme or an increase of traffic the calibration can be old next month or year most likely because of the experience of drivers.

This model could be directly useful for other model builders and research to the behavior of drivers on HOT lanes and the calibration of parameters to model that behavior. The data that the model provides could be useful for traffic operators because they can predict the consequences of their toll rate system. It can even help decision makers who want to know what would be the utility of HOT lanes instead of HOV lanes if they decide to build them. It makes it easier to compare HOT lanes to other solutions that could help to decrease congestion. Indirect also the users benefit from it because the lanes are better used and that means less congestion.

Recommendations

As said in the conclusion the model is not yet optimized, the parameters of the prospect theory need more study to determine the best values for HOT lane use. The reference point is also not indisputable, in this report it is the experienced time with the GP lanes, but it could be that experience with HOT lanes play a role in the reference point. Also losses and gains could influence the reference point.

This report did not look very close to the mathematical part of the theory, for the probability weighting function the formula of Pretec(1998) is used, analogous to the work of Connors(2009). Tversky and Kahneman used a different formula but the characteristics are alike, but the work of Connors was better to implement in the model. More study might show what the better way is to model the probability weightings.

A point that is also named with the reference point is the factors of money and time, it is the easiest way to convert one value into the other, for example with the value of time but in real life it might not be that easy. Maybe time and money have to be separated in the process. Also, money and more specific money that needs to be paid directly is different than indirect costs, the same thing can be true for time, the value depends how it is spent. More study can show if HOT lane choice is the same as route choice with an extra factor or that the experience of drivers is different.

There are several studies to attributes of drivers on HOT lanes, but more study is needed to the implementation of attributes with prospect theory models and if they can improve models.

To enhance the modeling with the cumulative prospect theory the most important research topics would be on the reference point, does it stay the same en-route and what influences the reference point, how do money and time relate to expectations and the reference point do people translate time to money or do they keep it separated? That research would provide a better insight on how drivers view tolls and how they relate it to time.

Loss aversion is also a factor that is not clear, there are results from Avineri (2008) that loss aversion changed from 0,76 to 1,62 but Chow(2010) found a value of 3,26, it may not be strange that loss aversion is not constant but the reason why it changes could help to understand drivers' behavior better.

