The Value of Travel Time Changes: Theoretical and Empirical Issues

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To my family

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Abstract

The value of travel time is a key input for the evaluation and comparison of transport projects. Travel time savings often constitute a great part of the benefits of a project, and therefore the value assigned to them is crucial for cost-benefit analyses. Less often, there may be some transport projects which lead to travel time increases (e.g. repair or maintenance works). In general, it is essential to determine the valuation of travel time changes (VTTC). The VTTC is defined as the marginal rate of substitution between travel time and travel cost for an individual. Hence, the VTTC is likely to differ across people and even for the same person under different circumstances. Therefore, for policy-making it is recommendable to have a set of VTTC based on factors that could influence time valuation: e.g. income or journey length. Stated choice (SC) experiments constitute the most popular method to estimate the set of VTTC of a population. These experiments offer travellers hypothetical choice scenarios to observe their VTTC. Therefore, the choice context may also play on role on valuation: e.g. size and sign of the time changes offered. The choices are analysed using discrete choice models to estimate the VTTC. The aim of this thesis is to increase our understanding of a population's underlying set of VTTC. To achieve this target, we first explore a series of key sources of variation of the VTTC and relate them within the framework of microeconomic theory. Potential confounding between sources is investigated. Secondly, this thesis identifies, relates and compares two popular modelling approaches to estimate the VTTC: Random Utility and Random Valuation. Finally, our research analyses the role of the design variables used in the SC experiment on the estimation of the set of VTTC. The empirical work has been carried out using datasets from the last national VTTC studies in the UK and Denmark. The results provide valuable insights, from which would highlight the following: i) the Random Valuation approach proves to be superior to the traditional Random Utility approach, and in general gives a systematically lower VTTC, ii) confounding is apparent between some sources of variation and the design variables influence most model estimates that determine the set of VTTC, iii) journey length effects do not exist in the data explored, as opposed to what earlier works report. The findings of this thesis have important implications for appraisal.

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Chapter 1
Introduction

"Time is the most valuable thing
a man can spend"
Theophrastus (c. 371 – c. 287 BC)

"Lost time is never found again"
Benjamin Franklin (1706 – 1790)

"My favourite things in life
do not cost any money.
It is clear that the most precious
resource we all have is time".
Steve Jobs (1955 – 2011)

1.1 The value of travel time changes

Time is the most precious resource humans have. At the same time, our existence seems to be surrounded by a necessity to travel. There is a necessity to physically move, from one place to another, in order to satisfy other needs. And this necessity to travel requires, given the available technology, part of our precious time.

In many cases, we would prefer to spend our time doing something else rather than travelling. When our needs require travelling, we would like to satisfy them using the minimum possible time for travelling. In economics, these ideas are summarised into one thought: travelling is a derived demand (e.g. de Rus and Nash, 1997). In simple terms, we spend time travelling because our *real* necessities require us to move from one place to another.

The reflection above has an important implication: travel time can be regarded as a *bad* in economics. Changes in our levels of consumption of this *bad* are possible and will impact on our welfare. A reduction in travel time is a benefit. An increase in travel time is a cost. Hence, there is a value associated with changes in travel time: *the value of travel time changes*.[1]

1.2 Relevance for policy

The value of travel time changes is a key factor in transport economics (Small, 2012; Daly and Tsang, 2009; Börjesson and Eliasson, 2014). Most benefits of transport investment projects are reductions in travel time (Wardman, 1998; Daly et al., 2014). In order to conduct cost-benefit analyses, it is important to translate all costs and benefits into monetary units. Therefore, it is necessary to assign a monetary value to those savings in travel time. Less often, there may be some transport projects which lead to travel time increases, and monetary valuation of those costs will also be needed. In general, it is crucial to determine the valuation of travel time changes. The *value of travel time changes* (VTTC) plays a major role in the evaluation and comparison of different transport projects. Additionally, it is also important for travel demand modelling. Understanding how people value travel time changes is necessary to make predictions on their travel choices. Travel time is a key component of travel demand models, and therein its role has been proved to be greatly benefited from the use of information on VTTC (Small, 2012). In this thesis, the focus is placed on the appraisal role of the VTTC. However, the issues that we address make our findings also useful for travel demand modellers.

1.3 Theory and practice overview

The theory of the VTTC has been well rehearsed over the last five decades, based mainly on the seminal work on time allocation by Becker (1965).

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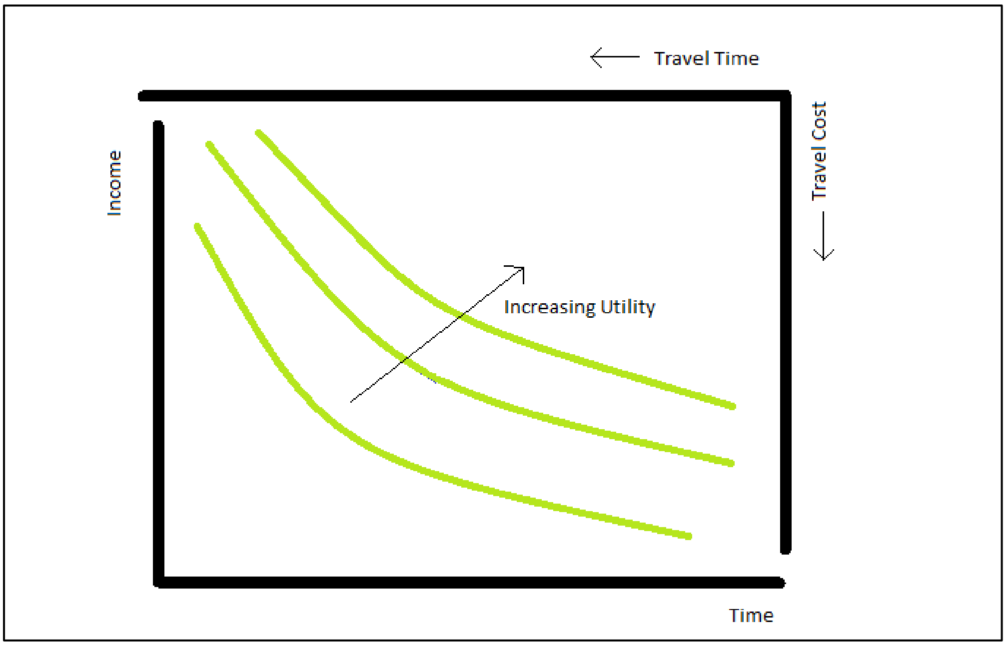
[1] We acknowledge that, in some cases, travelling can derive a positive utility on its own (see e.g. Mohktarian, 2009). In principle, a person may not wish to reduce his/her travel time to zero (due to e.g. physical, social or environmental needs). In those cases, there would not be a positive value associated to reductions in travel time. However, in the world we live, it is fair to assume that travel exists as a derived demand in many cases.

DeSerpa (1971) developed a framework, building upon Becker's work, from which a theoretical definition of the VTTC is obtained. In short, the VTTC is defined as the marginal rate of substitution between travel time and money that leaves a person indifferent. DeSerpa's work is still regarded as the central theory on the VTTC nowadays. In line with the basic foundations of cost-benefit analysis techniques, this theory of the VTTC is in accordance with classical microeconomic theory.

In practice, the VTTC cannot be observed directly. This is a critical problem. Following the definition of the concept, the general consensus is that the VTTC can be approximated if it is possible to observe how people trade-off travel time and money. Therefore, people's travel choices involving time-money trade-offs are needed. Simply imagine a classical convex indifference curve for the consumption of two goods, time and money, that can be changed by the allocation of time and money to travelling (as the figure below depicts).

Figure 1. Indifference curves for the income-time trade-off



In this framework, utility increases as the individuals reduce their allocation of time and income to travelling and the slope of each indifference curve represents the VTTC. While some data of this nature exist from real travel markets (i.e. revealed preference (RP) data), it is often very limited: individuals' travel choices are observable, but it is hard to observe the actual trade-off (if any) that the person faced at the moment of choice. Even worse, in some contexts there may have not been an actual trade-off. For this reason, experiments that mimic those necessary trade-offs and choices are typically conducted to collect data. These are known as stated preference (SP) or stated choice (SC) experiments and are the most common way of collecting data to approach, empirically, the VTTC. With this kind of data, the econometric analysis is normally carried out using discrete choice models. These models attempt to explain travellers' choices, providing an estimate of the underlying VTTC that (supposedly) influenced the choices. More recently, non-parametric techniques have also been employed, as a complement to discrete choice models, to gain further insights into the VTTC from the data.

Finally, there is not a single and unique VTTC. There is a distribution of the VTTC. The VTTC can vary among people and also for the same person under different circumstances (just imagine a person's convex indifference curve as in the figure above: the marginal rate of substitution may vary both across different curves and along the same curve). It is, in the end, just a subjective human's valuation. For example, the VTTC may vary with the level of income or other socio-demographic variables, with the characteristics of the trip for which a person considers a change in travel time, or with the characteristics of the change considered (e.g. Daly et al., 2014; Börjesson and Eliasson, 2014). At a deeper level of analysis, the VTTC could also vary if other behavioural paradigms, different from utility-maximisation, were followed by the decision-maker (see, e.g. Chorus et al, 2014; Dekker, 2014).

1.4 Main current issues

The field of valuation of travel time changes may be going through a critical stage. Although it has been regarded as a mature area where a great deal of consensus has been achieved (e.g. Small and Verhoef, 2007), this perception might have changed. Over the last few years, it has been recognised that several issues remain unresolved and further research is needed (Small, 2012, Daly et al., 2014, Börjesson and Eliasson, 2014). Below, some of the most relevant issues are summarised under three general headlines: heterogeneity, data collection methods and modelling.

1.4.1 Heterogeneity

Heterogeneity in the VTTC across and within people is one of the most cited unresolved issues due to its importance for appraisal. Small (2012) and Daly et al. (2014) coincide in that our understanding of the VTTC and its variation should increase in order to maintain the credibility of the VTTC concept. In particular, there are three topics which have been puzzling economists for the last few decades: low valuation of small time savings, loss aversion and cost damping. The first topic arises from the possibility that the VTTC varies with the characteristic of the change considered, i.e. whether it is a small or large change: *size effects.* The second comes from the observation that losses may weight more than gains, hence losses may be valued at a greater rate: *sign effects*. Sign effects explain why willingness-to-pay measures for travel time reductions are usually lower than willingness-to-accept measures for travel time increases. And the third is related to variation of the VTTC with the characteristics of the trip, e.g. whether the trip is cheap or expensive, short or long, etc.: *base level effects*. In particular, the term "cost damping" is often used to refer to the finding that the VTTC increases for more expensive journeys (sometimes associated with longer journeys). However, it is more accurate to refer to (and analyse) *journey length effects* as a combination of base level effects on both cost and time (wherein potential cost damping would only be one element of journey length effects). Additionally, there are potentially many other sources of VTTC heterogeneity, such as income effects or simply unobservable factors, which also need to be considered.

In the study of heterogeneity in the VTTC, a vast body of research has exposed inconsistency between theory and empirical evidence, in several respects. Although many different hypotheses have been suggested to explain the empirical findings in this area, including preferences being closer to alternative behavioural theories, unobserved heterogeneity or heteroscedasticity across individuals' responses (Ben-Akiva et al., 1987; Daly and Carrasco, 2010), the conclusion is that we are still some way from achieving full understanding. Understanding and capturing the true sources of heterogeneity of the VTTC is crucial.

1.4.2 Data collection

As in any other research field, it is essential to pay attention to how the data is collected. The artificial nature of SC experiments makes this especially important in VTTC research.

The current theory and methodology imply that it is necessary to observe individuals' choices where they trade-off travel time and travel cost. In real life travel choices, this kind of trade-offs may not exist or may not be observable. Hence, SC experiments are often employed. Furthermore, sometimes the trade-off of interest may not be isolated from other factors. For example, other factors affecting travel choices such as congestion, reliability, crowding or comfort could be disturbing the actual time-cost trade-off in which we are interested. In terms of microeconomic theory, this is similar to considering a consumption problem where external factors influence the slope of an indifference curve for two goods, making the analysis more complex. This is one of the reasons why most VTTC in European countries collect data where it is assumed that only cost and time matters for a travel choice. Therefore, it is possible to artificially disentangle the marginal rate of substitution between travel time and travel cost. Nonetheless, this simplification has been criticized (e.g. Hess et al., 2010) and more general SC experiments have been preferred in other studies. The last Dutch national study (Significance et al., 2013), for example, made greater use of more general SC experiments than previous European studies, using both an initial time-cost experiment and a second one which included travel time reliability. Acknowledging this, simple time-cost experiments have the advantage of facilitating the study of the VTTC without further disturbances (assuming respondents understand the ceteris paribus set-up). Some issues around the VTTC may also exist under more complex experiments, but are observed more easily under simple settings.

In simple cost-time experiments, individuals have to choose between a cheap but slow option and a fast but expensive one. This choice implies a "price" of travel time, i.e. a trade-off value, normally called the "boundary VTTC". Fowkes and Wardman (1988) early realised the importance of the boundary VTTC in this methodology, although it has not received much attention again until the last years. Ideally, we would like to observe, for each individual, the price of time that actually is his/her marginal rate of substitution: i.e. the price of time that makes a person indifferent between the fast and the slow options. However, an “indifference option” is never included in VTTC experiments (i.e. respondents cannot reveal they are indifferent between the two options). Perhaps the reason lies in the difficulties for modelling of including an “indifference option” (see Hess et al., 2014). Altogether, typical SC experiments allow us to observe only whether the VTTC of the individual is greater or lower than the price (the boundary VTTC) offered.

Using non-parametric modelling techniques (e.g. Fosgerau, 2006), Börjesson et al. (2012) proves empirically what Fowkes and Wardman (1988) suggested more than 20 years earlier: SC experiments should offer a very wide range of “prices of time” (boundary VTTCs) in order to capture the true VTTC of all individuals. Their work showed that earlier studies had failed to observe the right tail of the VTTC distribution: some individuals may have a very high VTTC, and therefore very high boundary VTTCs should be offered too.

Overall, very valuable progress has been made on data collection methods over the last years. However, it still seems that the artificial nature of the methods requires more attention. Recently, Fosgerau (2014) has shown that the “prices of time” selected for a SC design can crucially affect the final estimates of the VTTC under certain modelling approaches. While this may be obvious, it does not seem to have been dealt with extensively. Data collection methods will clearly benefit from further research.

1.4.3 Modelling

On top of the issues related to, first, heterogeneity of the VTTC and, secondly, to data collection methods, there are also several unresolved questions regarding models used for estimation.

The analysis of the data has mostly been carried out using discrete choice models. The standard modelling approach was, for decades, the multinomial logit model that assumes random utility with additive error terms, as proposed by McFadden (1974). In essence, it is assumed that individuals choose the travel alternative that maximises their utility. What matters for the decision is the utility difference between the alternatives, which is given by the differences in the attributes defining the alternatives (i.e. time and cost). The key assumption regarding the error term is that it is considered to have constant variance (Daly et al. 2014).

More recently, the additive error assumption has been challenged and other options are now considered. Since microeconomic theory does not specify any assumptions on the error terms (only required for econometric purposes), errors can also be entered multiplicatively (Fosgerau and Bierlaire, 2009) or in a flexible way that allows assumptions in-between both extremes (Daly and Tsang, 2009).

On the other hand, developments in econometric techniques have allowed more sophisticated models, such as mixed logit models or latent class models, to be implemented. These models allow for a better representation of the structure of the error terms and capture unobserved heterogeneity in the choices and hence the VTTC.

Finally, the simplicity of the time-cost SC experiments has facilitated another important innovation within parametric modelling: in such a simple setting, if the driver of decisions is the underlying VTTC, it is no longer necessary to assume random utility; instead, it is possible to assume random VTTC. This approach has been recently proposed in the field by Fosgerau (2006), building upon early work by Beesley (1965) and Cameron and James (1987). It has already been implemented successfully in the Danish, Swedish and Norwegian national VTTC studies, proving to explain the data better than random utility models. Nevertheless, there are only few works devoted to this alternative approach, which clearly deserves more attention. Overall, the underlying assumptions about the error terms, in various respects, are at the core of most new developments on VTTC modelling.

Outside the area of parametric modelling, a great innovation in the analysis of data has been the implementation of non-parametric techniques, following the approach suggested by Fosgerau (2006). This approach is also possible thanks to data from simple time-cost SC experiments. It consists on the observation of the share of respondents that rejected each price of time (boundary VTTC) offered in the experiment. This sort of analysis has been carried out using local constant regression (Fosgerau, 2007). The main outcome is a plot of the cumulative distribution function (CDF) of the VTTC, and the mean and other moments of the distribution can be directly obtained. Non-parametric techniques are a very useful complement to parametric models: they can be used to observe what the data is actually saying in terms of VTTC without imposing assumptions on its distribution. However, in order to account for heterogeneity in the VTTC (crucial for appraisal), and for the panel structure of the data (several responses per person), it is necessary to use parametric techniques (Börjesson and Eliasson, 2014).

It is expected to observe an increasing amount of research in relation to these “new doors” opened for the estimation of the VTTC.

1.5 Structure and objectives of the thesis

Following the introduction to the research topic provided in this chapter, the thesis consists of three main chapters (Chapters 2, 3 and 4) and the final conclusions (Chapter 5). The motivation of this work has been a personal interest on human’s valuation of time and social cost-benefit analysis together with the observation of multiple gaps in the existing knowledge on valuation of travel time.

This work is limited to personal travel. The empirical work uses data from car travellers (the vast majority of them are car drivers). Nevertheless, most of it, if not all, can be easily applied to other means of personal travel. The focus of this thesis is three-folded. Given the existing knowledge on the topic, this work is an attempt to: 1) improve our understanding on how the value of travel time changes truly vary across and within people, 2) gain insights into two popular modelling approaches through a comparative exercise, providing more empirical evidence, and 3) investigate the role of the data collection methods on the VTTC and on how it varies.

Chapter 2 investigates how the VTTC varies across people and within people. We revisit the issues of low valuation of small time changes, loss aversion and cost damping, sometimes disconnected from each other in the literature, and examine them together under the umbrella of neoclassical microeconomic theory. This constitutes a useful departure point, which allows us to develop theoretical expectations based on a standard strand of theory, on which the basis of the cost-benefit analysis framework settles. At the same time, it could allow us to discuss how insights from alternative behavioural theories may fit in. The focus is placed on four important sources of heterogeneity in the VTTC: size effects, sign effects, current trip or base level effects (in some contexts, e.g. car travel, these can be associated with journey length effects), and income effects. The core proposition of this chapter is the potential confounding among these sources of heterogeneity. Unobserved heterogeneity is not included in this work, as the analysis of the above behavioural phenomena is essential and unobserved heterogeneity in simple linear settings may in fact be confounded with the effects of interest.

In Chapter 3 we deviate provisionally our attention from VTTC heterogeneity, and analyse some underlying issues with the basic modelling of the VTTC. The simple nature of time-cost SC experiments allowed Fosgerau (2006) to implement an approach that notably departs from traditional practice and which offered good explanation of the data. In this chapter we offer details on the theoretical relationship between two approaches, namely random utility and random valuation, and provide valuable evidence on their comparison. Given that it is not only one factor what have made these approaches differ in practical applications, we disentangle the different factors to ensure fair comparisons at four levels of modelling sophistication. Additionally, this evidence is provided using two datasets from different countries (UK and Denmark), but which were collected using the same SC design. This is a unique opportunity to also observe differences across countries.

In Chapter 4 another step is taken on the path to understand the underlying set of VTTC in a population. In this occasion, through the angle of the data collection methods, i.e. the SC experiments. The empirical evidence gained through Chapter 2 an 3 directs our attention towards the role of the SC design variables: namely the travel time changes (Δt), the travel cost changes

(Δc), and their ratio (Δc/Δt) which defines the boundary VTTC. Chapter 4 investigates potential impacts of these three design variables on the estimation of the individuals' underlying set of VTTC (i.e. mean and covariates). Understanding the role of the SC design variables is important for the construction of SC experiments and for modelling. By understanding them, we would also get closer to understand the individuals' true set of VTTC. Nonetheless, this is not necessarily saying that the survey influences preferences. The idea is that, if preferences (and therefore the VTTC) are different in different settings, then by focussing the survey on specific settings, our sample level results will be affected accordingly. This is not an easy task, since we have not observed the same individuals making choices under different SC experiments. Therefore, our approach splits the data based on a given variable of interest (BVTTC, Δc or Δt) to generate sub-datasets which only contain observations for certain levels of that variable (e.g. Fosgerau, 2014), i.e. for certain settings. The estimation of the same model specification on each sub-dataset provides new insights into the roles of the SC design variables analysed. Consequently, the results will also reveal new insights on the reality of the set of VTTC. All the analysis in this chapter will be done using what is believed to be a state-of-the-art model specification, following the work conducted in Chapter 3.

Chapter 5 will provide the overall conclusions from all the work carried out for the thesis, together with policy recommendations and suggestions for further research.

Chapter 2

Four key sources of variation

2.1 Introduction

The value of travel time is a key input for the evaluation and comparison of different transport projects. Travel time savings often constitute a great part of the benefits of a project, and therefore the value assigned to them is crucial for cost-benefit analyses (see e.g. Wardman, 1998, Small, 2012). Less often, projects may also lead to travel time losses. Therefore, the economic good of interest is a travel time change. Unfortunately, the value of travel time or, more precisely, the value of travel time changes (VTTC) cannot be observed directly. The general belief is that travellers' VTTC can be inferred from travellers' choices where they trade-off a change in travel time against a change in travel cost. Consistent with traditional microeconomic theory of time (e.g. DeSerpa, 1971; Train and McFadden, 1978), the VTTC is calculated as the marginal rate of substitution between travel time and travel cost:

$$VTTC = \frac{MU_t}{MU_c} \tag{2.1}$$

Where MU_t and MU_c are the marginal utilities of travel time and travel cost respectively. Data is typically obtained from stated preference surveys (in particular stated choice (SC) surveys) and analysed using discrete choice models to estimate the VTTC.

However, it is well recognised that there is not a single value of travel time. The VTTC may vary across travellers and also for the same individual traveller. Overall, in a population one can expect to find a distribution of VTTC which depends on a number of aspects. Some crucial factors generating that distribution are: i) individual and trip characteristics such as income, purpose and distance (see e.g. Mackie et al., 2003; Daly and Carrasco, 2010), ii) non-linearities in the role of cost and time entering the utility space (Hensher, 1996), which means that the VTTC may differ depending on the magnitude and sign of the changes in time and cost considered, even for the same individual (see e.g. De Borger and Fosgerau, 2008; Stathopoulos and Hess, 2012; Hjorth and Fosgerau, 2012; Daly et al., 2014) and iii) unobserved factors (i.e. random differences) (e.g. Fosgerau et al., 2007). Against this background, a vast body of research has exposed inconsistency between theory and empirics, in a number of key respects.

Three recurrent topics in the literature on variations of the VTTC are:

a) journey length effects[2], with a focus on an apparent increase on the VTTC with journey length mainly due to a reduced sensitivity towards travel cost (this phenomenon is known as "cost damping"; see Daly, 2010). More generally, since there is also some evidence of "time damping" (e.g. Daly and Carrasco, 2010), it could be said that the increase on the VTTC is due to a more rapidly decreasing sensitivity to travel cost as opposed to travel time on longer trips. Formally, the damping phenomena can be expressed as:

$$\frac{\partial |MU_c|}{\partial Journey\ length} < 0 \tag{2.2}$$

$$\frac{\partial |MU_t|}{\partial Journey\ length} < 0 \tag{2.3}$$

If cost damping is more accentuated than time damping, then we should find that:

$$\frac{\partial |MU_c|}{\partial Journey\ length} < \frac{\partial |MU_t|}{\partial Journey\ length} < 0 \tag{2.4}$$

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[2] The concept "journey length effects" is used for ease of exposition and clarity. We acknowledge that it would be more precise to use the term "current level effects": the key assumption is that for a given person, journey length is highly correlated with the current levels of travel cost and travel time. However, the correlation between journey length and current levels of time and cost is not perfect. Keeping this in mind, we believe that the messages of this chapter will be transmitted in a clearer way if the term "journey length effects" is employed.

b) size effects, with a focus on an apparent low valuation of small travel time changes (normally changes of up to 5-10 minutes) (see Welch and Williams, 1997). Formally, this finding can be generalised as an increase in the VTTC with the size of the time changes:

$$\frac{\partial |MU_t|}{\partial |\Delta t|} > 0 \qquad (2.5)$$

Where Δt is the change in travel time. However, there is a possibility that the equation above might only apply up to a certain threshold of travel time changes (e.g. up to Δt=11 minutes according to the last UK study, Mackie et al., 2003).

c) sign effects, by which losses in travel time (i.e. increases in travel time) are valued more than gains of the same size (i.e. willingness-to-pay measures are lower than willingness-to-accept measures; e.g. Bates and Whelan, 2001; De Borger and Fosgerau, 2008). Sign effects can apply equally to the travel cost component. Formally:

$$|MU_t|_{(\Delta t<0)} < |MU_t|_{(\Delta t>0)} \quad \text{, for a given } |\Delta t| \qquad (2.6)$$

$$|MU_c|_{(\Delta c<0)} < |MU_c|_{(\Delta c>0)} \quad \text{, for a given } |\Delta c| \qquad (2.7)$$

Where Δc is the change in travel cost.

The reader may have already noted that there could be size effects related to changes in travel cost. This phenomenon, however, has normally been overlooked in the literature (with the exception of De Borger and Fosgerau (2008) and the last Dutch national study, Significance et al., 2013). The analysis size effects on the cost component, explained later on, is one of the main contributions of this chapter.

Large scale national studies on the VTTC carried out in several countries to provide official guidance for appraisal (e.g. UK, The Netherlands or Denmark) have identified the need for further research on these issues (see Mackie et al., 2003; Fosgerau et al., 2007). All topics are directly linked to two of the crucial factors concerning the VTTC distributions noted above, namely i) trip characteristics and ii) non-linear utility impact of attributes. Noting that topic a) is typically considered independently from topics b) and c) in the literature and topic c) is usually linked to alternative behavioural theories, this chapter reviews and relates them within the framework of traditional microeconomic theory. Income effects constitute the fourth source of variation considered. A general picture of the VTTC and its distributions is developed and tested using the data collected to provide official guidance on the VTTC in the UK.

The central proposition of this chapter is the potential confounding among the mentioned sources of variation of the VTTC. In this chapter we deal with the issues of interest in a progressive way. Income effects and sign effects are regarded as less controversial in light of the existing empirical evidence than size and journey length effects. Therefore they are simply controlled for during the analysis. A first proposition suggests a confounding between size and journey length effects, noting the consequences of omitting any of the effects. A second proposition hypothesises about the "true" journey length effects once they are isolated. The key lies in the lack of attention to the changes in travel cost (i.e. another source of size effects) and in the potential correlations among variables in the data: e.g. changes in travel cost considered by travellers are often positively correlated with journey length (to achieve realism in SP experiments, larger Δt and Δc are normally offered to people who report higher base cost and base time, associated with longer journeys). This would lead to potential confounding if either the *change in travel cost* or a measure of journey length (e.g. current cost) is omitted as a source of VTTC variation. An additional contribution of the chapter is the re-analysis of sign effects in the preamble, which provides strong evidence that supports the existence of sign effects (e.g. Gunn and Burge, 2001; De Borger and Fosgerau, 2008) as opposed to some works which earlier denied them (e.g. Mackie et al., 2003).

2.2 Theoretical exposition

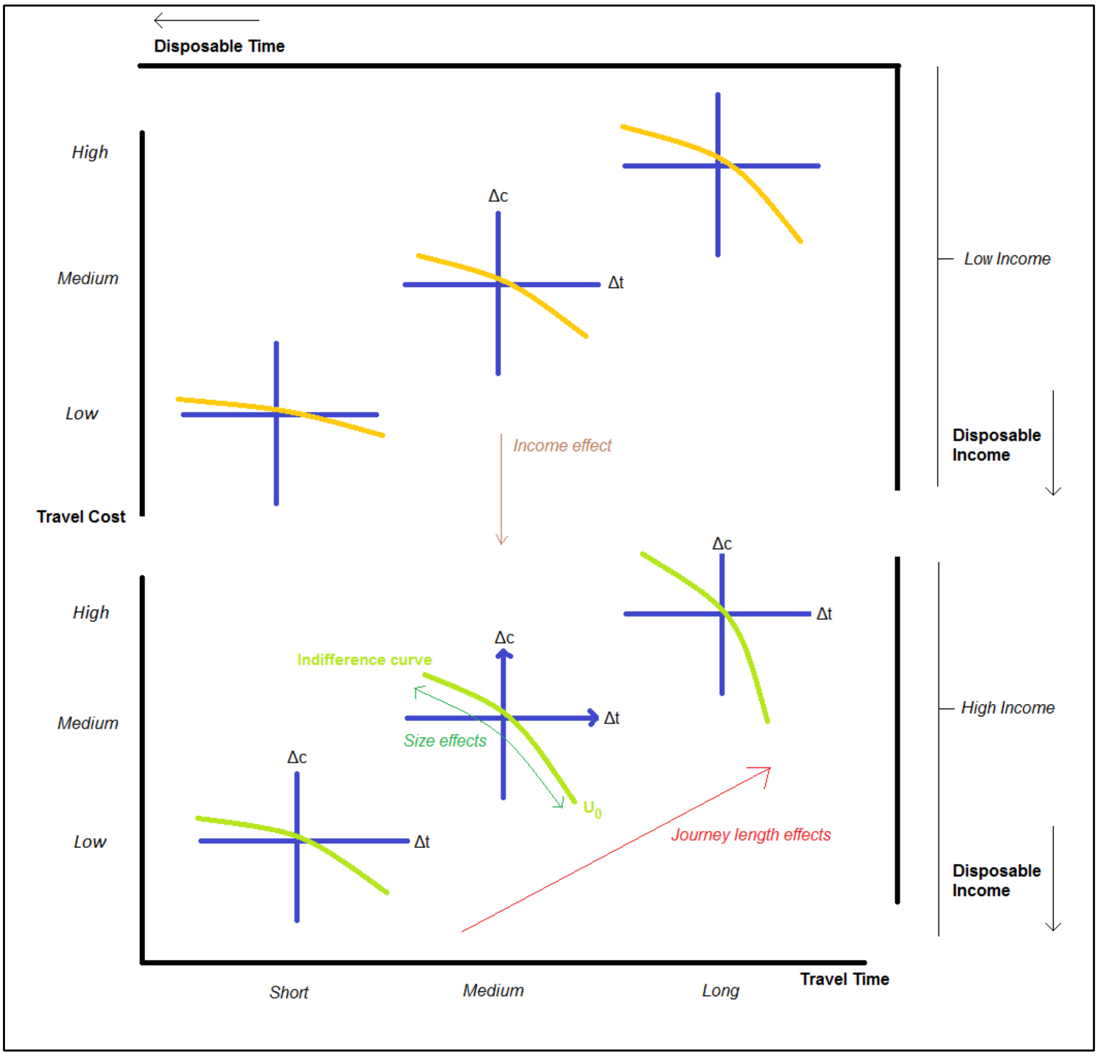
The VTTC is defined as the marginal rate of substitution between travel time and travel cost. Although the two main topics of interest, *size effects* and *journey length effects*, can both refer to travel time and travel cost, they are often approached separately (Daly et al., 2013 acknowledge their close relationship). The reason is that the focus has been placed on some particular interesting findings: cost damping and small time changes. Placing our attention on the broader concepts of "*size effects*" and "*journey length effects*" will help us to better understand the link between both topics. These effects are two of the four key observed sources of variation studied in this chapter, alongside with *sign effects* and *income* effects. Therefore, we are working under the assumption of an absence of additional observed and unobserved heterogeneity. The framework could easily be extended to capture this but that at this stage the consideration of these four behavioural phenomena is crucial and unexplained heterogeneity in simple linear settings may in fact be confounded with these effects.

Regarding our four phenomena, there is a lack of clarity in the existing literature and this chapter aims at filling the gap, organizing terms and concepts and providing a full picture of how the VTTC could vary along these key dimensions. The focus of this work is on car trips, although the analysis is sufficiently general to accommodate different types of travel contexts.

Figure 2 contains the essence of our research, summarising the theoretical exposition in a graph and leading to the key propositions that will be tested empirically. The graph is a representation of how the VTTC (which is measured by the slope of the individuals' indifference curves), according to our interpretation of standard microeconomic theory, may vary with the variables of main interest: *size* and *sign* of the changes, *journey length* and *income*. The idea is to look at these concepts through the eyes of the diagram, which may be regarded as a new spin on established ideas.

Among the four sources of variation of the VTTC, income is barely mentioned in the analysis: it is undoubtedly the least controversial one. Hence, note first of all that there are two almost "identical" graphs merged in this figure, the bottom half for individuals with high income and the top half for individuals with low income. Across those two halves, it can be observed how the VTTC increases with the level of income, all other things being equal (steeper slopes); within each half, both *journey length effects* and *size effects* (at the core of the research) can be studied in a way that is disentangled from *income effects*.

Figure 2. VTTC: General picture



The bottom horizontal axis represents the travel time of a trip. Three types of car trips are considered: short, medium and long trips. Analogously, the left vertical axis indicates the travel cost of a trip[3]. In the car travel context, the relationship between time and cost is usually positive. Therefore, short (long) journeys are associated with both low (high) travel time and cost. Opposite to these two axes we observe *disposable time* and *disposable income.* In the top horizontal axis, disposable time increases from right to left, being at its maximum (e.g. 24 hours if one day is considered) when travel time is zero. Note that the magnitude of this axis is fixed and identical for all individuals. In

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[3] Note that the axes do not have any specific scale. Therefore the graph only indicates the direction of the relationship between the VTTC and the values in the axes, but not the degree of linearity/non-linearity of the relationship.

the right vertical axis, disposable income increases from top to bottom, being at its maximum when travel cost is zero. Herein, the magnitude of this vertical axis varies across individuals (i.e. money budget differs across people). Note that individuals with low income are closer to the level of "zero disposable income" (i.e. the right top corner of the graph) for any given amount of travel cost.

2.2.1 Intra-individual sources of VTTC variation

Size and sign effects can occur at the intra-individual level: i.e. the same person may have different VTTC depending on the size and sign of the changes in time and cost. On the dimensions defined above, individual indifference maps are drawn for three different allocations of travel cost and travel time, repeatedly for the two levels of income considered. In other words, we assume that we are observing six individuals (or six classes of individuals), differentiated by their income level and the duration of their car journey. For each of the six individuals considered, the indifference map is explained as follows. According to first principles in microeconomic theory (Utility Theory), the concave downward-slopping indifference curves are expected. It is important to note that travel time and travel cost are both "bads" and not "goods". If the graph is turned 180º, the classical map of convex indifference curves of the income-leisure trade-off would be observed. The horizontal axis of each indifference map represents changes in travel time (Δt), and the vertical axis shows changes in travel cost (Δc). The origin, the point where both axes intersect, can be regarded as a "reference point" (the current trip of the individual), from which changes in the travel time and cost are evaluated. Each indifference curve represents a level of an individual's utility: all points along each curve are combinations of changes in cost and changes in time among which the individual is indifferent. The assumption of diminishing marginal utility of normal goods applies throughout the whole curve and gives rise to both size and sign effects. For clarity reasons, only one level of utility (U_0) has been displayed for each person. Additional curves towards the left (right) would represent higher (lower) levels of utility.

2.2.1.1 Sign effects

Diminishing marginal utility implies that, at a given point of the indifference curve, a loss (i.e. an increase) in travel time will be valued at a higher rate than a gain (i.e. a decrease) of the same size. Diminishing marginal utility applied to both time and cost domains implies, therefore, the relationship established by equations 2.6 and 2.7 of section 2.1.

Therefore, if the given point is the current trip (i.e. the origin of the graph), it is expected to find that the VTTC differs with the sign of changes in the following way: in a willingness-to-pay context (WTP; upper left quadrant), the VTTC is lower than in a willingness-to-accept situation (WTA; lower right quadrant) based on standard microeconomic theory (De Borger and Fosgerau, 2008):

$$WTP = \frac{|MU_t|_{(\Delta t<0)}}{|MU_c|_{(\Delta c>0)}} < WTA = \frac{|MU_t|_{(\Delta t>0)}}{|MU_c|_{(\Delta c<0)}} \qquad (2.9)$$

This is in line with most empirical evidence, as reported in the introduction. Nevertheless, it has been argued that the WTP-WTA gap has been found to be too large to be supported by standard microeconomic theory (Horowitz and McConell, 2003) and consequently justified using alternative behavioural theories such as Prospect Theory (Tversky and Kahneman, 1991). Other works have debated whether sign effects are confounded empirically with "inertia effects", i.e. a systematic preference to avoid changes from a reference point (Mackie et al., 2003; Gunn and Burge, 2001).

2.2.1.2 Size effects on the time attribute

Diminishing marginal utility also implies a changing slope within each quadrant. Moving from the origin of the indifference map towards the upper left quadrant (WTP), subsequent decreases in travel time are expected to be associated with (diminishing) increases in travel cost, as the time budget constraint becomes less binding. Similarly, moving to the bottom right quadrant (WTA), subsequent increases in travel time should be associated with (increasing) reductions in travel cost, as the time budget constraint binds tighter (see Mackie et al., 2003, p.15).

In terms of the VTTC, this shape of the curves implies that small travel time savings should be valued at a higher unit value than larger savings, while small travel time increases should be valued at a lower unit value than greater increases. Overall, for each individual the VTTC increases from left to right along the whole curve. Formally, based on standard microeconomic theory we would expect:

$$\frac{\partial |MU_t|}{\partial |\Delta t|} > 0 \quad ; \text{for } \Delta t > 0 \tag{2.10}$$

$$\frac{\partial |MU_t|}{\partial |\Delta t|} < 0 \quad ; \text{for } \Delta t < 0 \tag{2.11}$$

2.2.1.3 Size effects on the cost attribute

So far, it has been assumed that time is *valued* in monetary units of travel cost. The monetary value of the travel time changes is the object of interest. Nevertheless, people may not only consider changes in travel time but also changes in travel cost as they have sensitivities (i.e. feel disutility) towards both travel time and travel cost. Hence, the so-called size effects may also apply to the cost attribute. Nonetheless, out of all national VTTC studies reviewed, only the last Dutch study (Significance et al., 2013) explored this possibility. The interpretation of the size effects on cost would be analogous to that provided for the time attribute above. Due to the budget effects explained above, we would expect the VTTC to decrease for greater increases in cost (to the left) and to increase for greater decreases in cost (to the right). Formally:

$$\frac{\partial |MU_c|}{\partial |\Delta c|} > 0 \quad ; \text{for } \Delta c > 0 \tag{2.12}$$

$$\frac{\partial |MU_c|}{\partial |\Delta c|} < 0 \quad ; \text{for } \Delta c < 0 \tag{2.13}$$

Alternatively, because travel time changes are the object of interest, one could make the assumption that travel cost is simply seen as a way of valuing the object of interest and has no intrinsic effect on individuals' perceptions[4]. In that manner, the variation of the VTTC with the size of changes could be based only on how individuals perceive each change in travel time. In general, observing variation with the size of cost changes increases the complexity of the study of size effects: there would be an interaction of non-linear utility impacts from the time and cost dimensions respectively which could be conflicting. However, it seems appropriate to test empirically all possible size effects (e.g. De Borger and Fosgerau, 2008).