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Appendix A: I-95 HOT lanes

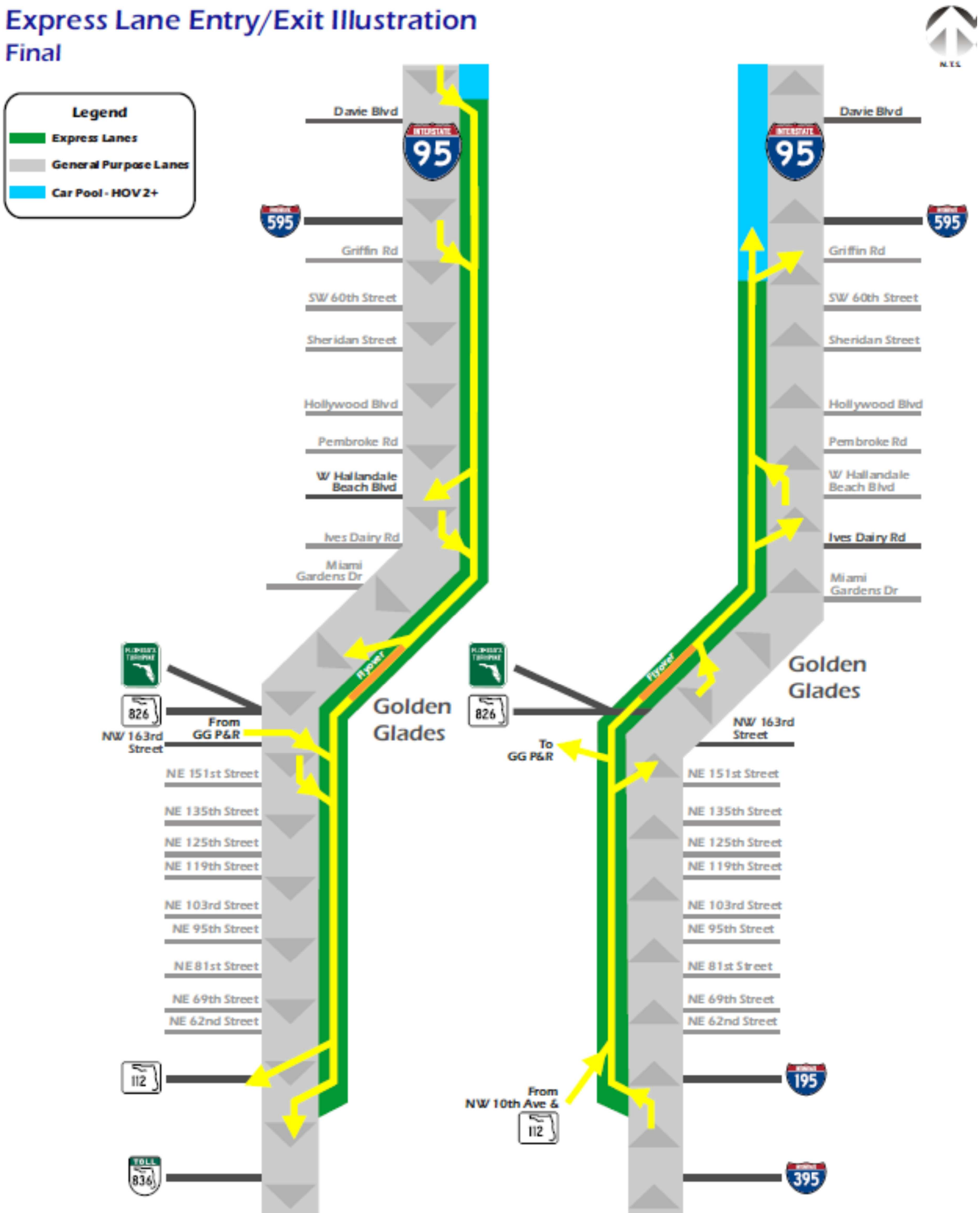


Figure A: Scheme of the I-95 HOT lanes near Miami

Appendix B: HOT lane model

Value of travel time (VOT):

The VOT for each traveler is randomly generated at the beginning of the simulation process. Although the value may be different for different traveler, each traveler will keep the same value throughout the simulation process. Several studies have used empirical data from existing HOT or express lane projects to calibrate travelers' VOT. The estimated VOT ranges from $7 to $65 with a median varying from $18 to $33 per hour. We assume that VOT is normally distributed among travelers with a mean of 25 and standard deviation of 5 respectively. Both values fall in the range of results from the previous empirical studies.

Early and late arrival penalty parameter: f_{early} and f_{late}

Previous studies, e.g., Small and Hendrickson and Plank, have calibrated the early and late arrival penalty parameters. However, the results differ substantially. One consistent conclusion is that for work trip in the morning peak hours, the weight for the late arrival is significantly higher than that for the early arrival, and commuters may choose to suffer a longer travel time to avoid a late arrival. Therefore, the value of f_{early} *and* f_{late} is set to be 0.6α and 3α respectively. The selected values are close to the estimates by Hendrickson and Plank, and seem reasonable for the setting of the simulation model.

Toll Determination

The tolling algorithm implemented in this model is the one used for I-95 Express. The rate is determined based on the current traffic density and the change in traffic density of the HOT lane [18]. The toll determination procedure is as follows:

1. Calculate the change in density $\Delta D = D_t - D_{t-1}$, where D_t and D_{t-1} are the density at time interval t and $t-1$.
2. Find the corresponding toll rate adjustment $\Delta\tau$ from Table 1 based on D_t and ΔD .
3. Calculate toll rate $\tau_t = \tau_{t-1} + \Delta\tau$, where τ_t and τ_{t-1} are the toll rate for period t and $t-1$, respectively.
4. Finalize the toll rate according to the following:

$$\tau_t = \begin{cases} \tau_{\max}(D_t), if \tau_t > \tau_{\max}(D_t) \\ \tau_{\min}(D_t), if \tau_t < \tau_{\min}(D_t) \\ \tau_t, otherwise \end{cases}$$

where $\tau_{\max}(D_t)$ and $\tau_{\min}(D_t)$ are the bounds of toll ranges determined by the current traffic density. The value of $\tau_{\max}(D_t)$ and $\tau_{\min}(D_t)$ can be found in Table 2.

Table 1. Toll setting table of I-95 Express

LOS	Traffic Density	Δ - Change in Traffic Density (TD)					
		-6	-5	-4	-3	-2	-1
	0	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	1	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	2	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	3	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	4	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
A	5	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	6	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	7	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	8	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	9	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	10	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25	-$0.25
	11	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	-$0.25
	12	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	-$0.25
	13	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	-$0.25
	14	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	-$0.25
B	15	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	16	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	17	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	18	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	19	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	20	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	21	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	22	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	23	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
C	24	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25	$0.00
	25	-$1.25	-$1.00	-$0.75	-$0.50	$0.00	$0.00
	26	-$1.25	-$1.00	-$0.75	-$0.50	$0.00	$0.00
	27	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	28	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	29	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	30	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	31	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
D	32	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	33	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	34	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	35	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	36	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	37	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	38	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	39	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
E	40	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	41	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	42	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	43	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	44	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
	45	-$1.50	-$1.25	-$1.00	-$0.75	-$0.50	-$0.25
F	> 45	-$2.00	-$2.00	-$2.00	-$2.00	-$1.00	$0.00

Table 1 (cont.). Toll setting table of I-95 Express

LOS	Traffic Density	Δ- Change in Traffic Density (TD)					
		+1	+2	+3	+4	+5	+6
A	0	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	1	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	2	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	3	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	4	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	5	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	6	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	7	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	8	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	9	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	10	$0.25	$0.25	$0.25	$0.25	$0.25	$0.25
	11	$0.25	$0.25	$0.50	$0.75	$1.00	$1.25
B	12	$0.25	$0.25	$0.50	$0.75	$1.00	$1.25
	13	$0.25	$0.25	$0.50	$0.75	$1.00	$1.25
	14	$0.25	$0.25	$0.50	$0.75	$1.00	$1.25
	15	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	16	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	17	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	18	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
C	19	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	20	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	21	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	22	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	23	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	24	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	25	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	26	$0.00	$0.25	$0.50	$0.75	$1.00	$1.25
	27	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	28	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	29	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
D	30	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	31	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	32	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	33	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	34	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	35	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
E	36	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	37	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	38	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	39	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	40	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	41	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	42	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	43	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	44	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
	45	$0.25	$0.50	$0.75	$1.00	$1.25	$1.50
F	> 45	$0.00	$1.00	$2.00	$2.00	$2.00	$2.00

Table 2. Toll range for I-95 Express [18]

Level of Service	Traffic Density (vpmpl)	Toll Range	
		Min	Max
A	0 - 11	$0.25	$0.25
B	> 11 - 18	$0.25	$1.50
C	> 18 - 26	$1.50	$3.00
D	> 26 - 35	$3.00	$3.75
E	> 35 - 45	$3.75	$5.00
F	> 45	$5.00	$6.20

Appendix C: Results

Cumulative Distribution

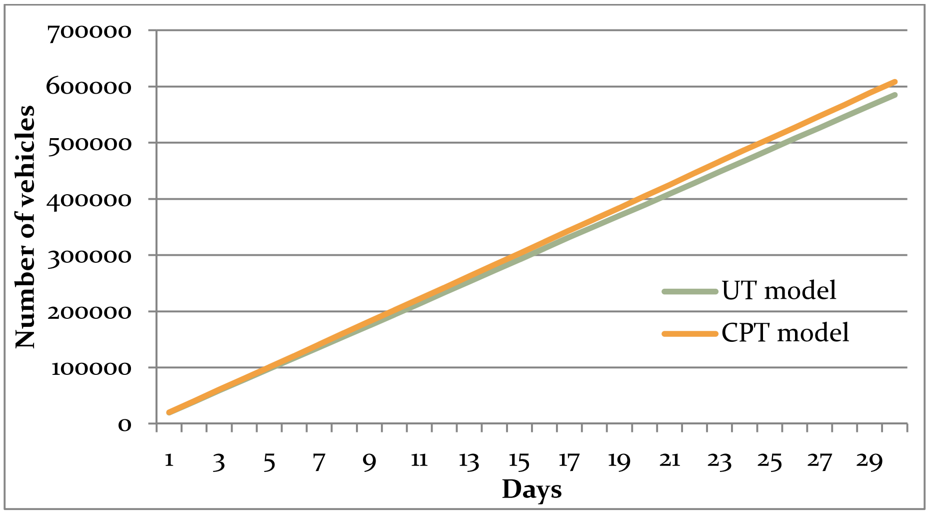


Figure 1: cumulative distribution of traffic on GP lanes

Distribution by vehicle type

Table 2: distribution on HOT lanes and on the facility by vehicle type in the CPT mode and the UT model