2.2.1.4 Size effects based on alternative behavioural theories

It is worth mentioning that there are alternatives to the standard microeconomic theory postulated above. Prospect Theory (Tversky and Kahneman, 1991), provides a different theoretical view on size effects. Essentially, in relation to the VTTC, it is hypothesised that both time and cost sensitivities decrease for greater changes in time and cost respectively, and irrespectively of sign (i.e. S-shaped value functions):

$$\frac{\partial |MU_t|}{\partial |\Delta t|} < 0 \quad \text{; for all } \Delta t \qquad (2.14)$$

$$\frac{\partial |MU_c|}{\partial |\Delta c|} < 0 \quad \text{; for all } \Delta c \qquad (2.15)$$

This is strongly supported by a number of empirical studies (e.g. Hjorth and Fosgerau, 2012; and Stathopoulos and Hess, 2012) which also point towards the S-Shaped curves depicted in figure 3 below, where the VTTC increases with the size of time changes, i.e. suggesting that the diminishing effect on cost sensitivities is stronger than the diminishing effect on time sensitivities. Our framework could accommodate this by changing the curvature of the indifference curves, allowing them to be in line with S-shaped value functions from Prospect theory rather than convex throughout the whole

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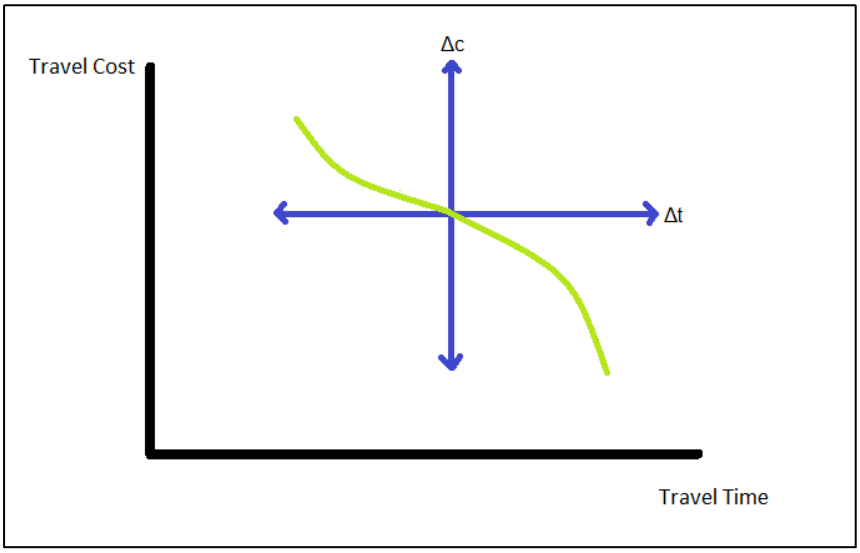
[4] In another analyses of individuals' preferences, Tversky and Kahneman (1991) make a similar assumption to avoid dealing with individuals' perception of two dimensions instead of one.

(Δt, Δc) spectrum. Note that sign effects still apply, although specifically related to the reference point (i.e. the current trip conditions).

Figure 3. Indifference curves based on Prospect Theory



2.2.2 Inter-individual sources of VTTC variation

In this section journey length effects are explored. Income effects are also a source of VTTC variation at the inter-individual level (i.e. varying across individuals) and therefore belong here, but they are less controversial and were already introduced at the beginning of section 2.2 for ease of exposition.

2.2.2.1 Journey length effects

Journey length effects occur, at least at a given point in time, at the inter-individual level. Hence, in relation to figure 2, the focus is now placed on the relationship among the three individuals within a given income range. This source of VTTC variation can be seen by looking at the change in the VTTC (slope) following the arrow labelled as "journey length effects". The three individuals considered, bearing a *low*, *medium* and *high* travel time and travel cost respectively, are assumed to have a different VTTC based precisely on the time and cost levels of their current journey. It is not clear whether microeconomic theory informs the direction of this variation (Daly, 2010), although some researchers argue that it is explained by *budget effects*. According to this argument, time and cost sensitivities should increase as their respective budget constraints bind tighter (i.e. as journey length increases). Formally:

$$\frac{\partial|MU_c|}{\partial C} > 0 \quad ; \quad \frac{\partial|MU_t|}{\partial T} > 0 \qquad (2.16)$$

Where C and T are the current levels of travel cost and travel time respectively.

In addition, because the time budget constraint is "fixed", equal for everyone and cannot be transferred between periods, time sensitivity should increase relatively faster than cost sensitivity (e.g. Mackie et al., 2003). Under this argument, the VTTC would increase with journey length. If the VTTC increases with journey length, the slope of the curves gets steeper for individuals facing a longer journey. This argument is at the core of our second testable proposition.

2.2.2.2 Journey length effects based on alternative behavioural theories

Alternative behavioural theories would suggest *relative effects* as another possibility for this VTTC variation. According to relative effects, time and cost sensitivities should decrease as the current levels of time and cost increase:

$$\frac{\partial|MU_c|}{\partial C} < 0 \quad ; \quad \frac{\partial|MU_t|}{\partial T} < 0 \qquad (2.17)$$

This would reflect that a given change in time or cost (e.g. 10 minutes or 100 pence) is less important the greater the travel time and travel cost the person is already incurring. If the sensitivity towards time decreases less rapidly than the cost sensitivity (again, because time is fixed and cannot be transferred between periods), the VTTC would still increase with journey length. The existing empirical evidence (e.g. Daly, 2010) seems to point towards "relative effects" as opposed to "budget effects".

2.2.3 Confounding between size effects and journey length effects

The theoretical difference between journey length and size effects may seem clear so far. Nonetheless, it is possible to confound them, especially in practical applications. According to the definition of cost damping (and time damping), the analysis of each single individual's indifference map does not allow us to infer any conclusions in relation to such phenomena (or, more generally, journey length effects) at a given point in time: it only allows us to analyse size effects. This is perhaps one of the main confusions that are causing controversies in analysing some of the key variations of the VTTC in several studies.

Mackie et al. (2003, p.27), for the official study on VTTC in the UK, approach the issue of cost damping looking at a single map of individual's indifference curves. There are several reasons not to do this. First, the VTTC for each individual is known (and inferred in standard empirical works) only at a given point in time: each person values a given travel time change given his current travel conditions. The variation of the current time and cost of a journey is something that does not happen at a given point in time for a given person. It has been shown (figure 2) how this effect, defined as journey length effect, should not be studied within a single map, but across maps for several individuals. The two arrows with the labels "size effects" and "journey length effects" summarise this argument. Secondly, looking at cost damping within a single standard indifference map may lead the researcher to forget that there may be size effects on the cost attribute as well, which seems to have been the case in the official VTTC study in the UK (and most European studies).

The key for potential confounding lies in the lack of attention to the changes in travel cost and in the potential correlations among variables in typical data. It is known that the changes in travel cost considered by travellers are often correlated with their current cost: in a realistic context of changes in travelling conditions, passengers facing a low cost are more likely to consider small cost changes while those facing higher costs would consider bigger changes, a factor often recognised in the construction of stated preference (SP) designs. Similarly, passengers reporting a short trip are more likely to receive shorter time changes in the survey to increase realism. These correlations lead to potential confounding if one variable (being correlated with another) is omitted as a source of VTTC variation.

2.2.4 Two testable propositions

From our theoretical exposition, two propositions arise:

Proposition 1: Journey length effects can easily be confounded with size effects. Failure to account for size effects on the cost attribute (if they exist) may bias the estimation of journey length effects. Additionally, their omission may also affect the estimation of any other correlated factors, such as size effects on the time attribute, sign effects or income effects.

First, it is postulated that both size and journey length effects should be accounted for simultaneously to avoid confounding which could cause bias in the model estimates. Once they are disentangled, the second proposition focuses on our expectations regarding the direction of the journey length effects:

Proposition 2: Regarding journey length effects, the VTTC should be higher the higher the travel time and cost that an individual is already bearing. The effect should be caused by an increase in the marginal disutility towards travel cost accompanied by a relatively larger increase in the marginal disutility towards travel time[5]*. This, however, is not a requirement imposed by traditional microeconomic theory based on an individual's indifference map.*

These propositions are tested empirically in the next section.

2.3 Empirical work

2.3.1 Dataset

The dataset employed to test our theoretical propositions was collected in 1994 by Accent and Hague Consulting Group (AHCG, 1996). It was collected using a stated choice (SC) experiment specifically constructed to isolate how individuals trade off travel time and travel cost in the context of car travel. This SC experiment is typically used in most European VTTC studies to estimate the

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[5] Note that this is contrary to what the majority of empirical works (e.g. Daly and Carrasco, 2010; Statophoulos and Hess, 2012) find. This paper is precisely trying to increase our understanding of such findings.

VTTC, but more complex experiments have been used elsewhere. The simplicity of the experiment helps us to address the issues of interest. Each questionnaire is composed of eight hypothetical choice scenarios, where travellers were asked to choose their preferred travel alternative out of two options. This was a forced choice, with no option not to travel. The following table is an example of a choice scenario:

Table 1. Example of a Stated Choice scenario

	Please choose your preferred travel option:	
Attribute	*Option A*	*Option B*
Time	As now	10 minutes shorter than now
Cost	As now	50 pence higher than now

The two (*i*) alternatives were defined in terms of changes in travel time (Δt) and changes in travel cost (Δc) relative to their reported current journey [i.e. current time (T) and current cost (C)], where $\Delta t = t_i - T$ and $\Delta c = c_i - C$. With this basic setup, the SC design of the experiment has some interesting properties. Under each stated choice scenario, one of each Δt and Δc are set to zero (i.e. time and cost are "as now" in one of the options), so travellers are always comparing a given change in time (Δt) against a given change in cost (Δc). However, this does not mean that one option is always the current option (e.g. table 1). Such situation only occurs in two of the four different "types" of choice scenarios used (1 and 4 from the list below). Those four types, based on the four quadrants of an indifference curves map with a reference point, are defined as follows:

1) $\Delta t < 0$, $\Delta c > 0$ (*current journey* vs. faster but more expensive option; willingness to pay or WTP)

2) $\Delta t < 0$, $\Delta c < 0$ (faster option vs. cheaper option; equivalent gain or EG)

3) $\Delta t > 0$, $\Delta c > 0$ (slower option vs more expensive option; equivalent loss or EL)

4) $\Delta t > 0$, $\Delta c < 0$ (*current journey* vs. slower but cheaper option; willingness to accept or WTA)

Each trade-off contains an implicit “boundary value of travel time change” (BVTTC), defined as the ratio $\Delta c/\Delta t$, around which individuals will position themselves at the moment of choice: i.e. their choice will reveal whether their VTTC is lower or higher than the implied BVTTC of each scenario. The design includes eight different BVTTC (pence/minute), derived from the different combinations of $(\Delta t,\Delta c)$: 1, 2, 3.5, 5, 7, 10, 15, 25. Those were considered to cover a realistic and sufficient range of VTTC at the time of the study, although recent studies (e.g. Fosgerau, 2006) have suggested that a much larger range of BVTTC is required to identify the true mean VTTC over a sample of choices.

The dataset employed for this chapter contains 4,737 observations of individuals’ choices (from 695 respondents)[6]. All are travellers commuting by car (the vast majority of them, drivers). In addition to completing the SC tasks, respondents were asked for details of their reported current journey and socio-economic characteristics (these included income but, surprisingly, did not include distance). The data was first analysed by AHCG to explore the VTTC in the UK. Their work paid special attention to size and sign of travel time changes for valuation, as well as the role of numerous factors related to the traveller and the journey (AHCG, 1996). A few years later, the Institute for Transport Studies (ITS) at the University of Leeds undertook a review and re-analysis of the data, commissioned by the Department for Transport after it experienced difficulties in implementing AHCG’s recommendations (Mackie et al., 2003, p.3). The work by ITS (e.g. Bates and Whelan, 2001; Mackie et al, 2003), using a much simpler and pragmatic model, led to the establishment of the current VTTC values officially employed in the UK (Department for Transport, 2013). Using this dataset constitutes a great opportunity to test the theoretical issues of interest in a context of high practical relevance.

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[6] Numerous observations were removed following certain reasonable conditions suggested by both AHCG (1996) and Bates and Whelan (2001), although it is questionable that “incomplete individuals” were kept.

In relation to our theoretical propositions, the following correlations are observed among the key variables at the core of the different (*size* and *journey length*) effects: |Δc| is positively correlated with current cost (correlation coefficient of 0.24) and with |Δt| (0.35); |Δt| is positively correlated with current time (0.34); and current time and current cost are highly correlated (0.82) as would be expected for car travel. Although the correlations on some of these pairs of variables (below 0.4) may be regarded as low, they still reflect certain relationships between variables.

2.3.2 The reference model

In what follows, discrete choice models (more specifically, Multinomial Logit, MNL, models) are employed to estimate the VTTC of the sampled individuals. More complex models (e.g. mixed MNL) with the ability to incorporate random taste heterogeneity have not yet been explored for the reasons exposed in the previous section. Their application in the context of this chapter remains an important area for future developments[7]. Models are formulated in terms of *utility*. For each traveller and journey, *utility* is defined for each of the *i* travel alternatives considered.

For practical reasons and policy relevance however, it is interesting to test our theoretical discussion in relation to the empirical work from which the current official VTTC in the UK were estimated. The utility function of the UK discrete choice model (Mackie et al., 2003) can be derived from standard microeconomic theory. The UK model combines considerations regarding size effects on the time attribute, cost damping, income effects and inertia effects, but does not include size effects on the cost domain, time damping and sign effects. However, the way this model introduces size effects is restrictive and does not allow us to fully test the theory highlighted above. It also contains

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[7] The following chapters of the thesis will incorporate random heterogeneity in the analysis.

unnecessary complications. A generalized version of the UK model accounting also for sign effects, reproduced in equation (2.18) below, is employed[8]:

$$U_i = \left[\beta_{\Delta c_{loss}} * (|\Delta c| > 0) + \beta_{\Delta c_{gain}} * (|\Delta c| < 0)\right] \left(\frac{y}{y_0}\right)^{\eta_y} \left(\frac{C}{C_0}\right)^{\eta_c} (\Delta c_i) +$$

$$\left[\beta_{\Delta t_{loss}} \left(\frac{|\Delta t|}{|\Delta t|_0}\right)^{\eta_{\Delta t_{loss}}} * (|\Delta t| > 0) + \beta_{\Delta t_{gain}} \left(\frac{|\Delta t|}{|\Delta t|_0}\right)^{\eta_{\Delta t_{gain}}} * (|\Delta t| < 0)\right] (\Delta t_i) + \beta_{Ine} * Ine_i \tag{2.18}$$

Where:

U_i is the utility for travel option $i = 1,2$

$\Delta c_i = c_i - C$ is the change in travel cost for options *i=1,2*

c_i is travel cost for travel option $i = 1,2$

C is travel cost for the current (reported) travel option

c_0 is a ‘reference’ current travel cost

$|\Delta c| = \left|\sum_{i=1,2} \Delta c_i\right|$ is the absolute change in travel cost offered in the choice scenario

$\Delta t_i = t_i - T$ is the change in travel time for options *i=1,2*

t_i is travel time for travel option $i = 1,2$

T is travel time for the current (reported) travel option

$|\Delta t| = \left|\sum_{i=1,2} \Delta t_i\right|$ is the absolute change in travel time offered in the choice scenario

$|\Delta t|_0$ is a ‘reference’ absolute change in travel time

y is income

y_0 is a ‘reference’ income

Ine_i is a dummy variable for inertia, equal to 1 when alternative i coincides with the current travel option (i.e. when both (Δc) and (Δt) are equal to zero).

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[8] This model works in differences in attributes but is formally equivalent to a model with linear in attributes effects (due to the simplified nature of the SC experiment).

$(|\Delta t| \lesseqgtr 0)$ and $(|\Delta c| \lesseqgtr 0)$ are dummy variables expressed as conditions, equal to 1 if the condition is satisfied.

$\beta_{\Delta c_{loss}}, \beta_{\Delta c_{gain}}, \eta_y, \eta_c, \beta_{\Delta t_{loss}}, \beta_{\Delta t_{gain}}, \eta_{\Delta t\_loss}, \eta_{\Delta t\_gain}, \beta_{Ine}$ are parameters to be estimated.

This specification constitutes an interesting starting point. The mean VTTC (pence/minute) can be calculated as follows:

$$VTTC = \frac{\partial U_i}{\partial \Delta t_i} \Big/ \frac{\partial U_i}{\partial \Delta c_i} \tag{2.19}$$

With:

$$MU_c = \frac{\partial U_i}{\partial \Delta c_i} = \left[\beta_{\Delta c_{loss}} * (|\Delta c| > 0) + \beta_{\Delta c_{gain}} * (|\Delta c| < 0)\right] \left(\frac{y}{y_0}\right)^{\eta_y} \left(\frac{c}{c_0}\right)^{\eta_c} \tag{2.20}$$

$$MU_t = \frac{\partial U_i}{\partial \Delta t_i} = \left[\beta_{\Delta t_{loss}} \left(\frac{|\Delta t|}{|\Delta t|_0}\right)^{\eta_{\Delta t_{loss}}} * (|\Delta t| > 0) + \beta_{\Delta t_{gain}} \left(\frac{|\Delta t|}{|\Delta t|_0}\right)^{\eta_{\Delta t_{gain}}} * (|\Delta t| < 0)\right] \tag{2.21}$$

It is important to note that with the term 'reference' level we refer to an arbitrary level of the variable (e.g. the sample average, or a selected convenient value), used simply to stabilize the estimation process and which has no effect on the results. The values used on the last UK study have also been used here for cost and income (c_0=100 pence, y_0=35 thousands£/year). For $|\Delta t_0|$, present in a different way in the UK original model, 11 minutes was used (since this was their selected threshold to define small time changes in their model; Mackie et al., 2003).

Since the marginal utilities of time and cost depend on the sign of the attribute, it is possible to derive a VTTC for each quadrant of the indifference map. However, it is also possible to calculate an average VTTC using an average of coefficients for losses and gains (De Borger and Fosgerau, 2008, apply a similar approach):

$$\beta_{\Delta c} = \frac{\beta_{\Delta c_{loss}} + \beta_{\Delta c_{gain}}}{2}; \ \beta_{\Delta t} = \frac{\beta_{\Delta t_{loss}} + \beta_{\Delta t_{gain}}}{2} \tag{2.22}$$

Hence, at the reference values c_0, y_0 and $|\Delta t_0|$ the VTTC is equal to $\beta_{\Delta t} / \beta_{\Delta c}$. All parameters $\beta_{\Delta t\_loss}$, $\beta_{\Delta t\_gain}$, $\beta_{\Delta c\_loss}$ and $\beta_{\Delta c\_gain}$ are expected to be negative, reflecting the negative impact of additional time and cost for travelling. If losses weigh more heavily than gains, it is expected to find $|\beta_{\Delta c\_loss}| > |\beta_{\Delta c\_gain}|$ and $|\beta_{\Delta t\_loss}| > |\beta_{\Delta t\_gain}|$. On top of this, the model accounts for income effects (η_y), size effects on the time attribute ($\eta_{\Delta t\_loss}$ and $\eta_{\Delta t\_gain}$), journey length effects on the cost attribute (through current cost; η_c) and inertia (which accounts for the possibility that people might have a systematic preference to stay with their current travel conditions).

Let us now explain how each effect can be picked up through this model. All effects (except inertia) are captured adding covariates with a *power specification*. To study the presence of cost damping, the covariate current cost is added with the power term η_c. This allows the marginal utility of cost to vary with the level of current cost (c). Mackie et al. (2003) interpret η_c as “distance elasticity”, although it should be noted again that distance was not actually collected in their survey and other effects may well be at play. If $\eta_c > 0$ then $\partial|MU_c|/\partial C > 0$ (in line with the *budget effect,* i.e. a given change in cost is more “painful” the higher the current cost is). On the other hand, $\eta_c < 0$ would imply $\partial|MU_c|/\partial C < 0$ (i.e. cost damping). Now, since the marginal disutility of travel time is not varying with journey length in this model, $\eta_c > 0$ ($\eta_c < 0$) would imply that the VTTC decreases (increases) with journey length.