	HOT Lanes		Facility (HOT & GP lanes)
	CPT Model	UT Model	CPT & UT Model
HOV 3+ & toll exempt	639	1.051	2.000
SOV & HOV 2	4.196	4.617	23.000
Total	4.835	5.668	25.000

Table 3: Measured data of the distribution by vehicle type

Table 14 Person Throughput by Vehicle Type in Managed Lanes
2008 vs 2009 (Northbound; PM Peak Period – 4 to 6pm)

Vehicle Type	Managed Lanes (Total Person Vol per Peak Period)			Facility (Total Person Vol per Peak Period)		
	2008	2009	% Change	2008	2009	% Change
SOV	1,061	3,778	256.1%	9,141	12,206	33.5%
HOV 2	3,040	1,899	-37.5%	10,437	8,181	-21.6%
HOV 3	477	171	-64.2%	2,335	2,558	9.6%
Transit	810	821	1.4%	810	821	1.4%
Total	5,387	6,669	23.8%	22,723	23,766	4.6%

Average speed

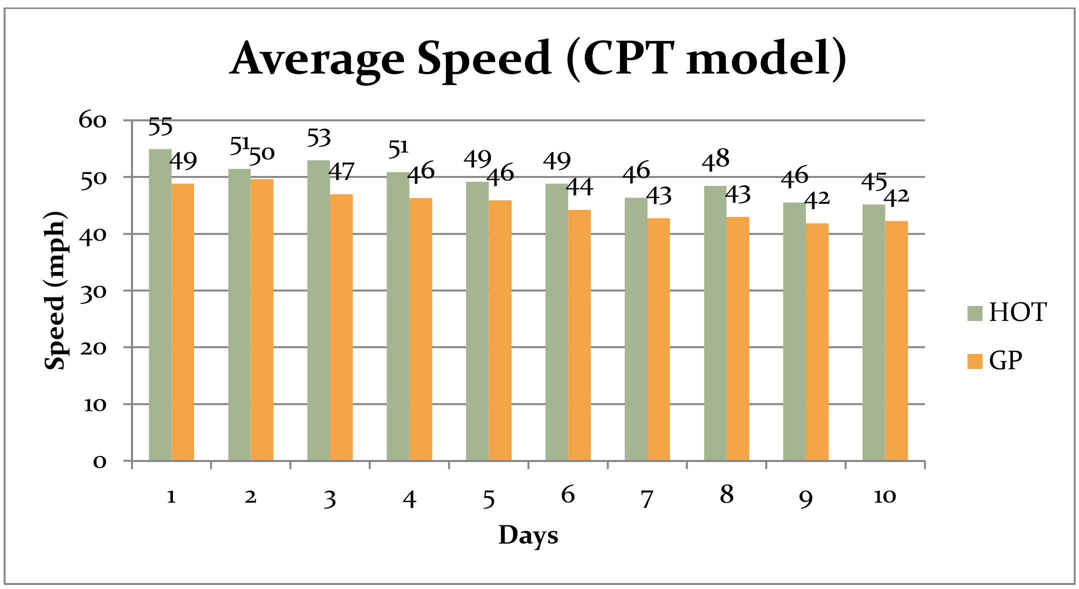


Figure 4: Average speed on HOT lanes and GP lanes in the CPT model

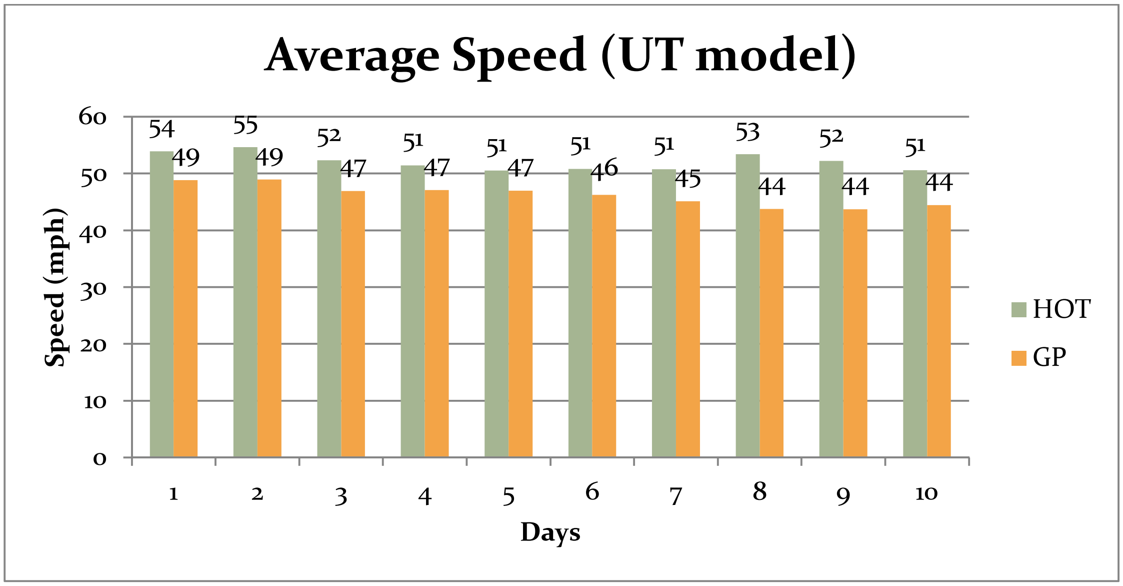


Figure 5: Average speed on HOT lanes and GP lanes in the UT model

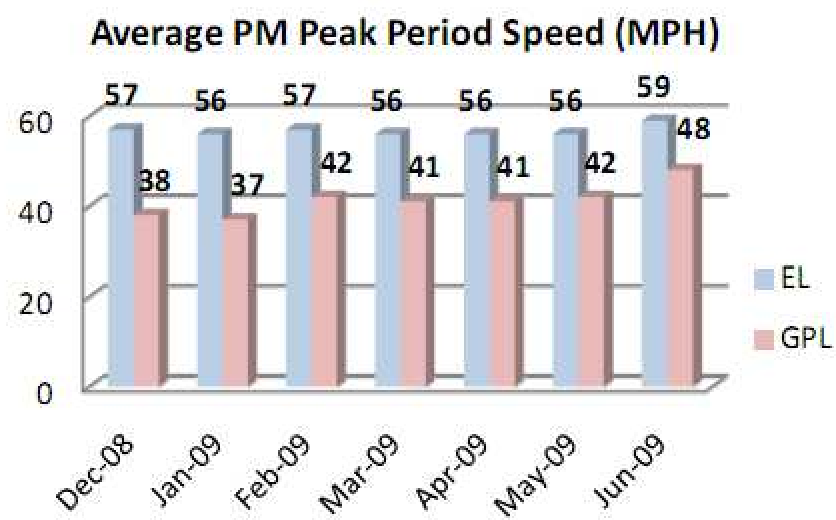


Figure 6: Measured data from average PM peak speed

Toll Revenue

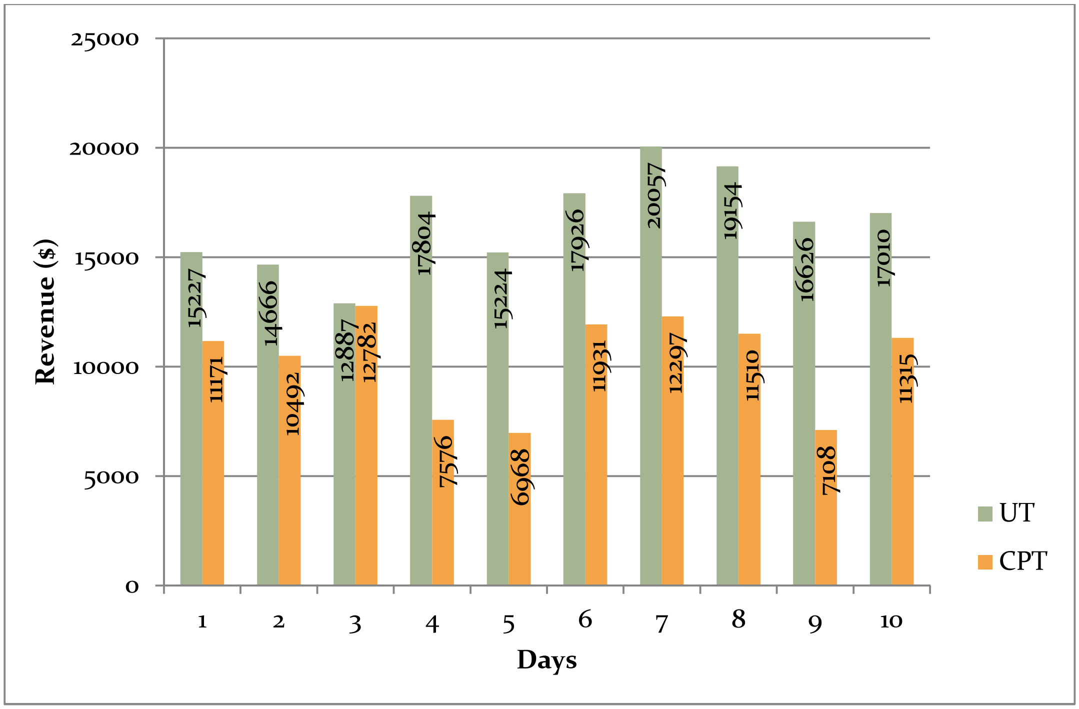


Figure 7: Daily PM peak revenue of Toll with the UT model and the CPT model

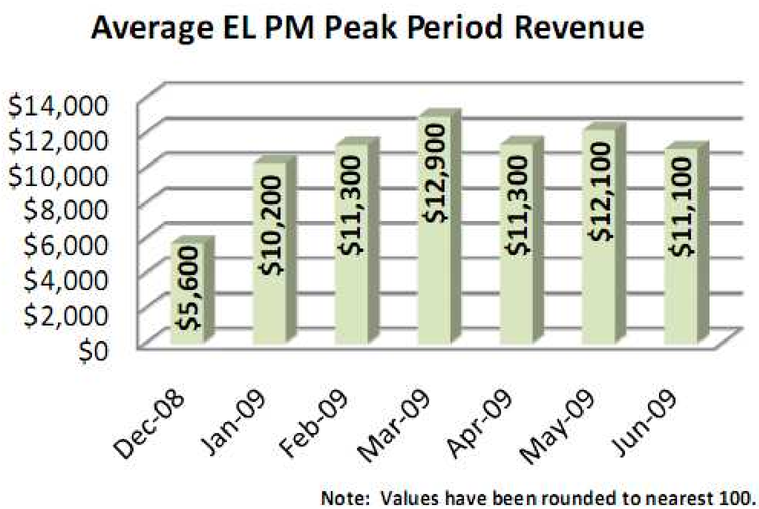
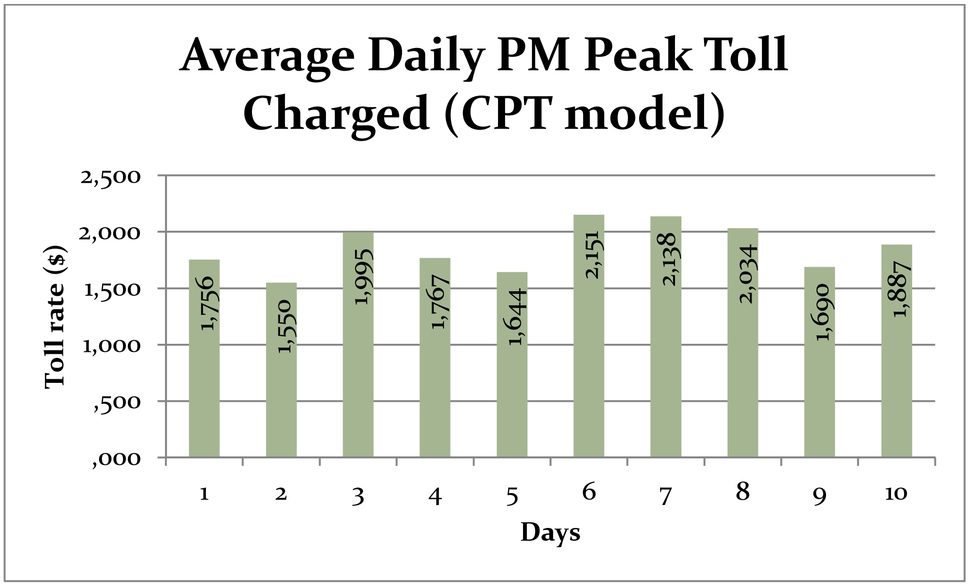
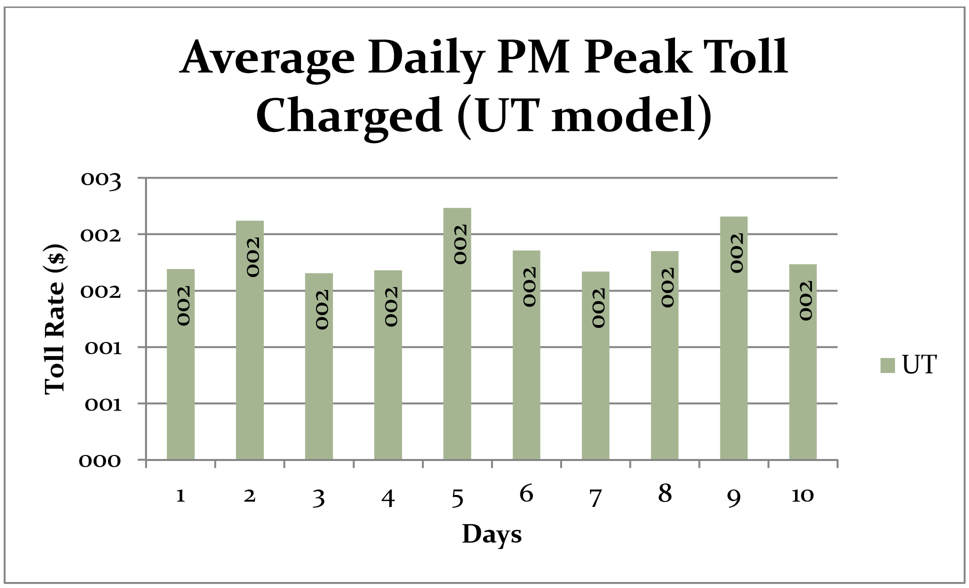