Regarding size effects, the power terms $\eta_{\Delta t\_loss}$ and $\eta_{\Delta t\_gain}$ capture variations in the time sensitivity with the size of the travel time change offered in each scenario. Note that the theoretical expectation of a convex indifference curve (Figure 2) could not be inferred using the original UK model (Mackie et al., 2003), which directly attempted to estimate size effects according to an S-shaped curvature (Figure 3) in line with behavioural theories[9] (and only within the range $0 < |\Delta t| < 11$). Our generalised “UK model” allows for different curvatures for gains and losses in travel time. Both parameters work in the same way. In both cases, if $\eta_{\Delta t} < 0$, then $\partial|MU_t|/\partial|\Delta t| < 0$. For values of $\eta_{\Delta t} > 0$, then $\partial|MU_t|/\partial|\Delta t| > 0$ (i.e. low value of small changes). Based on standard microeconomic theory, we would expect $\eta_{\Delta t\_loss} \geq 0$ and $\eta_{\Delta t\_gain} \leq 0$.

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[9] A symmetric shape would always be obtained since they used the same power term for gains and losses in Δt: i.e. same curvature in both sides from the origin.

The results of the generalised UK model are shown in Table 2 (along with estimates from the other models to be explained subsequently).

Table 2. Summary of parameter estimates and goodness of fit

Parameter	**Generalised "UK model"**		**M1**		**M2**	
	Est.	*t-test*	Est.	*t-test*	Est.	*t-test*
Inertia	0.775	8.44	0.704	1.24	0.161	0.36
$\beta_{\Delta t\_gain}$	-0.0914	-9.99	-0.295	-4.32	-0.261	-4.6
$\beta_{\Delta t\_loss}$	-0.0967	-9.73	-0.302	-3.93	-0.313	-4.33
$\beta_{\Delta c\_gain}$	-0.0217	-12.38	-0.0651	-4.47	-0.0593	-4.89
$\beta_{\Delta c\_loss}$	-0.0304	-11.94	-0.0735	-4.28	-0.0802	-4.97
η_c	-0.399	-8.24	-0.0874	-3.23	-0.151	-3.72
η_y	-0.381	-7.43	-0.17	-4.64	-0.18	-4.95
$\eta_{\Delta t\_gain}$	0.352	2.89	-0.597	-6.11	-0.486	-3.85
$\eta_{\Delta t\_loss}$	0.651	3.79	-0.533	-3.76	-0.511	-3.73
$\eta_{\Delta c\_gain}$			-0.730	-10.77	-0.694	-9.56
$\eta_{\Delta c\_loss}$			-0.694	-9.01	-0.697	-9.8
η_t					-0.131	-2.96
Null Log-Likelihood	-3283.44		-3283.44		-3283.4	
Final Log-Likelihood	-2681.5		-2625.78		-2615.66	
Parameters	9		11		12	
Adjusted ρ^2	0.181		0.197		0.2	
VTTC (pence/minute) [10]	4.42		4.33		4.43	

Results from the generalised *"UK model"* are very close to the original recommended UK model in most respects[11]. Mackie et al. (2003) reported a

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[10] Average across individuals in the sample, taking into account their income and current trip characteristics, for values of $|\Delta t|=11$ (the threshold level of interest in the official UK study) and, where relevant, $|\Delta c|=50$ (the average cost change in the sample). The average of $\beta_{\Delta t\_gain}$ and $\beta_{\Delta t\_loss}$ is used for the time coefficient, and the average of $\beta_{\Delta c\_gain}$ and $\beta_{\Delta c\_loss}$ for the cost coefficient.

"distance elasticity" (η_c) of -0.409 (i.e. cost damping), which is of a considerable magnitude (-0.399 in our generalised UK model). Hence, the VTTC increases with "journey length" according to the UK model. Additionally, income elasticity (η_y) was reported to be -0.366 (-0.381 in our generalised UK model), so the VTTC increases with income. Finally, their "$\eta_{\Delta t}$" parameter (unified for gains and losses) indicated that sensitivity towards travel time changes (Δt) is lower when small travel time changes are considered; our generalised UK model finds essentially the same result, with both $\eta_{\Delta t\_loss} > 0$ and $\eta_{\Delta t\_gain} > 0$ (there are no sign differences here, since the estimates of $\eta_{\Delta t\_loss}$ and $\eta_{\Delta t\_gain}$ are not significantly different from each other). Graphically, size effects in the generalised UK model would be in line with an indifference curve as depicted in Figure 3, typical of behavioural theories. This was regarded as counter-theoretical and the recommended set of VTTC for appraisal were all based on the estimates for travel time changes over 11 minutes, without taking into account any size effects. Obviously, this was a controversial decision. While the choice of a travel time change (e.g. X minutes) is common practice for appraisal (see Daly et al., 2014), it seems to rely on the assumption that the VTTC that respondents reveal in a context of Δt=X is more adequate and reliable. If a small value for X is not chosen, this also avoids penalizing transport projects which offer small changes (in fact, most projects in reality are of this nature). A key argument is that, in the long-term, projects add up and so the changes in travel time would add up too. The models, in any case, must pick up size effects if these are present, as otherwise the sample values of Δt would play a role on the final estimates. The selection of Δt, if any, would always remain a task for policy-makers.The mean VTTC across individuals in the sample is 4.42 pence per minute under the generalised "UK model", compared to the 5.19 pence per minute that would correspond to the original UK model[12] (all for a travel time

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[11] The equation for the original current UK model (Mackie et al., 2003) and the estimated results are provided in the Appendix A.

[12] This is a comparable value, calculated in the same way using just the sample, i.e. without additional expansion or reweighting as it was done to provide official values in 2003. Obviously, reweighting is needed for appraisal, but this is out of the scope of this thesis and all values refer to the same sample.

change of 11 minutes), a sizable difference with major implications for practice. An additional model which did not introduce sign effects[13] suggest that it is the more general modelling of size effects on the time attribute that causes the difference. Therefore, the specification chosen to model size effects can actually play a role on the mean VTTC, even if this source of variation is not going to be employed in practice afterwards. An interesting remark is that losses in cost weigh more than gains, and the inertia term is now not significant as opposed to the UK report: sign effects are therefore not eliminated by inertia, as Gunn and Burge (2001) suggested. In fact, our evidence could be interpreted as a sign that inertia was only significant in the UK report because their models were not accounting properly for sign effects (i.e. their models were omitting sign effects through the cost domain). Once the model accounts for size and sign effects on both time and cost domain, the inertia effect disappears. In this sense, the true effect that seems to be reflected through people's choices is that VTTC is greater in a choice context of a WTA measure compared to a context of a WTP measure.

From the last UK VTTC study report, it is clear that Mackie et al. (2003) had already tested our *Proposition 2* in their own manner. However, this chapter postulates that credible results for *Proposition 2* are dependent on the test of *Proposition 1* (which they do not consider). Their specification, in essence equation (2.18), is missing journey length effects on the time sensitivity and size effects on the cost sensitivity. Both are critical factors required for the tests of *Propositions 1* and *2*.

2.3.3 Testing Proposition 1: Incorporating variation of VTTC with the size of cost changes

The presence of size effects on the cost attribute, something that is missing in both AHCG and ITS reports, is now investigated. To do so, variation of cost sensitivity with the size of the cost change is incorporated into the utility function of the generalised UK model (3). This is done by adding another

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[13] Additional models not shown here are available on request from the author.

interaction to the parameters $\beta_{\Delta c}$. Two power terms $\eta_{\Delta c\_loss}$ and $\eta_{\Delta c\_gain}$, are employed to capture this source of variation (e.g. Stathopoulos and Hess, 2012) in model M1:

$$U_i =$$

$$\left[\beta_{\Delta c_{loss}}\left(\frac{|\Delta c|}{|\Delta c|_0}\right)^{\eta_{\Delta c\_loss}} * (|\Delta c| > 0) + \beta_{\Delta c_{gain}}\left(\frac{|\Delta c|}{|\Delta c|_0}\right)^{\eta_{\Delta c_{gain}}} * (|\Delta c| < 0)\right]\left(\frac{y}{y_0}\right)^{\eta_y}\left(\frac{c}{C_0}\right)^{\eta_c}(\Delta c_i) +$$

$$\left[\beta_{\Delta t_{loss}}\left(\frac{|\Delta t|}{|\Delta t|_0}\right)^{\eta_{\Delta t_{loss}}} * (|\Delta t| > 0) + \beta_{\Delta t_{gain}}\left(\frac{|\Delta t|}{|\Delta t|_0}\right)^{\eta_{\Delta t_{gain}}} * (|\Delta t| < 0)\right](\Delta t_i) + \beta_{Ine} * Ine_i \qquad (2.23)$$

Where:

$|\Delta c|_0$ is a 'reference' level of the change in travel cost.

The terms $\eta_{\Delta c\_loss}$ and $\eta_{\Delta c\_gain}$ are new coefficients to be estimated. Their interpretation is analogous to that provided in equation (2.18) for $\eta_{\Delta t\_loss}$ and $\eta_{\Delta t\_gain}$. The variable $|\Delta c|_0$ is a 'reference' level of cost change.

Compared to the generalised UK model, the log-likelihood of model M1 improves by more than 50 units with only 2 extra parameters, both significant above the 99% level. Interestingly, the estimates on $\beta_{\Delta c}$ and $\beta_{\Delta t}$ reflect a greater scale (about three times higher) than the UK model estimates. This suggests that choices are now explained with greater precision (even though the t-ratios are generally lower, this can partially be caused by the introduction of the two new, and highly significant, coefficients),. The estimates of $\eta_{\Delta c\_loss}$ and $\eta_{\Delta c\_gain}$ indicate that cost sensitivity is lower the higher the $|\Delta c|$, for both gains and losses (no significant difference between gains and losses). This means that, *ceteris paribus*, VTTC increases as $|\Delta c|$ increases. Graphically, in relation to our theoretical exposition, and strictly for the relationship inferred between VTTC and Δc, for each individual these estimates would imply the indifferences curves of figure 3. However, this is *not necessarily* how the indifference curves look according to our dataset, but only a partial analysis of the size effects on one of the two dimensions, namely cost. The true indifference curves would require variations on both dimensions (time and cost) to be accounted for simultaneously (e.g. Hjorth and Fosgerau, 2012). This partial graphical analysis is however sufficient for the purposes of the present chapter.

Therefore, size effects on the cost attribute are undoubtedly present and highly significant (although they only match the theoretical expectations of a traditional indifference curve in the domain of Δc<0). This is then an ideal situation to test *Proposition 1*.

2.3.3.1 Biases in journey length, income effects and inertia effects

The key question now is whether the omission of size effects on cost biased the findings from the UK model. Let us compare the estimates of M1 with their counterparts in the generalised UK model, which will allow us to draw conclusions regarding Proposition 1. First, although *current cost* is still statistically relevant in M1 (η_c is significant), its impact is of a considerably lower magnitude than in the UK model, with an estimate of -0.087 compared to -0.399. Hence, the impact of current cost is now very small, far from official UK estimations, when size effects on the cost attribute are accounted for. This empirically proves the first part of *Proposition 1.*

Additionally, it is worth mentioning that M1 only captures cost size effects through two additional coefficients. A model which included a more complete distribution for the cost sensitivity, with 35 additional parameters (one for each level of Δc), was also estimated. Interestingly, this resulted in a non-significant interaction of cost sensitivity with current cost[14]. Hence, it is arguable that our *distance elasticity* η_c (in model M1) may still be capturing part of the *cost size effect* that the power terms $\eta_{\Delta c\_loss}$ and $\eta_{\Delta c\_gain}$ might not be able to capture on their own. In any case, journey length effects are, at least, dramatically smaller than suggested in the official study for the VTTC in the UK. Similar results are observed for the income effects, where the estimate of the income elasticity changes from -0.381 in the UK model to -0.171 in model M1. This suggests a second overestimation, now of income effects, in the UK official report.

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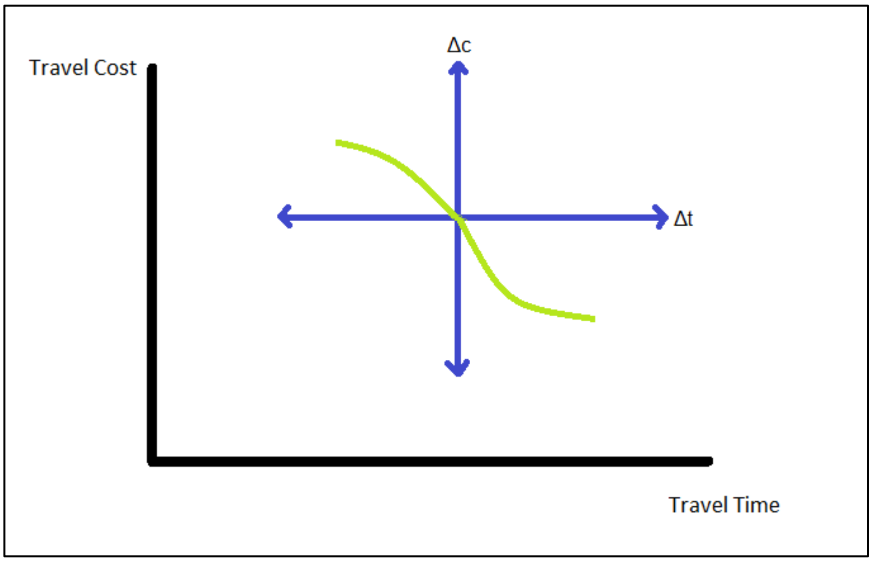
[14] This and other models that are not reported here are available from the author on request.

2.3.3.2 Biases in size effects

Regarding size effects on the time attribute, there is a dramatic change in the estimation of $\eta_{\Delta t\_loss}$ and $\eta_{\Delta t\_gain}$. The UK model gave estimates of $\eta_{\Delta t\_loss} > 0$ and $\eta_{\Delta t\_gain} > 0$, which would normally be interpreted as a proof of lower valuation of small time savings. Under model M1, both parameters take a value lower than 0. It is not possible to state anything regarding the shape of the indifference curve, since the VTTC variations with Δt and Δc indicate each a different shape for the indifference curve. However, the estimation of $\eta_{\Delta t\_loss} < 0$ and $\eta_{\Delta t\_gain} < 0$ suggests that, *ceteris paribus*, the sensitivity towards travel time decreases as $|\Delta t|$ increases (see figure 4).

Figure 4. Graphical illustration of the estimated size effects on travel time (models M1 and M2)



Graphically, it can be observed that the impact of “*Δt size effects*” on VTTC according to the UK model (figure 3) do not match our results (figure 4), but follows the same pattern that is now derived from and associated to “*Δc size effects*” (also representable by figure 3. Hence, confounding is apparent. The non-linear effect of Δc on the cost sensitivity resembles the non-linear effect of Δt on the time sensitivity. Our findings are in line with Hjorth and Fosgerau (2012), who used data from a similar design for the Danish VTTC study.

At the very least though, our estimates can be interpreted as a sign that people do not necessarily neglect small time changes: the size of the changes matter in both time and cost domains. Overall, it is likely that, in the UK model, $\eta_{\Delta t\_loss}$, $\eta_{\Delta t\_gain}$, η_c, η_y and β_{Ine} were capturing part of the omitted effect from $\eta_{\Delta c\_loss}$ and $\eta_{\Delta c\_gain}$.

2.3.4 Testing Proposition 2: Incorporating journey length effects on the sensitivity towards travel time

Testing Proposition 2 only requires the inclusion of journey length effects on the time component. The model (M2) is formulated as:

$$U_i = \left[\beta_{\Delta c_{loss}} \left(\frac{|\Delta c|}{|\Delta c|_0}\right)^{\eta_{\Delta c\_loss}} * (|\Delta c| > 0) + \beta_{\Delta c_{gain}} \left(\frac{|\Delta c|}{|\Delta c|_0}\right)^{\eta_{\Delta c_{gain}}} * (|\Delta c| < 0)\right] \left(\frac{y}{y_0}\right)^{\eta_y} \left(\frac{c}{C_0}\right)^{\eta_c} (\Delta c_i) + \left[\beta_{\Delta t_{loss}} \left(\frac{|\Delta t|}{|\Delta t|_0}\right)^{\eta_{\Delta t_{loss}}} * (|\Delta t| > 0) + \beta_{\Delta t_{gain}} \left(\frac{|\Delta t|}{|\Delta t|_0}\right)^{\eta_{\Delta t_{gain}}} * (|\Delta t| < 0)\right] \left(\frac{T}{T_0}\right)^{\eta_t} (\Delta t_i) + \beta_{Ine} * Ine_i \tag{2.24}$$

Where η_t is the new coefficient to be estimated and which interpretation is identical to that provided for η_c in equation (2.18). The power term η_t hence captures any effect of the current travel time (T) on the sensitivity towards travel time. First of all, the results are very similar for the parameters that were also part of model M1. Hence, *Proposition 1* holds also on model M2, given the significant values of -0.486 and -0.511 on the estimates of $\eta_{\Delta t\_gain}$ and $\eta_{\Delta t\_loss}$. In model M2, again the income elasticity is substantially lower than what is reported by the UK model (-0.181) and there are no inertia effects. Sign effects are slightly significant for the cost attribute, and not significant in the time domain. Size effects are symmetrical in both domains, with $\partial|MU_c|/\partial|\Delta t| < 0$ and $\partial|MU_c|/\partial|\Delta c| < 0$.

2.3.4.1 Disentangling the true journey length effects

Focusing now on *Proposition 2,* the significance of the estimate on η_t reflects the presence of journey length effects also on the time attribute. Its negative value of -0.131 indicates that individuals reporting a higher travel time on their current trip are slightly less sensitive to travel time changes. This is not what was expected theoretically according to the budget effects, but entirely in line with many empirical findings. However, the effect is very small (the estimate is close to 0). On the other hand, journey length effects on the cost attribute also remain small, just as in model M1 (now $\eta_c = -0.151$). Hence, both time and cost sensitivities are reduced for longer journeys, contrary to our theoretical expectations. These results are in line with the "relative effect", suggested in behavioural theories. According to the *relative effect*, individuals may be less affected by a given change in time (or cost) when it is relative to a larger amount.

Model M2 allows for a more consistent discussion of the overall impact of journey length on the VTTC. The results show that there is no significant difference between its impact on time and cost sensitivities (i.e. η_t and η_c). Therefore, it cannot be said that the VTTC actually changes in one way or another as journey length increases. Graphically, in relation to figure 2, this would imply that the slope of the indifference curves of the three individuals considered for a given income range might be identical. Interestingly, current cost works well as a proxy for the impact of journey length on the cost sensitivity, while current time works as the proxy of journey length on the time sensitivity. However, additional models tested (available on request from the author) show that current cost and current time would not work as proxies on the other sensitivity. Therefore, the journey length effects that have been analysed in this chapter may be better described purely as "current level effects". There is a possibility that the SC design is playing a significant role in these effects.

2.3.5 Implications for the recommended set of VTTC

Some basic estimates of the VTTC have been provided with the aim of highlighting the impact of the different model specifications. The mean VTTC values are surprisingly close across models, all around 4.4 pence per minute. However, the mean values that would correspond with the original UK model, not reported, were higher: 5.19 pence per minute. Our analysis suggest that this is due to their particular introduction of size effects on the time attribute, which has been generalised in this chapter. However, the target of this work is not to provide a different mean VTTC, which would anyway increase if random heterogeneity had been considered (chapter 3 will provide evidence on this issue). The key finding is that some questions arise in relation to the weighted VTTC distributions employed in practice in the UK. It should also be acknowledged that practical issues such as parsimony were also driving the choice of the established UK model (Mackie et al., 2003). Our suggested models M1 and M2 give different distributions - namely narrower – of the VTTC with respect to journey length (lack of variation) and income (narrower variation). These models also control for size and sign effects in a general way that allow the estimation of a mean VTTC that is not affected by them. For appraisal purposes, our findings have relevant implications. For example, transport projects for long corridors and projects benefiting people from the highest ranges of income would no longer have the argument of providing much greater benefits to society. Finally, variation of the VTTC with the size of time changes is not necessarily pointing to low valuation of small time savings. The size of cost changes also matters.