Figure 8: Actual Toll revenue, from measured data


Average Daily PM Peak Toll Charged (CPT model)
Toll rate ($)
2,500
2,000
1,500
1,000
,500
,000
1,756
1,550
1,995
1,767
1,644
2,151
2,138
2,034
1,690
1,887
1
2
3
4
5
6
7
8
9
10
Days


Average Daily PM Peak Toll Charged (UT model)
Toll Rate ($)
003
002
002
001
001
000
002
002
002
002
002
002
002
002
002
002
1
2
3
4
5
6
7
8
9
10
Days
UT

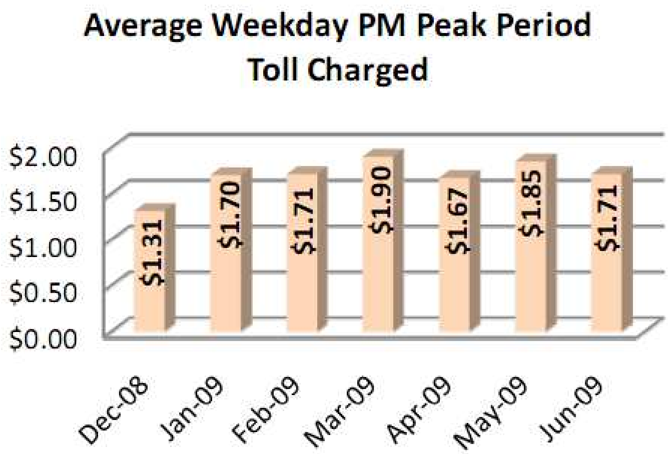


Figure 9: Measured data from Average Charged toll

Appendix D: Sensitivity Analysis

	RP[1]: GP lanes		RP= 1,1*GP lanes		RP= 1,2*GP lanes	
Total traffic	25.000	100%	25.000	100%	25.200	100%
GP lanes	20.277	81%	19.773	79%	19.377	77%
HOT lanes	4.723	19%	5.227	21%	5.623	23%

[1] -Reference Point