2.4 Discussion and conclusions

This chapter reflects on several critical issues around individuals' valuation of travel time changes (VTTC): *cost damping*, *valuation of small time savings, loss aversion and income effects*. These issues, some of them typically disconnected from each other in the literature, have been reviewed and related within the framework provided by microeconomic theory. To do so, we have analysed how the VTTC could vary in theory, according to a number of key sources of variation (namely income, journey length and size and sign of changes). Two theoretical propositions were presented and tested using standard methodology. The distinction and potential confounding between journey length and size effects in particular has been emphasized in light of our proposed theoretical perspective and popular empirical methods for VTTC estimation, bringing the issues of cost damping and value of small time changes together. Our perspective is suggested as an alternative way of looking at microeconomic theory in the context of VTTC, emphasizing the existence of intra-individual and inter-individual levels of variation.

The empirical work, using the dataset employed to estimate the VTTC for official guidance in the UK served to test our theoretical propositions, providing substantial results. In line with previous literature on the topic, it has not been possible to observe in practice that the VTTC varies with all the variables of interest according to our theoretical expectations. Empirical evidence and theory only matched in the case of income effects and sign effects.

Our central proposition of the danger of *confounding effects* among the key sources of VTTC variation analysed was supported empirically. Size effects on the cost attribute, usually omitted in VTTC studies, were found to be highly significant (although not fully in line with a typical convex indifference curve). Failure to account for them was proven to cause important biases in the other key sources of VTTC variation. These included journey length effects (impact of current levels of time and cost on the VTTC): the so-called cost damping phenomenon, previously claimed to be relevant on the preferences of travellers from this dataset, was shown to be less relevant with a possibility of being actually non-existent. The overall journey length effects reported in the official VTTC study were overestimated. Even if some cost damping still remains significant, time damping was also found in a very similar magnitude, resulting in a VTTC that would not vary with journey length. Further research is needed. To a lesser extent, income effects also seem to have been overestimated due to the omission of the mentioned size effects. Also, sign effects were found to be significant in the cost domain, causing WTP measures to be lower than WTA measures, in line with microeconomic theory. Interestingly, accounting for sign effects and size effects on the cost domain made “inertia effects” non-existent.

One important issue is that we have reported what can be said empirically on VTTC distributions based on pure statistical inference. However, the confounding between impacts from current levels (c, t) and impacts from design levels (Δt, Δc) is driven by correlations in the dataset, which is influenced by the SC design. The following question will remain unsolved: what would happen if everybody (regardless the levels of c and t) had been presented with the same levels of Δt and Δc? This could be addressed if different data was collected. Data where the pairs of variables (Δt,t) and (Δc,c) are not correlated is not currently available to us. That kind of data, at least for experimental purposes[15], would certainly provide further valuable insights on the reality of journey length effects.

In relation to recent work in the area, our analysis of the cost damping phenomenon might be in line with research pointing towards the potential presence of heteroskedasticity or unobserved heterogeneity across individuals' responses as its explanation (e.g. Daly and Carrasco, 2010; de Borger and Fosgerau, 2008). This could be the case if the reported omitted size effects were actually the main underlying reason to find heteroskedasticity.

Similarly, size effects on the time sensitivity were also subject to bias. Size effects were present and relevant in both time and cost domains, but partially inconsistent with microeconomic theory. However, the previous finding of low valuation of small time saving is now far from obvious. In another recent paper, Hjorth and Fosgerau (2012) postulate that size effects may be matching the expectations of alternative behavioural theories (e.g. Prospect Theory). Our findings coincide with their results, encountering that both time and cost sensitivities decrease for greater absolute changes in time and cost respectively, i.e. S-shaped perception (also in line with Stathopoulos and Hess, 2012). This results in the interaction of two similar non-linear sensitivities operating at the numerator and denominator of the VTTC respectively. Hence, drawing conclusions regarding the final distribution of VTTC with the size of time changes becomes a complex task. At the very least though, our results can be interpreted as a sign that people do not necessarily neglect small time changes: the size of the changes matter also in the cost domain, something which is often neglected in national VTTC studies. One possible reason for these findings on size effects might be the data (in concrete, the SC design). Unlike in other econometric studies, VTTC are typically inferred from SC experiments designed by researchers. Research on this topic often relies on simple SC designs based on pure "time-cost" trade-offs (e.g. Mackie et al., 2003; Börjesson and Eliasson,

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[15] This would not be recommended for studies conducted for implementation, since this proposition would weaken the realism of the choice scenarios.

2014). These trade-offs provide a boundary VTTC which serve as a threshold to observe whether individuals' VTTC is over or below it. Crucially, the boundary VTTC is defined precisely by the levels of Δt and Δc, which are the variables responsible for size effects and which levels are decided by the researcher. The role and suitability of these designs to deal with size effects are again called into question (see also Daly et al., 2014).

We conclude that the divergences between theory and empirical evidence typically found on these key issues for the VTTC can be better understood if confounding effects are kept in mind. A broad theoretical perspective that emphasizes the distinction across different sources of VTTC variation, as depicted in Figure 2, is suggested. This leads to a more complete empirical analysis able to distinguish and disentangle, to the extent allowed by the existing methodology, some of the main sources of VTTC variation. The final result would be a set of less biased estimates of VTTC distributions.

Chapter 3

Random utility versus random valuation

3.1 Introduction

The value of travel time changes (VTTC) is a key input for the evaluation and comparison of different transport projects. Travel time savings often constitute a major part of the benefits of a project, and therefore the value assigned to them is crucial for cost-benefit analyses (De Rus and Nash, 1997; Wardman, 1998). National studies are conducted in several countries to estimate an official VTTC. Unfortunately, the VTTC is a subtle concept that cannot be observed directly. The general agreement is that individual's travel choices that involve trading off between travel time and travel cost can provide researchers with an approximation to the underlying true VTTC of the decision-maker. To make things harder, the VTTC varies across individuals and travel choice contexts.

Stated Choice (SC) experiments are typically employed to collect data on travellers' choices, which are then analysed using discrete choice models to estimate the VTTC. Many SC experiments, including a majority of national studies in Europe, have used a very simple design: respondents are presented with hypothetical choice scenarios that contain two travel alternatives that differ only in terms of travel time and travel cost (i.e. a time-cost trade-off). This has been the case in the UK (Mackie et al., 2003), The Netherlands (HCG, 1998), Denmark (Fosgerau et al., 2007), Norway (Ramjerdi et al., 2010) and Sweden (Börjesson and Eliasson, 2014).

Multinomial logit models and more recently, thanks to the advances in econometrics, mixed logit models have been commonly used to estimate the VTTC (Börjesson and Eliasson, 2014). From this point, the existing literature starts to be unclear. There is a lack of clarity in the definition and classification of the main modelling approaches used on datasets of the type described above.

The first objective of this chapter is to make clear what the main modelling approaches are, avoiding confusing definitions or descriptions.

To begin with, there are parametric and non-parametric estimation techniques. Only parametric models are considered in this thesis (non-parametric techniques are useful, as they allow the estimation of the statistical distribution of the VTTC, but only as a complement). The more informative parametric models allow the VTTC to vary with covariates, which seems essential and is highly recommended (Börjesson and Eliasson, 2014). With a focus on official national VTTC studies using binary time/money trade-offs, two main parametric approaches are identified; the first (Random Utility) assumes that the random component of the model relates to the difference between the utilities of travel options, the second (Random Valuation) assumes that it relates to the difference between the actual value of travel time and the suggested valuation threshold offered. Both approaches are equivalent in a deterministic domain and can be derived from standard microeconomic theory.

The theoretical relationship between the two modelling approaches is known (Fosgerau et al., 2007; Börjesson and Eliasson, 2014; Hultkranz et al., 1996), but we are not aware of any work which formally shows its derivation fully. It is also known that the choice of approach is an empirical matter (Börjesson and Eliasson, 2014*;* Fosgerau, 2007). However, the few studies that acknowledge both approaches merely state the superiority of the approach they select. Only Hultkrantz et al. (1996) offer some comparative results in an unpublished working paper. Furthermore, the two approaches can also be identified within the series of model transformations tested by Daly and Tsang (2009), which provide additional empirical evidence.

In this chapter, the rationale of the two approaches is clarified, inspired by Cameron and James (1987)'s original exposition, crucial for the development of the Random Valuation approach. This is followed by the full derivation of the theoretical relationship between the two. The main contribution of this chapter is the empirical comparison of the two approaches at several levels of model sophistication. These levels include: i) base linear specification, ii) base logarithmic specification, iii) observed heterogeneity, and iv) random heterogeneity. This procedure ensures fairness in the comparison and allows us to disentangle the real differences between the two approaches, and among levels of sophistication, in terms of VTTC estimates and model fit.

The models are estimated on two datasets corresponding to the national VTTC studies in the UK and Denmark. Since both datasets were obtained using the same SC design, this is also a unique opportunity to observe potential differences across countries.

3.2 The "problem" of the data collection

The main problem is that the VTTC cannot be observed directly. In most markets, prices serve as indicators of consumers' valuation of the good. Here, the good analysed is *one minute of travel time*. Changes in travel time are bundles (of different sizes, e.g. 5, 10 or 20 minutes) of this good. However, there is not an obvious market for this good: only travel choice contexts between fast-and-expensive *versus* slow-and-cheap options resemble a market. The implicit time-cost tradeoff would be the "price" of the good. The VTTC is conceptualized as a measure of how much money (monetary travel cost) a person is willing to exchange for one minute of travel time.

The most popular way to collect information about the VTTC is through SC experiments. It is common, especially in Europe, to find SC experiments that simply offer individuals two travel alternatives that differ only in time and cost. This is equivalent to say that a "price" is offered to respondents at which they can buy or sell the good (time). Normally, several "prices" are offered to each individual in separated choice scenarios (often around 8 or 9). In each scenario, individuals choose whether to accept the offered price or not. Hence, they reveal whether, in that context, their VTTC is below or above the offered price. In a more general valuation context, these relatively simple SC experiments are known as "referendum surveys" or "closed-ended contingent valuation surveys" (Cameron and James, 1987). Compared to more complex SC experiments where additional attributes and/or alternatives are included, a key feature of referendum surveys is that they have directly observable threshold levels for the unobservable variable of interest (in this case the VTTC): i.e. referendum surveys mimic a market offering a price.

Most national VTTC studies use this kind of SC experiment, including the most recent UK and Danish studies.

3.2.1 A common Stated Choice design

Given the hypothetical nature of SC experiments, it is common to relate choice scenarios to respondents' previous travel experiences. In the UK and Danish national studies, respondents were recruited while travelling and information about a recent trip was collected. This trip, defined by current travel time T and current travel cost C, is used as the reference trip throughout the survey. The participants are then presented with eight choice scenarios, each with two travel options (i=1,2) varying in cost (c_i) and time (t_i) with values around the reference trip. One option is always faster but more expensive. Data can always be reordered to give an option 1 that is cheaper but slower than option 2 (i.e. $t_1>t_2$ and $c_1<c_2$). A special characteristic of the SC designs in several of these European national studies, including the most recent UK and Danish ones, is that T and C always coincide with one of the time and cost levels. Therefore, travellers are always considering a given change in time ($\Delta t_i = t_i - T$) against a given change in cost ($\Delta c_i = c_i - C$). Those changes coincide, under this setting, with the differences in time and cost between the alternatives. In short, there is always an implicit "price" which is called the boundary VTTC (BVTTC). The BVTTC is defined as:

$$BVTTC = \frac{-(c2-c1)}{(t2-t1)} = -\frac{\Delta c}{\Delta t} \qquad (3.1)$$

It should be noted that the same boundary valuations can of course also be calculated in other binary time/money trade-offs where neither of the alternatives uses the reference time or cost values.

3.2.2 Datasets in the UK and Denmark

The information presented so far constitutes the essence of the SC design, common for the most recent UK and Danish studies. The range of values employed and the presentation of the scenarios differ according to the specific circumstances of each study. At the end of the survey, once each respondent had completed the eight scenarios, information about several socio-demographics was also collected in both studies. For reasons of comparability and homogeneity, this chapter focuses on car travel for non-business (i.e. commute and other travel) purposes. Only small differences exist in these datasets between commute and other travel, and they are not relevant for the purpose of our analysis. In particular, only drivers' responses are used (i.e. no use is made of passengers' responses in this chapter).

The dataset employed in the UK was collected in 1994 by Accent and Hague Consulting Group (AHCG, 1996) using paper questionnaires. It contains 10,598 valid observations of individuals' choices from 1,565 respondents. The re-analysis by Mackie et al. (2003) led to the establishment of the current VTTC values officially employed in the UK.

The dataset employed for the Danish Value of Time study (DATIV) was collected in 2004. It was designed by RAND Europe (Burge et al., 2004) and analysed by Fosgerau et al. (2007) to update the official VTTC in Denmark. Travellers were interviewed online or face-to-face through computer assisted personal interview. It contains 17,020 observations from 2,197 respondents.

Travel time is expressed in minutes in both countries, while travel cost is shown in pence in the UK and in Danish Kroner (DKK) in Denmark (1£ ≈ 9 DKK). The selected attribute levels and consequent boundary VTTC cover the following ranges:

Table 3. Stated Choice design variables

	Minimun level		**Maximum level**	
Design variable	UK	Denmark	UK	Denmark
Δt_i	-20	-60	+20	+60
Δc_i	-300 pence	-200 DKK	+300 pence	+175 DKK
Boundary VTTC	1 pence/minute	2 DKK/hour	25 pence/minute	200 DKK/hour[16]

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[16] Approximately 30 pence/minute

It is interesting to see that the range for the changes in travel time and travel cost is much broader in Denmark, while the maximum boundary VTTC levels are rather similar. This shows that the Danish study did not focus particularly on the right tail of the VTTC distribution.

Both studies differed also in the way choice scenarios were presented. While in the UK the values of Δc_i and Δt_i were displayed under each travel option, the Danish respondents are presented with the final levels of cost (c_i) and time (t_i), made possible by the computer based presentation. For example, given T=20 and C=100, the same scenario would be presented respectively as:

Table 4. Presentation of Stated Choice scenarios

	UK		**Denmark**	
Attribute	*Option A*	*Option B*	*Option A*	*Option B*
Time	As now	10 minutes shorter than now	20	10
Cost	As now	50 pence higher than now	100 DKK	150 DKK

3.3 Rationale of two modelling approaches for the VTTC

Two relevant modelling approaches are identified in the literature. Both are well rooted in microeconomic theory (they are equivalent in a deterministic domain) and use discrete choice models to analyse choices from SC experiments. A microeconomic consumption problem, where individuals are assumed to make choices in order to maximise their utility, is the starting point (e.g. Becker, 1965; DeSerpa, 1971; Jara Diaz, 2003). From the microeconomic problem, a conditional indirect utility function V_i is derived. V_i is the key element of the discrete choice models. Together with V_i, an error term ε_i that accounts for unobserved factors is also necessary to enter the stochastic world of econometrics. Based on the varied interpretations of the error term (e.g. Block and Marschak, 1960; McFadden, 1976; Train, 2009), ε_i would account for any inter-individual and intra-individual variation in preference orderings that is unobservable to the researcher.

3.3.1 Random Utility (RU) approach

For a long time, it has been standard to define utility (U_i) as an observable measure of the attractiveness of each travel alternative (V_i) plus an error term (ε_i) assumed to follow a Gumbel distribution (type-I generalized extreme value -GEV- distribution) with constant variance (Daly et al., 2014). The attractiveness of each alternative is represented by its main attributes (time and cost in this case):

$$U_i = (V_i, \varepsilon_i) = \beta_c c_i + \beta_t t_i + \varepsilon_i \tag{3.2}$$

Where β_t and β_c are the marginal utilities of time and cost respectively. Then the differences in utility between travel alternatives drive people's choices (y):

$$y = 1\{\beta_c c_1 + \beta_t t_1 > \beta_c c_2 + \beta_t t_2 + \varepsilon\} \tag{3.3}$$

The VTTC is obtained as the ratio between time and cost marginal utilities, i.e. the ratio of the partial derivatives of the utility against travel time and cost:

$$VTTC = \frac{\beta_t}{\beta_c} \tag{3.4}$$

Adding an i.i.d extreme value error term to "$\beta_c c_i + \beta_t t_i$" implies that the difference in the attractiveness of each travel option is distributed with a constant variance across observations.

This approach is known as the Random Utility Model (RUM) and has been widely used since McFadden (1974)'s seminal work and Daly and Zachary

(1975)'s work on the VTTC context. However, there are other options. If the utility function V_i is derived from microeconomic theory (see e.g. Train and McFadden, 1978; Jara Diaz, 2002), it is only required to be modelled as a function of the levels of cost and time (c_i and t_i) of the i options considered by the decision-maker. This is:

$$V_i = f(c_i, t_i) \tag{3.5}$$

But microeconomic theory does not state anything regarding the introduction of the error term, which is purely empirical issue. The introduction of the error in line with equation (3.2) is just one option. In other words, another element of the model could, in principle, be assumed to be distributed with constant variance. However, the tendency to think in terms of "utility" and the complexity of many choice scenarios made the RU approach standard for many years. The "automatic" thinking in terms of "travel options" and the utilities associated to them has been restrictive and may have been the source of misunderstandings and biases on VTTC estimation.

3.3.2 Random Valuation (RV) approach

Cameron and James (1987) realised this and suggested an alternative approach, feasible with a particular type of data. Referendum data (employed in most VTTC national studies) are different from typical discrete choice data (Cameron, 1988). Its simplicity facilitates simpler interpretations of the stated choices. The rationale for the RV approach is hence related to the existence of referendum data.

Having only two travel options differing in time and cost (i.e. referendum data), a price of *one minute of travel time* is implicit and is observable (i.e. the BVTTC). Therefore, people's travel choices can be rationalized as part of a hypothetical "time market", where they directly accept or reject the price offered based on their valuation of the good. One can alternatively see the choice options as *"buying time"* and *"not buying time"* at a given price. If the objective is the VTTC, this is a more direct approach than thinking about "random utility" in the sense of equation (3.2), and is possible because a threshold price is observable.

The individual can therefore decide whether: 1) to buy time, in which case a VTTC equal or greater than the price is revealed; 2) not to buy time, revealing a VTTC lower than the price. The individuals' choice probabilities will be driven by the difference between the true VTTC and the BVTTC:

$$y = 1\{VTTC < \mathrm{BVTTC} + \varepsilon\} \tag{3.6}$$

Adding an i.i.d extreme value error term to the VTTC and the BVTTC implies that the difference between valuation and price is distributed with a constant variance across observations, which is a reasonable alternative to the RU approach. This is the essence of the approaches described by Cameron and James (1987), Cameron (1988) and more recently by Fosgerau et al. (2007), being implemented for the last Danish, Norwegian and Swedish national VTTC studies.

With the existing methodology, this dichotomy between approaches has only been developed in a binary choice context with two attributes. It is clear that "buying time" is equivalent to choosing the fast option, and "not buying time" is equivalent to choosing the slowest option. Hence both ways of approaching the decision-making process are totally equivalent in a deterministic context. It is the two different assumptions on the inclusion of the error terms what give place to two econometric approaches.

3.3.3 Terminology

Confusion exists around how to distinguish the approaches with adequate terminology. This thesis uses the terminology employed by Hultkrantz et al. (1996), who name the latter (equation 3.6) the Random Valuation (RV) approach. Nevertheless, *utilities* are associated with *options*, and *options* can be rationalized in different ways. Hence, a model based on equation (3.6) could still be rationalized as a Random Utility (RU) model (e.g. Fosgerau et al. (2007) define VTTC and BVTTC as "pseudo-utilities"). Similarly, some particular type of RU in the sense of equation (3.2) would include random valuation (e.g. mixed logit model). On the other hand, Börjesson and Eliasson (2014) define them as "Estimating in Marginal Utility (MU) space" and "Estimating in Marginal Rate of Substitution (MRS) space" respectively. This seems also confusing, as models based on marginal utilities (also known as "preference space") are often transformed to estimate in MRS-space (also known as "willingness-to-pay space") but without changing the error term structure. As a consequence (continuing with the confusing terminology), the typical specification for a RV model, which is in logarithms (i.e. log RV), has also been referred to as log-WTP model (e.g. Börjesson and Eliasson, 2014). Having noted the potential confusions, Hultkrantz et al. (1996)'s terminology is still for us the most accurate one and is employed throughout the thesis.

3.4 Theoretical relationship between two approaches

The theoretical relationship between the two modelling approaches is known (Börjesson and Eliasson, 2014; Hultkranz et al., 1996; Fosgerau, 2007), but we are not aware of any work which formally shows its derivation in the stochastic domain step by step.

3.4.1 Deterministic domain

The observable part of the utilities can be defined according to the RU approach as:

$$\begin{cases} V_1 = \beta_t * t_1 + \beta_c * c_1 \\ V_2 = \beta_t * t_2 + \beta_c * c_2 \end{cases} \tag{3.7}$$

And according to the RV approach as follows:

$$\begin{cases} V_1 = \text{BVTTC} = \frac{-(c_2 - c_1)}{(t_2 - t_1)} \\ V_2 = \text{VTTC} = \frac{\beta_t}{\beta_c} \end{cases} \tag{3.8}$$

The equivalence between equations 3.7 and 3.8 in terms of individuals' choices can be formally shown as follows (e.g. Fosgerau et al., 2007). If the slow option 1 is chosen, then the VTTC is lower than the BVTTC:

$$\beta_t * t_1 + \beta_c * c_1 > \beta_t * t_2 + \beta_c * c_2 \tag{3.9}$$

$$\beta_t * (t_1 - t_2) > -\beta_c * (c_1 - c_2) \tag{3.10}$$

$$\frac{\beta_t}{\beta_c} < -\frac{(c_1 - c_2)}{(t_1 - t_2)} \tag{3.11}$$

3.4.2 Stochastic domain

The difference between the two approaches lie in the way randomness is introduced (Fosgerau et al., 2007). The most common procedure is to add an extreme value error term to V_i. As Hultkrantz et al. (1996) reflect, the key question is which element of the choice problem is distributed with a constant variance, (or, similarly, which element is used to define the observable utility function):

a) a measure of the attractiveness of a travel option, i.e. $\beta_c c_i + \beta_t t_i$ or

b) the VTTC.

The utility functions in equations (3.7) and (3.8) need to be extended for estimation. An additive error term is added, leading to RU and RV approaches respectively. The errors in each model have different implications and hence different notation is employed:

$$\begin{cases} \widetilde{U_1} = \widehat{\beta_t} * t_1 + \widehat{\beta_c} * c_1 + \widetilde{\varepsilon_1} \\ \widetilde{U_2} = \widehat{\beta_t} * t_2 + \widehat{\beta_c} * c_2 + \widetilde{\varepsilon_2} \end{cases} \tag{3.12}$$

$$\begin{cases} U_1 = \mu * \mathrm{BVTTC} + \varepsilon_1 \\ U_2 = \mu * \mathrm{VTTC} + \varepsilon_2 \end{cases} \tag{3.13}$$

Where the errors (ε_i) are i.i.d, μ is a scale parameter, $\widehat{\beta_t} = \mu\beta_t$ and $\widehat{\beta_c} = \mu\beta_c$ (μ cannot be identified in equation (3.12) separately from the marginal utilities). In order to show the theoretical relationship, equation (3.13) will be related to equation (3.12) through a series of transformations.

Equation (3.13) can be rearranged to obtain:

$$\begin{cases} U_1 = 0 + \varepsilon_1 \\ U_2 = \mu * \mathrm{VTTC} - \mu * \mathrm{BVTTC} + \varepsilon_2 \end{cases} \tag{3.14}$$

Multiplying (14) by the marginal utility of cost β_c:

$$\begin{cases} \beta_c U_1 = 0 + \beta_c * \varepsilon_1 \\ \beta_c U_2 = \beta_c * \mu * \mathrm{VTTC} - \beta_c * \mu * \mathrm{BVTTC} + \beta_c * \varepsilon_2 \end{cases} \tag{3.15}$$

Multiplying (15) by the change in travel time (Δt) offered:

$$\begin{cases} \Delta t \beta_c U_1 = 0 + \Delta t * \beta_c * \varepsilon_1 \\ \Delta t \beta_c U_2 = \Delta t * \beta_c * \mu * \mathrm{VTTC} - \Delta t * \beta_c * \mu * \mathrm{BVTTC} + \Delta t * \beta_c * \varepsilon_2 \end{cases} \tag{3.16}$$

Substituting in (16) based on the definition of the VTTC (4) and BVTTC (1):

$$\begin{cases} \Delta t \beta_c U_1 = 0 + \Delta t * \beta_c * \varepsilon_1 \\ \Delta t \beta_c U_2 = \mu * \beta_t * \Delta t + \mu * \beta_c * \Delta c + \Delta t * \beta_c * \varepsilon_2 \end{cases} \tag{3.17}$$

Equation (3.17) can be written as:

$$\begin{cases} \widetilde{U_1} = 0 + \widetilde{\varepsilon_1} \\ \widetilde{U_2} = \widehat{\beta_t} * \Delta t + \widehat{\beta_c} * \Delta c + \widetilde{\varepsilon_2} \end{cases} \tag{3.18}$$

where:

$$\widetilde{\varepsilon_i} = \Delta t * \beta_c * \varepsilon_i$$

$$\widetilde{U_i} = \Delta t \beta_c U_i$$

$$\widehat{\beta_t} = \mu * \beta_t$$

$$\widehat{\beta_c} = \mu * \beta_c$$

$$\Delta t = (t2 - t1)$$

$$\Delta c = (c2 - c1)$$

The utilities in (18) resemble those of model (12). The relationship between the approaches is summarized in the following expression: $\widetilde{\varepsilon_i} = \Delta t * \beta_c * \varepsilon_i$. Both approaches can be interpreted as variant of the other but with a particular form of heteroskedastic errors (Börjesson and Eliasson, 2014). If the VTTC has in fact constant variance (*RV approach*), defining the model in line with *RU approach* would cause the error terms to be heteroskedastic with their variance being proportional to the change in travel time (Hultkranz et al., 1996).

Which approach is the best representation of reality is an empirical matter. Existing evidence suggest the RV approach explain choices better (Börjesson and Eliasson, 2014*;* Fosgerau, 2007*;* Börjesson et al., 2012). Nonetheless, there is very limited evidence and the comparison between approaches has been made in a different way. Fosgerau (2007) uses non-parametric techniques to observe which model would be more consistent with the data before making any modelling assumptions. Interestingly, all empirical works known using the RV approach consider a logarithmic extension of the model, while that is not the case for most works based on the RU approach. The only works reporting comparative results using parametric techniques are: i) an unpublished working paper by Hultkrantz et al. (1996), where it is shown that there may be substantive differences in the VTTC estimation from both approaches; ii) a paper by Daly and Tsang (2009) in which they explore impacts of different transformations and scaling of utility functions, among which we could identify the specifications that would correspond to the RU and RV approaches.

3.5 Empirical work: comparing the two approaches

In this section the two approaches are compared empirically. The comparison is carried out at several levels of model sophistication. The two base linear models in equations (3.12) and (3.13) are incrementally extended. The objective is to investigate:

i) The difference in the VTTC and model fit between the approaches after subsequent identical modifications: additive error terms (linear base), multiplicative error terms (logarithmic base), observed heterogeneity and random heterogeneity.

ii) The impact of each model extension on the VTTC and model fit separately within each approach.

3.5.1 Model specification 1: Linear base models (additive error terms)

The first level of comparison is the linear base models described in the previous section. However, to make the comparison more straightforward, *the RU approach* will be expressed in terms of the VTTC (this needs a rearrangement of equation (3.12) which does not affect any of the results). Additionally, to simplify notation the error terms are introduced in each model using the same Greek letter *epsilon.* The relationship between the two models should be kept in mind as explained in the previous section.

RU approach

$$\begin{cases} U_1 = \beta_c(\frac{\beta_t}{\beta_c} * t_1 + c_1) + \varepsilon_1 \\ U_2 = \beta_c(\frac{\beta_t}{\beta_c} * t_2 + c_2) + \varepsilon_2 \end{cases} \tag{3.19}$$

RV approach

$$\begin{cases} U_1 = \mu * \mathrm{BVTTC} + \varepsilon_1 \\ U_2 = \mu * \mathrm{VTTC} + \varepsilon_2 \end{cases} \tag{3.20}$$

With the VTTC defined as:

$$\mathrm{VTTC} = \frac{\beta_t}{\beta_c} = \beta_0 \tag{3.21}$$

Where β_0 is a parameter to be estimated. Both models are defined in VTTC space, where β_0 is used to represent the main coefficient for the VTTC.

Throughout the comparison, the VTTC is defined for both approaches in the same way. However, and that is precisely one of the key points of this work, the estimates from both models may differ: any difference would be an empirical matter, related to how the error terms are conceived in each model.

3.5.2 Model specification 2: Logarithmic base models (multiplicative error terms)

The second specification considers also a base model, but now with multiplicative error terms. Introducing error terms in an additive way is not a requirement of microeconomic theory (Harris and Tanner, 1974). The intuition beyond suggesting multiplicative errors over additive errors is the following: relative differences between the utilities of the choice options may be more important for decisions than absolute differences (see Fosgerau and Bierlaire, 2009). In order to estimate models with multiplicative error terms, Fosgerau and Bierlaire (2009) suggest a logarithmic transformation of the utility function.

This allows the use of common software. The counterpart logarithmic base specification can be derived for both approaches as follows:

RU approach

$$\begin{cases} U_1 = \beta_c(\frac{\beta_t}{\beta_c} * t_1 + c_1) * \varepsilon_1 \\ U_2 = \beta_c \left(\frac{\beta_t}{\beta_c} * t_2 + c_2\right) * \varepsilon_2 \end{cases} \tag{3.22}$$

$$\begin{cases} U_1{}' = \mu * ln(\mathrm{VTTC} * t_1 + c_1) + \varepsilon_1{}' \\ U_2{}' = \mu * ln(\mathrm{VTTC} * t_2 + c_2) + \varepsilon_2{}' \end{cases} \tag{3.23}$$

.

RV approach

$$\begin{cases} U_1 = \mu * \mathrm{BVTTC} * \varepsilon_1 \\ U_2 = \mu * \mathrm{VTTC} * \varepsilon_2 \end{cases} \tag{3.24}$$

$$\begin{cases} U_1{}' = \mu * \ln(\mathrm{BVTTC}) + \varepsilon_1{}' \\ U_2{}' = \mu * \ln(\mathrm{VTTC}) + \varepsilon_2{}' \end{cases} \tag{3.25}$$

Where:

β_c is normalized to 1 for identification reasons in the RU approach.

$U_i{}' = \ln(U_i)$

$\varepsilon_i{}' = \mu \ln(\varepsilon_i)$

μ is a scale parameter associated with ε_i

With:

$$\mathrm{VTTC} = \frac{\beta_t}{\beta_c} = \beta_0 \tag{3.26}$$

Note, however, that in the multiplicative RV approach equation (3.26) implies that the error term is not interpreted as part of the individuals' preferences. Given that in the RV approach the error relates to the VTTC, one could assume that the calculation of the mean VTTC should take the error into account (e.g. Fosgerau et al., 2007). In that case, if the error is part of individuals' preferences, then the VTTC should be calculated taking the logistic distribution of the error (the difference of two type-I GEV distributed error terms follows a logistic distribution) into account as follows:

$$\mathrm{VTTC} = \exp[\ln(\beta_0) + \frac{1}{\mu}(\varepsilon_1' - \varepsilon_2')] \tag{3.27}$$

This expression can be calculated using simulation for the logistic distributions. Additionally, given that those distributions will be unbounded, it is necessary to make an assumption for the VTTC values which our data (given mainly by the range of BVTTC) does not support (see Börjesson et al., 2012). One possibility is to censor the VTTC distribution, restricting it to be close to the BVTTC range.

3.5.3 Model specification 3: Observed heterogeneity (covariates)

The third specification builds on the base logarithmic specification above (both approaches in logarithms provided better model fit than when constructed linearly). Now, the VTTC may vary with individuals' and trip characteristics. Models can be extended to accommodate more precise definitions of the VTTC based on observed heterogeneity. Income and individuals' reported levels of current travel cost and current travel time are selected for this extension. The VTTC that enters equations (3.23) and (3.25) is now defined as:

$$\mathrm{VTTC} = e^{\beta_0 + \beta_{BC}\ln(\frac{C}{C_0}) + \beta_{BT}\ln(\frac{T}{T_0}) + \beta_I\ln(\frac{I}{I_0})} = \beta_0 * \left(\frac{C}{C_0}\right)^{\beta_{BC}} \left(\frac{T}{T_0}\right)^{\beta_{BT}} \left(\frac{I}{I_0}\right)^{\beta_I} \tag{3.28}$$

Where:

C = Current travel cost

C_0 = Reference level of current travel cost (e.g. average)

T = Current travel time

T_0 = Reference level of current travel time (e.g. average)

I = Income of the individual

I_0 = Reference level of income (e.g. average)

$\beta_0 = \frac{\beta_t}{\beta_c}$.

The VTTC has been defined using two identical expressions in equation (3.27). The inclusion of each covariate divided by a reference value allows the researcher to readily obtain a VTTC at the reference levels of the covariates (e.g. sample average). The coefficients on the covariates can be directly interpreted as elasticities. The essence of this particular way of defining the VTTC was employed in both the UK and Danish studies. However, defining the VTTC using the exponential function is more beneficial for estimation because it ensures positivity of the VTTC (especially important when logarithms are employed). For the reference values, an approximation to the sample average value has been used for all covariates. For the UK dataset the reference values are: (C_0 = 440, T_0 = 60, I_0 = 27). For the Danish dataset: (C_0 = 5360, T_0 = 45, I_0 = 26). The key comparisons of our work are carried out within country: therefore it is safe to simply work at sample averages in both datasets. Of course, many other exogenous individual and trip characteristics could be used as explanatory variables for the VTTC (e.g. gender, age class, occupation, congestion, etc.). However, the target of this model specification is to add only a few critical covariates rather than conduct a full specification search. The three selected covariates typically account for a great amount of observed variation in VTTC studies.

Again, equation (3.27) would need to be applied if the errors are assumed to be part of the travellers' preferences. For model specifications 2 and 3, three estimates of the VTTC, depending on the interpretation on the logistic error and the censoring assumption, will be shown.

3.5.4 Model specification 4: Random heterogeneity

The last model specification considered in this chapter extends the previous one to account for unobserved random heterogeneity. It is common to find additional variability in the VTTC that the models have not accounted for yet through covariates. This can be introduced by adding a random parameter which follows a particular distribution to the VTTC definition. Let us assume the VTTC follows a log-normal distribution across travelers:

$$\mathrm{VTTC} = e^{\beta_0+\beta_{BC}\ln\left(\frac{C}{C_0}\right)+\beta_{BT}\ln\left(\frac{T}{T_0}\right)+\beta_I\ln\left(\frac{I}{I_0}\right)+u} \quad (3.29)$$

Where u is a random parameter that follows a normal distribution N(0, σ) and hence the VTTC is log-normally distributed across individuals, with mean:

$$\mathrm{E(VTTC)} = e^{(\beta_0+\beta' \mathrm{X})}e^{\left(\frac{\sigma^2}{2}\right)} \quad (3.30)$$

Where σ is the standard deviation of u and X represents the set of covariates. Given the definition in (28), at the reference values chosen for the covariates, the mean is simply calculated as:

$$\mathrm{E(VTTC)} = e^{\beta_0}e^{\left(\frac{\sigma^2}{2}\right)} \quad (3.31)$$

3.5.5 Results

In this section the model estimation results are presented. All models have been estimated using Biogeme (Bierlaire, 2003). Tables 5 and 6 below show the results on the UK and Danish dataset respectively. For each dataset, the eight models are presented by pairs. The two approaches (RU and RV) are compared at four levels of model specifications. At the same time, the changes within each approach as the model specification improves are observed.

All estimated coefficients are significant at the 99% level of confidence. Surprisingly, the overall results of interest are very similar in both datasets. In all cases, models from the RV approach fit the data better than their counterparts based on the RU approach: although the models are not nested, the final Log-Likelihood improves significantly with the same number of parameters. Therefore, the empirical issue of selecting the modelling approach favours the RV approach, in line with existing literature (Börjesson and Eliasson, 2014; Hultkranz et al., 1996; Fosgerau, 2007). This means that, given a set of travelers' choices on time-cost tradeoffs, it is better to incorporate the error term assuming that the difference between VTTC and BVTTC (rather than the utility difference between travel options) is distributed with constant variance.

Within each approach (RU and RV), the use of logarithms improves the model fit. Since they are justified as a mean to introduce multiplicative error terms, this finding suggests that relative differences between utilities (V_i) are more important than absolute differences for individuals' choices. (Fosgerau and Bierlaire (2009) report similar findings). However, this was only tested with a base model. We are aware that other works (e.g. Significance et al., 2013) have found that logarithms may not improve linear specifications when the utility specification is refined (i.e. accounting for significant sources of heterogeneity)[17]. On top of this, as usual, the major improvement in model fit comes from the introduction of the random parameter *u.*

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[17] Testing the comparison between linear and logarithmic models under more refined model specifications would be an interesting extension of the empirical work presented here.

Table 5. Results - UK dataset

	1. Linear				**2. Logarithms**			
	RU		**RV**		**RU**		**RV**	
	Est.	t-test	Est.	t-test	Est.	t-test	Est.	t-test
β_c	1	na	na	na	1	na	na	na
β_0	4.89	18.64	3.22	11.76	3.71	22.38	2.75	23.71
μ	-0.0138	-20.81	0.115	24.03	-6.42	-23.12	0.79	33.15
VTTC pence/min	4.89		3.22		3.71		2.75	
							4.28*	5.1**
Obs.	10598		10598		10598		10598	
Parameters	2		2		2		2	
Null LL	-7345.974		-7345.974		-7345.974		-7345.974	
Final LL	-6746.152		-6570.224		-6690.042		-6465.961	
Adj. Rho^2	0.081		0.105		0.089		0.120	

	3. Logarithms + Covariates				**4. Log + Covariates + Random Het.**			
	RU		**RV**		**RU**		**RV**	
	Est.	t-test	Est.	t-test	Est.	t-test	Est.	t-test
β_c	1	na	na	na	1	na	na	na
β_0	1.70	30.23	1.30	28.25	1.58	28.64	1.29	28.11
μ	7.39	25.26	0.859	34.24	11.5	24.06	1.09	33.00
β_{BC}	0.470	8.78	0.431	7.57	0.431	7.45	0.428	25.29
β_{BT}	-0.362	-4.81	-0.196	-2.68	-0.279	-3.50	-0.189	-2.61
β_I	0.273	5.13	0.411	8.06	0.344	6.40	0.382	7.77
σ	na	na	na	na	1.07	21.22	1.11	25.29
VTTC pence/min	5.47		3.67		8.61		6.72	
			4.85*	5.8**				
Parameters	5		5		6		6	
Final LL	-6607.502		-6300.028		-6306.561		-5910.137	
Adj. Rho^2	0.100		0.142		0.141		0.195	

* Logistic error is part of preferences (VTTC distribution censored at 25p/min.).

** Logistic error is part of preferences (VTTC distribution censored at 35p/min).

Table 6. Results - Danish dataset

	1. Linear				**2. Logarithms**			
	RU		**RV**		**RU**		**RV**	
	Est.	t-test	Est.	t-test	Est.	t-test	Est.	t-test
β_c	1	na	na	na	1	na	na	na
β_0	63.3	14.6	20.5	11.9	31	13.3	31.1	23.91
μ	-0.00058	-14.5	0.0169	28.7	-3.14	-18.47	0.711	35.36
VTTC	37.95		20.5		18.6		18.66	
DKK/hour							22.2*	28.84**
Obs.	17020		17020		17020		17020	
Parameters	2		2		2		2	
Null LL	-11797.4		-11797.4		-11797.4		-11797.4	
Final LL	-11378.7		-10807.6		-10922.3		-10763.2	
Adj. Rho^2	0.035		0.084		0.074		0.087	

	3. Logarithms + Covariates				**4. Log + Covariates + Random Het.**			
	RU		**RV**		**RU**		**RV**	
	Est.	t-test	Est.	t-test	Est.	t-test	Est.	t-test
β_c	1	na	na	na	1	na	na	na
β_0	4.33	62.25	3.89	87.25	4.12	68.27	3.89	84.77
μ	4.41	20.37	0.768	36.3	10.3	24.4	1.06	34.84
β_{BC}	0.571	6.51	0.701	9.44	0.581	7.00	0.705	9.23
β_{BT}	-0.48	-3.87	-0.643	-6.06	-0.451	-3.67	-0.633	-5.77
β_I	0.501	6.63	0.638	9.76	0.611	8.47	0.633	9.74
σ	na	na	na	na	1.49	26.8	1.47	30.21
VTTC	45.57		29.35		112.08		86.45	
DKK/hour			26.65*	35.8**				
Obs.	17020		17020		17020		17020	
Parameters	5		5		6		6	
Final LL	-10748.8		-10313.8		-9690.48		-9185.81	
Adj. Rho^2	0.088		0.125		0.178		0.221	

* Logistic error is part of preferences (VTTC distribution censored at 200DKK/h).

** Logistic error is part of preferences (VTTC distribution censored at 300DKK/h).

The following graphs in figures 5 and 6 summarise the mean VTTC across the eight model specifications (for the RV approach where logarithms are used with type-I GEV errors, the VTTC selected for the graph is that where errors are assumed to be part of preferences and the simulated VTTC distribution was censored to the range of BVTTC in the data):

Figure 5. VTTC results - UK dataset

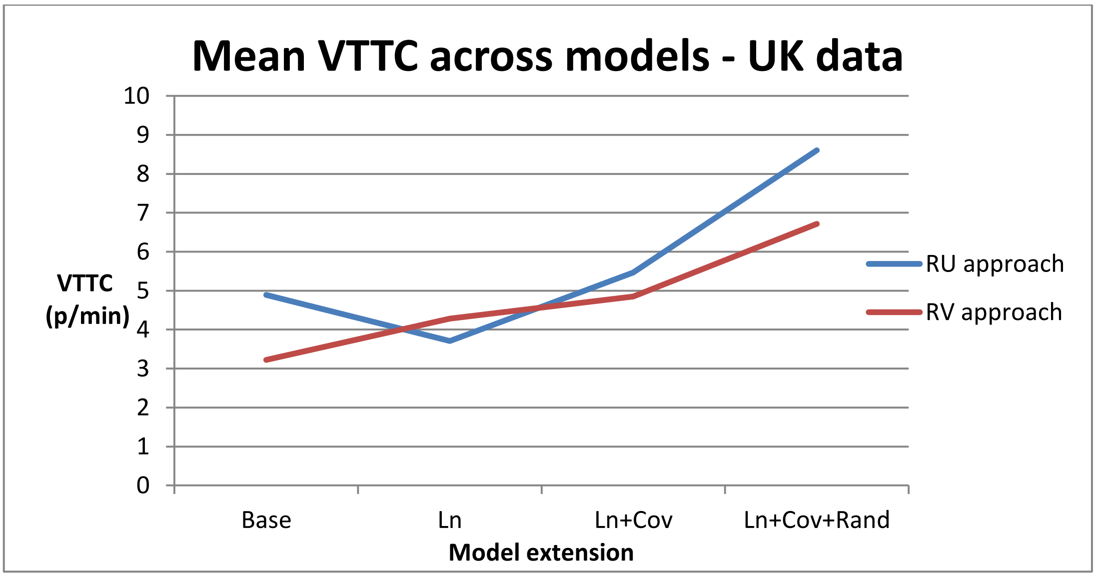
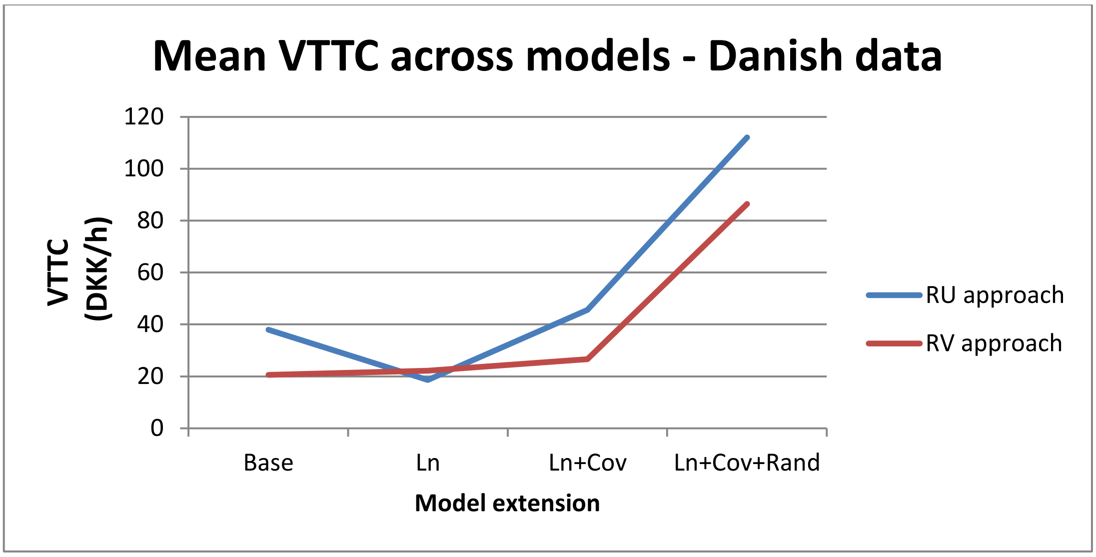


Figure 6. VTTC results - Danish dataset



In both countries, the RV approach gives systematically lower VTTC estimates at all levels of model sophistication (with exception of the base logarithmic specification in the Danish dataset and also in the UK dataset when the errors are assumed to be part of the preferences for the selected levels of censoring). The use of logarithms decreases the VTTC estimates compared to the linear base specification in the RU approach. This would also be true for the RV approach unless the errors are taken into account as part of the preferences, which is probably the correct assumption. Consistently with other works in the field, the introduction of observed and, especially, unobserved heterogeneity significantly increases the mean VTTC, as it allows the model to capture the right tail of the highly skewed VTTC distribution (Börjesson and Eliasson, 2014). The most recent similar VTTC study (Significance et al., 2013) found this only for unobserved heterogeneity.

Surprisingly, the variation of the VTTC across the eight model specifications is remarkably similar in both datasets (see figures 5 and 6), which were collected using the same basis for the SC design. The similarity exists regardless of the interpretation of the logistic error in two of the four RV models. Similarly, the effects of all covariates occur in the same direction in both datasets (same sign of parameters) and are only slightly more accentuated in the Danish dataset. This leaves us with a feeling that the SC designs may be playing a relevant role in the results.

3.5.6 Recommendations

Acknowledging that the VTTC can be modelled in many different ways, the *RV approach* seems very promising and, when feasible, should at least always be considered as an option for modelling.. The nature of referendum data makes the *RV approach* a very reasonable option, which has been confirmed in this chapter. Classical utility settings (i.e. *RU approach*) are likely to contain heteroskedastic error terms that need correction. In cases of more complex choice scenarios (e.g. more attributes or alternatives) where a valuation threshold (the BVTTC) cannot be observed and RU approach is employed, correcting for heteroskedasticity is highly recommended. The researcher should look for potential causes of heteroskedasticity and adjust the models accordingly (see e.g. Daly and Carrasco, 2009; and Munizaga et al., 2000). In the time-cost tradeoff case analysed here, a correction term for heteroskedasticity would divide the utility function of the *RU approach* by the change in travel time (Δt). The biases in the VTTC can be significant if the right form of heteroskedasticity is not identified.

Additionally, although logarithms seem to fit the data better, testing always both linear and logarithmic specifications seems a sensible approach. Although it has not been implemented in this chapter, it is also possible to test intermediate options between linear and logarithmic transformations, such as a Box-Cox transformation (see Daly and Tsang, 2009).

Although the results of our work would point towards the recommendation of the RV approach, we believe that more research is needed in order to fully understand what causes the differences in results between RU and RV. Especially, it should be borne in mind that the only difference between the two approaches lies in how the error terms are related to the observable part of the model. The use of simulated data could be a very useful tool to shed more light on this debate.

Several questions are left open. Why is the VTTC generally lower with the RV approach? If the RV approach actually explains choices better, has the VTTC been overestimated in applications using RU approach that did not correct for heteroskedasticity? And why are individuals' preferences so similar in two different countries? What can be said about traveller's behaviour in light of the evidence provided by RU and RV approaches? How would our results change if different data collection methods were employed? Further research regarding SC designs and methods for VTTC estimation is encouraged.

3.6 Conclusions

In this chapter, two popular approaches for the estimation of the VTTC have been identified, related and compared. The focus is placed on official national VTTC studies using data from travellers' choices on binary time/money trade-offs. The theoretical relationship between the two approaches, namely Random Utility approach and Random Valuation approach, has been shown. They simply differ in the assumptions regarding the introduction of the error term, and so none of them is theoretically preferred to the other. An extensive empirical comparison using two datasets from the national studies in the UK and Denmark has led us to conclude that the RV approach should be preferred, regardless the level of model sophistication employed. Several levels of model sophistication have been considered, in order to disentangle the impact of certain factors such as the use of logarithms and the introduction of observed and random heterogeneity. The VTTC is, in general, systematically lower using the RV approach, which highlights the risk of significant biases if the correct form of error heteroskedasticity is not employed. Finally, a surprisingly similar pattern of results across models in both datasets, based on a similar SC design, is found. Several questions are left open. Further research on the current techniques to collect data and estimate the VTTC would be welcome. In particular, simulated data could be very useful to shed some light on this topic.

Chapter 4

The role of stated choice design variables

4.1 Introduction

The value of travel time is a key element in the appraisal of transport projects (Small, 2012; Börjesson and Eliasson, 2014). Big national studies are carried out every certain number of years to obtain an estimate of how the population would value changes in travel time. The objective is therefore a measure of the value of travel time changes (VTTC). Since valuation is likely to vary across the population and with the trip context, the interest is not placed on obtaining a single VTTC but an index according to some variables that could have an impact on travellers' VTTC. Among these variables are individual characteristics (e.g. income) and trip characteristics (e.g. journey length). The recommended set of VTTC for appraisal has significant economic implications, and it crucially affects which projects are carried out in a country. Small (2012) and Daly et al. (2014) concur that our understanding of the VTTC and its variation should increase in order to maintain the credibility of the VTTC concept. Hence, it is important to pursue both an unbiased estimate of the VTTC and unbiased estimates of VTTC elasticities with respect to the variables of interest.

It is widely agreed that the VTTC can be found in individuals' travel choices where they trade-off money and time. The VTTC is defined as the marginal rate of substitution between travel time and travel cost. Since real life choices of this nature are not easy to observe and usually involve undesired correlations between time and cost, national VTTC studies typically rely on hypothetical stated choice (SC) experiments for data collection. Through these methods the researcher has more control over the variables of interest: time and cost. Discrete choice models grounded in traditional microeconomic theory are then employed to estimate the VTTC from the data. In this context, the artificial nature of the SC experiments has sometimes generated doubts on the validity of estimation results (e.g. Daly and Tsang, 2009). For example, in chapter 3 we found surprisingly similar patterns in the variation of the VTTC with income and journey length in two different countries (UK and Denmark) which had used the same SC design. Furthermore, the modelling specification can also affects the estimation results, as it was shown in chapter 3 (see also Fosgerau et al., 2007).

Our global aim is to increase our understanding of the set of VTTC in a population. In this chapter we do not question the validity of VTTC estimation results using SC experiments. However, we acknowledge that the variables used in the SC experiments (i.e. decided by the researcher) can influence the estimated set of VTTC. In the simplest VTTC experiment, the design variables are travel time changes (Δt) and travel cost changes (Δc). The ratio Δc/Δt forms a valuation threshold (Boundary VTTC). The impacts of the SC design variables may or may not be a true feature of individuals' preferences, but it is essential to understand how they influence the VTTC in order to control for them.

The objective of the chapter is to investigate potential impacts of the SC design variables on the estimation of the true underlying set of VTTC. For this, a series of empirical exercises which we refer to as partial data analysis are conducted. Ideally, one would like to observe the same group of individuals completing different SC experiments. With the data currently available, an alternative approach is to use a large dataset of individuals' responses, and split it according to different levels of the variable of interest. The data can then be analysed *as if* the design had a restricted range for the variable of interest (e.g. Fosgerau, 2014). The estimation of the same model on each sub-sample provides insights into potential effects of the variable of interest. This approach is applied in relation to three design variables (boundary VTTC, Δt and Δc) on the data for the last national VTTC study in the UK, using state-of-the-art model specifications.

The chapter is structured as follows. Section 2 presents some existing evidence on how the VTTC has been found to vary across and within individuals, which shapes the current perceptions about the set of VTTC in a population. Section 3 reviews the standard methodology applied in most

European studies to estimate the VTTC, explaining the essence of SC experiments and the most common discrete choice models in the field. Section 4 introduces the dataset and section 5 shows the empirical work. Section 6 concludes.

4.2 Evidence on variation in the VTTC

Empirical evidence strongly suggests that the VTTC varies across individuals and even for the same person under different circumstances. For VTTC studies, researchers have always been interested, and found empirical evidence, on how the VTTC varies with certain observable variables. In this section, we provide a brief review on some of the most recurrent sources of variation: current trip conditions, personal income and the size and sign of the changes (in time and cost) considered. There may be other important variables explaining the VTTC, but this chapter will focus on those mentioned above. Note that, for appraisal purposes, the first two are particularly important. The others are related to the choice context and, in principle, the only certainty is that one should at least try to explain and control for their effects.

Current trip conditions, in a simple context, can be understood as the current travel time and current travel cost an individual is facing. These variables may influence how the individual values a change in travel time. This impact is sometimes referred to as “journey length effect” (e.g. Mackie et al., 2003): although the correspondence between current time/cost and distance is not precise, this approximation is practical for appraisal purposes (see e.g. Börjesson and Eliasson, 2014). Many empirical applications on the VTTC report the so-called “cost damping” phenomenon, by which the sensitivity towards travel cost decreases as current cost increases, (Daly, 2010). Analogously, some works also report “time damping”, where times sensitivity decreases as current travel time increases. Overall, it is typically found that the effect on the cost domain is greater and the VTTC increases with journey length (e.g. Mackie et al., 2003; Börjesson and Eliasson, 2014).

Secondly, it is theoretically expected that the VTTC increases with income. To our knowledge, all existing empirical evidence confirms this expectation. Income and journey length effects are variations that occur across individuals (at least at a given point in time if each person considers just one particular trip). The next two sources of variation may also occur for the same individual: the VTTC may be different depending on the choice context.

Thirdly, the VTTC may be different depending on the sign of the changes considered. Due to diminishing marginal utility, losses would be weighted more than gains (Tversky and Kahneman, 1991; De Borger and Fosgerau, 2008). Consequently people may value a given saving of 10 minutes differently when compared to a loss of 10 minutes. In the same way, "loss aversion" can also be found for the cost attribute. This effect seems undesirable for appraisal purposes (projects are evaluated with a long-term horizon, where a short-term concept such as loss aversion on a travel choice does not apply) and may be, at least partially, caused by the SC design (e.g. De Borger and Fosgerau, 2008; Daly et al., 2014). How to fully remove this design effect is unclear, but current consensus is that models should at least control for it (Borjeson and Elliason, 2014). De Borger and Fosgerau (2008) suggest a formula to obtain one measure of a "reference-free" VTTC.

Fourthly, the VTTC may also vary with the size of the changes considered: again, this effect may apply in both time and cost domains. Facing two travel options, the difference in travel time between them may be, for example, 5, 10,15 or 20 minutes. How the individual values one minute of travel time may vary depending on whether he is considering a bundle of 5,10,15 or 20 minutes. This is often referred to as "size effects". Welch and Williams (1997) claimed that small travel time changes (typically below 10 minutes) should be valued at a lower rate based on SC empirical evidence. The argument is usually supported by signs that individuals may even neglect small time changes (e.g. Mackie et al., 2003). Daly et al. (2014) review this issue, pointing out that although many studies in fact report low valuation of small time changes, the implementation of this finding is controversial and therefore rare. There are certain suspicions that the existing SC methods may not be the suitable to accurately estimate this effect due to their artificial nature (Daly et al., 2014). In particular, the difference between two alternatives in a binary survey may have different behavioural implications from the difference between two schemes over time in real world behaviour. Börjesson and Eliasson (2014, p.157) conclude that the interpretation and treatment of size effects is "perhaps the outstanding unresolved issue in SC valuation". Furthermore, other recent studies (Significance, 2013), as well as chapter 2 of this thesis, recall that there may also be size effects on the cost domain: i.e. VTTC varies with the size of the travel cost change. In chapter 2 we found evidence that the inclusion of size effects on the cost domain can crucially affect the estimates of other sources of variation (e.g. income effects or journey length effects). However, size effects on the cost attribute may not be as intuitive as in the time attribute (one minute is the target of valuation, while money may sometimes be seen simply as the unit in which valuation is provided rather than as an attribute itself). Also, money (as opposed to time) can be saved, which could also cause differences in the perception of the two attributes. These different ways in which the VTTC has been found to vary empirically have been the object of debate for many years.

4.3 Methodology to estimate the VTTC

4.3.1 Data collection: Stated Choice experiments

The underlying assumption is that the VTTC can be inferred from individuals' travel choices where there is a trade-off between travel time (t) and travel cost (c). SC experiments are the most common method to obtain data on this kind of choices. In most European national studies for the VTTC, a binary choice setting is often employed. Each traveller is asked to choose between two travel options: the *fast and expensive* option and the *slow and cheap* option. For ease of exposition, the subscript 1 will always refer to the slow and cheap option, such that: $t_1 > t_2$ and $c_1 < c_2$; in actual surveys, the order of these is obviously randomized across choices. In each choice scenario, there is always a difference in travel time (Δt) and a difference in travel cost (Δc). The ratio $\Delta c / \Delta t$ constitutes the BVTTC, an implicit "price of travel time":

$$BVTTC = \frac{-(c2-c1)}{(t2-t1)} = -\frac{\Delta c}{\Delta t} \tag{4.1}$$

In essence, the respondent choosing the fast and expensive (slow and cheap) option would reveal a VTTC equal or higher (lower) than the BVTTC. The BVTTC acts as a valuation threshold.

When researchers design a SC experiment, there is always an expectation regarding the range in which the true VTTC will be. This expectation is normally transformed into some kind of "target VTTC", and SC designs are constructed accordingly to be able to pick up the true VTTC. The distribution of the BVTTC presented in the survey defines the *target VTTC.* At the moment of choice, individuals will reveal whether their VTTC is higher or lower than the threshold. In simple terms, researchers are interested in inferring the value of a good, and for that purpose a range of prices for that good is offered to respondents; the distribution of the price defines the target value. The importance of the target VTTC was acknowledged early on by Fowkes and Wardman (1988), Fowkes (1996) and Clark and Toner (1997).

4.3.2 Estimation: Discrete Choice Models

Discrete choice models are used to analyse the data from SC experiments. These models are grounded in microeconomic theory. It is assumed that individuals choose between two travel options (*i=1,2*) to maximise their utility. Each travel option *i* is assumed to provide the individual with certain level of utility. The utility (U_i) is a function with an observable component and an error (unobservable) component. The observable part (V_i) is defined as a function of the attributes of the option *i:*

$$\begin{cases} V_1 = \beta_t * t_1 + \beta_c * c_1 \\ V_2 = \beta_t * t_2 + \beta_c * c_2 \end{cases} \tag{4.2}$$

Where β_c and β_t are parameters to be estimated. In this basic setting, they represent the marginal utilities of travel cost and travel time respectively. The

VTTC is defined as the marginal rate of substitution between travel time and travel cost, equal to:

$$VTTC = \frac{\beta_t}{\beta_c} \tag{4.3}$$

The intuition of the estimation approach, explained at the beginning of section 2, can be seen more easily if the terms in equation (4.2) are re-arranged (see, e.g. Fosgerau et al., 2007a). If the data is re-ordered such that option 1 is always the slow and cheap option, then:

$$\begin{cases} V_1 = \text{BVTTC} = \frac{-(c_2-c_1)}{(t_2-t_1)} \\ V_2 = \text{VTTC} = \frac{\beta_t}{\beta_c} \end{cases} \tag{4.4}$$

It can be seen that when the *fast and expensive* option 2 provides greater utility then the VTTC is greater than the BVTTC, and vice versa.

In order to estimate the model, an error term must be introduced: these are often extreme value (i.i.d.) error terms, which give rise to logit models. Error terms account for unobserved factors. At this point, as highlighted in chapter 3, two approaches have been identified in the existing national VTTC studies: the random utility (RU) approach and the random valuation (RV) approach (e.g. Hultkrantz et al., 1996). The first assumes that utility is distributed with constant variance (McFadden, 1974), while the second poses the constant variance assumption on the VTTC (Cameron and James, 1987).

For many years, the random utility model (RUM) has been commonly used (including all European VTTC studies up to 2007; see e.g. Daly et al., 2014). The error terms in these RUM models have typicially been incorporated in an additive way, although this is not a requirement of the theory:

$$\begin{cases} U_1 = \beta_t * t_1 + \beta_c * c_1 + \varepsilon_1 \\ U_2 = \beta_t * t_2 + \beta_c * c_2 + \varepsilon_2 \end{cases} \tag{4.5}$$

More recently, the random valuation (RV) model has been used for the last VTTC studies in Denmark, Sweden and Norway (Fosgerau et al., 2007b; Börjesson and Eliasson, 2014; Ramjerdi et al., 2010). In all these studies, the error terms were incorporated in a multiplicative way (again noting that this is not an inherent requirement of the RV approach, just as additive is not a requirement for RU), which in practice translates to the specification of the utility functions in logarithms (see Bierlaire and Fosgerau, 2009) as follows:

$$\begin{cases} U_1 = \mu * \ln(BVTTC) + \varepsilon_1 = \mu * \ln(-\frac{\Delta c}{\Delta t}) + \varepsilon_1 \\ U_2 = \mu * \ln(VTTC) + \varepsilon_2 = \mu * \ln(\frac{\beta_t}{\beta_c}) + \varepsilon_2 \end{cases} \tag{4.6}$$

With:

$$\mathrm{VTTC} = \frac{\beta_t}{\beta_c} = e^{\beta_0} \tag{4.7}$$

Where:

β_0 is a parameter to be estimated (the exponential function simply ensures positivity of the argument of the logarithm and does not affect the results), and μ is a scale parameter to be estimated associated with ε_i.

Additionally, regardless of the approach selected (i.e. RUM or RV), observed and unobserved heterogeneity on the VTTC are generally taken into account. This is done extending the definition of the VTTC in (3) or (7).

To account for observed heterogeneity, interactions between the X_j, variables of interest (i.e. those likely to affect the VTTC) and the VTTC are introduced. These interaction terms can modify the VTTC directly. To account for unobserved or random heterogeneity, a random parameter u is introduced in the VTTC. For example, u can be assumed to follow a normal distribution: $u \sim N(0, \sigma^2)$. In that case, it can be seen straightforwardly that the VTTC follows a log-normal distribution across individuals. The lognormal distribution has the advantage of restricting the VTTC to positive values and has been proven to be convenient in several VTTC applications (see e.g. Börjesson and Eliasson, 2014).

If these modifications of the VTTC are introduced, the VTTC could be defined alternatively as follows:

$$\mathrm{VTTC} = e^{\beta_0 + \beta_{X_j}{}' X_j + u} \tag{4.8}$$

Where:

$\beta_{X_j}{}'$ is a set of parameters to be estimated

The mean VTTC under this more sophisticated setting can be calculated as:

$$\mathrm{E(VTTC)} = e^{(\beta_0 + \beta_{X_j}{}' X_j)} e^{(\frac{\sigma^2}{2})} \tag{4.9}$$

In previous national studies, the same type of interaction terms to account for observed heterogeneity had been applied to either the marginal utility of travel time or the marginal utility of travel cost under the RU approach (e.g. UK study; see Mackie et al., 2003). Under simple cost-time settings in SC experiments, the RV approach and this particular way of introducing observed and unobserved heterogeneity can be regarded as part of the state-of-the-art in model estimation for the VTTC. This approach has been employed in some of the last European national VTTC studies (see Börjesson and Eliasson, 2014).

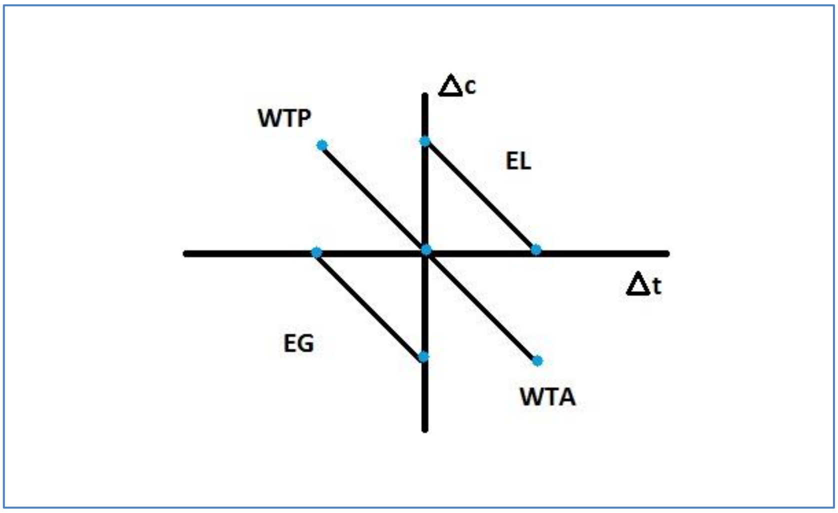
4.4 Dataset

The dataset used in this chapter was collected for the national VTTC study in 1994 by Accent and Hague Consulting Group (ACHG, 1996). It contains

12,706 choice observations[18] from car travellers for non-business (i.e. commute and other) purposes.

The respondents were recruited while travelling and information about a recent trip was collected. This trip, defined by current travel time (T) and current travel cost (C), is used as the reference trip throughout the survey. The participants are then presented with eight choice scenarios, each with two travel options (*i=1,2*) varying in travel cost (c_i) and travel time (t_i) with levels designed around the reference trip, where $\Delta t = t_i - T$ and $\Delta c = c_i - C$. Travellers were asked to choose their preferred travel alternative. This was a forced choice, with no option not to travel. With this basic setup, the SC design of the experiment has some interesting properties. Under each scenario, one of each Δt and Δc are set to zero, so travellers are always comparing a given change in time (Δt) against a given change in cost (Δc). Those pairwise comparisons are classified into four "types", based on the four quadrants of an indifference curve map (see figure below):

Figure 7. Four types of choices present in most European VTTC studies.



1) $\Delta t < 0$, $\Delta c > 0$ (*current journey* vs. faster but more expensive option; willingness to pay or WTP)

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[18] 70 observations were removed due a mistake in the design which offered a negative BVTTC in those cases.

2) Δt < 0, Δc < 0 (faster option vs. cheaper option; equivalent gain or EG)

3) Δt > 0, Δc > 0 (slower option vs more expensive option; equivalent loss or EL)

4) Δt > 0, Δc < 0 (*current journey* vs. slower but cheaper option; willingness to accept or WTA).

The point where the axes intersect represents the current trip of the individuals, i.e. Δt=0, Δc=0, from which changes in time and cost are considered. The lines linked by dots are a representative example of the slope of the indifference curve that the design tries to capture in each quadrant. In practice, these slopes do not need to be equal for all quadrants; it is theoretically expected and typically found that the following relationship holds for the slope: WTP < EL, EG, < WTA (see e.g. De Borger and Fosgerau, 2008). This relationship can be explained through diminishing marginal utility in line with microeconomic theory: a WTP scenario involves a gain in travel time and a loss in travel cost, as opposed to a WTA scenario (loss in travel time and gain in travel cost). EL and EG choice scenarios are intermediate cases.

Each choice scenario contains an implicit BVTTC. The design includes eight different BVTTC (pence/minute), derived from the different combinations of (Δt, Δc). The values used in the UK experiment for the BVTTC, as well as the time and cost differences making up the BVTTC, are shown in the table 7 below. The eight BVTTC included were considered to cover a realistic and sufficient range of VTTC at the time of the study, although recent studies (e.g. Börjesson et al., 2012) have suggested that a much larger range of BVTTC is required to identify the true mean VTTC over a sample of choices.

Table 7. SC design attribute levels

Design variable	**Values used for the SC experiment**
Δt (minutes)	-20, -15, -10, -5, -3, +5, +10, +15, +20
Δc (pence)	-300, -250, -225, -150, -140, -125, -105, -100, -75, -70, -50, -35, -30, -25,-20, -15, -10, -5, 5, 10, 15, 20, 25, 30, 35, 50, 70, 75, 100, 105,125, 140, 150, 225, 250, 300
Boundary VTTC (pence/minute)	1, 2, 3.5, 5, 7, 10, 15, 25

In addition to completing the SC tasks, respondents were asked for information on socio-economic characteristics (e.g. income). The data was first analysed by AHCG to explore the VTTC in the UK. Their work paid special attention to observed heterogeneity in the VTTC (AHCG, 1996). A few years later, the Institute for Transport Studies (ITS) at the University of Leeds undertook a review and re-analysis of the data, commissioned by the Department for Transport after they experienced difficulties in implementing AHCG's recommendations (Mackie et al., 2003, p.3). The work by ITS (Mackie et al, 2003) led to the establishment of the current VTTC values officially employed in the UK. This re-analysis provided a more synthetised model, with a focus on few key sources of observed heterogeneity in the VTTC. The analysis carried out in this chapter also aims at providing new valuable insights into the results obtained a decade ago, through a focus on the role of the SC design variables.

4.5 Empirical work

The *valuation threshold* is the key element of an SC experiment to estimate *individuals' valuation* if simple time-money trade-offs are employed in the experiment. In the context of the VTTC, this is the BVTTC. A key question is whether it is possible that the BVTTC plays a role on the estimation of the set of VTTC. This is not necessarily saying that the survey influences preferences, but that, if preferences (and hence VTTC) are different in different settings, then by focussing the survey on specific settings, our sample level results will be affected accordingly. Fosgerau (2014) analyses the impact of the BVTTC on the estimation of the mean VTTC if basic Random Utility models, with no covariates, are employed. Fosgerau "manipulates" a stated choice survey in order to analyse certain impacts of a design variable, in particular the BVTTC. His work shows empirically that basing the design of the SC experiment on some target VTTC, defined by the distribution of the BVTTC, will bias the estimated VTTC towards the target (if the VTTC is distributed across the sample). In particular, in Fosgerau's paper, the "bias" is claimed to be related to model misspecification when a simple Random Utility model (e.g. equation 4.5) is used. His conclusions simply require that the underlying VTTC in the population vary between individuals (heterogeneity), something which is typically observed in most applications and is therefore acceptable (Fosgerau, 2014).

However, much more can be explored. Our empirical work will also: a) test different modelling specifications, especially those at the state-of-the-art; b) analyse the impact of BVTTC on the estimation of VTTC heterogeneity and not only on the mean VTTC; and c) test, in a similar fashion, the impact of the components of the BVTTC, namely the change in travel time and the change in travel cost.

Our empirical work will try to increase our understanding of the role of these design variables and their potential influence on estimation results. In this section, a particular series of modelling estimation is carried out.

4.5.1 Partial analysis of the data

The series of empirical exercises conducted to investigate our research questions may be regarded as *partial data analysis*: the term "manipulation" employed by Fosgerau (2014) might be misleading. *Partial data analysis* can be very useful to study the impact of some SC design variables. However, a big dataset, which is not always available, is necessary. In each of these exercises, the dataset of travel choices is split into several sub-samples based on some variable of interest. In this work, three variables of interest are investigated: the BVTTC, Δc and Δt. Consequently, three exercises will be presented. The levels of these three variables have been decided by the researchers when constructing the SC experiment. In each exercise, the same model/s will be estimated on each sub-sample, as well as on the full dataset. The objective is to investigate patterns on the estimation results across sub-samples, in relation to the VTTC and its covariates.

In order to divide the data, Fosgerau (2014) employs the quartiles of the BVTTC distribution. This gives four sub-datasets of similar size, each with an exclusive range of BVTTC. Afterwards, the same discrete choice model is estimated on the four sub-datasets. The use of this technique has a different purpose in this chapter, as we are not trying to show the inabilities of an inferior (RU) model. Our target is the understanding of the VTTC and VTTC covariates.

In our three exercises, we will make use of the same state-of-the-art model specifications (a logarithmic RV model), in line with equations (4.7) to (4.10). The first exercise also includes a replication of Fosgerau (2014)'s approach on the UK dataset for car travellers, using a simple RU model, for illustrative and comparison purposes. The set of *X* covariates employed for the definition of the VTTC (equation 4.10) in the RV model is the following:

$$\beta_{X_j}{}'X_j = \beta_{BC}\ln\left(\frac{C}{C_0}\right) + \beta_{BT}\ln\left(\frac{T}{T_0}\right) + \beta_{I}\ln\left(\frac{I}{I_0}\right) + \beta_{\Delta c}\ln\left(\frac{\Delta C}{\Delta C_0}\right) + \beta_{\Delta t}\ln\left(\frac{\Delta T}{\Delta T_0}\right) \quad (4.10)$$

where:

C = Current travel cost

C_0 = Reference level of current travel cost (e.g. average = 550 pence)

T = Current travel time

T_0 = Reference level of current travel time (e.g. average = 70 minutes)

I = Income of the individual

I_0 = Reference level of income (e.g. average = £25,000)

ΔC = Change in travel cost

ΔC_0 = Reference level of change in travel cost (e.g. average = 60 pence)

ΔT = Change in travel time

ΔT_0 = Reference level of change in travel time (e.g. average = 7.7 minutes)

This VTTC definition allows us to capture all sources of variation mentioned in section 2, together with random heterogeneity. Note that, for identification purposes, from the VTTC variations with Δc and Δt, only one can be identified in a given RV model. This is because the BVTTC, Δc and Δt are multicollinear and the BVTTC is already part of the model. Additionally, the base estimate for the VTTC in equation (4.9), represented by β_0, will be estimated separately for each of the four types of choices (i.e. quadrants) present in the data. The objectives of this chapter require us to account for all possible important sources of variation to avoid further biases as much as possible. To simplify the analysis, the geometrical average of the four measures of the VTTC present in the dataset (i.e. related to the four choice scenarios or quadrants of the indifference map) will be provided as an approximation to the mean VTTC over the sample.

$$VTTC_{Reference-free} = (\mathrm{VTTC_{WTP}} * \mathrm{VTTC_{WTA}} * \mathrm{VTTC_{EL}} * \mathrm{VTTC_{EG}})^{1/4} \qquad (4.11)$$

This would be equal to what De Borger and Fosgerau suggest as "reference-free" VTTC only if $(\mathrm{VTTC_{WTP}} * \mathrm{VTTC_{WTA}})^{1/2} = (\mathrm{VTTC_{EL}} * \mathrm{VTTC_{EG}})^{1/2}$. This approximation is sufficient for the purposes of this chapter. Note that, if random heterogeneity is not accounted for through a random parameter u such that $u \sim N(0, \sigma^2)$, the direct model estimates of the VTTC will correspond to the median instead of the mean of the distribution. Simulation would be required to calculate the mean (see chapter 3), but the median can be equally used as a VTTC measure in some of the exercises for the purposes of this work. In this sense, it is worth mentioning that the correct measure for use in the Cost-Benefit Analysis framework for appraisal is the mean, since it is the mean, when multiplied by the population who benefit from a project, which gives the total benefit derived from the change considered. The median, on the other hand, is less sensitive to the skew of a distribution (the VTTC distribution is typically skewed to the right, due to some people with very high valuation levels), and to changes in the model specification (see Johannesson, 1996). Some researchers, consequently, have argued that the median might be used for Cost-Benefit Analysis (Hanemann, 1984). For this work, the calculation of the mean through simulation is of little benefit, and therefore we only report the median in those cases where simulation is needed.

4.5.1.1 Exercise 1 - Data split by BVTTC

In the first exercise, the data is also split into four based on the quartiles of the BVTTC distribution. A simple RU model (equation 4.5) is then estimated on the four sub-datasets to replicate Fosgerau's (2014) exercise on the UK data. This kind of model (i.e. RU model) was also the basis of the recommended model in the national UK study (Mackie et al., 2003). The model is estimated for each sub-dataset (each represented by a range of the BVTTC in the first column). The results are shown in table 8. All models have been estimated using Biogeme (Bierlaire, 2003).

The results from the RUM model confirm Fosgerau (2014)'s findings on the UK dataset. The estimated VTTC tends towards the range of bVTTC available in each quartile of the data if a simple RU model is employed. This was expected (Fosgerau (2014) employed both simulated and real data to reach the same conclusions) and it only provides reassurance on the limitations of simple RU models in the context of data from binary time-cost trade-offs (i.e. where an observable BVTTC is present). It is important to bear in mind that there will be differences in the sub-datasets with respect to sample representation (e.g. one sub-dataset could contain a higher proportion of rich people, who are generally found to have a higher VTTC). While this may be relevant, overall the table shows that the vast majority of individuals of the full sample (1,874) are represented in each sub-dataset, and therefore each sub-dataset is a considerably representative sub-sample of the full sample.

Table 8. Data split by BVTTC - Estimation results RU model (Standard errors in parentheses)

	Model 1 - RU					
bVTTC (p/min)	Est. VTTC	β_c	βt	obs.	Individuals	LL
[1,2]	3.04	-0.037 (0.008)	-0.112 (0.011)	3452	1846	-2256.47
(2,5]	3.59	-0.0677 (0.007)	-0.243 (0.025)	3468	1839	-2334.62
(5,10]	6.00	-0.0283 (0.003)	-0.17 (0.026)	3238	1742	-2124.64
(10,25]	10.2	-0.0193 (0.002)	-0.197 (0.032)	2547	1465	-1272.47

Following this introductory test, the same exercise will be carried out using better model specifications, in line with state-of-the-art techniques. Three RV models are estimated:

i) RV accounting for VTTC variation with Δt ($\beta_{\Delta t}$) and random heterogeneity

ii) RV accounting for VTTC variation with Δt ($\beta_{\Delta t}$)

iii) RV accounting for VTTC variation with Δc ($\beta_{\Delta c}$).

For a more complete analysis, the models are also estimated for the full sample. The models on the full sample will also be comparable with the models from sections 4.5.1.2 and 4.5.1.3 that will be presented later on.

We will look at differences in the VTTC and in the estimation of observed and random heterogeneity. The estimation results are shown in table 9 (it contains the results from the three models, in the form of three tables joint together). The first column of each table shows the range of the design variable for which the model is estimated. These ranges are exclusive. The second column shows an estimate of the VTTC, at the sample average of the covariates. Where a lognormal distribution is assumed for the VTTC, the mean can be easily calculated using equation (4.10) (Fosgerau et al., 2007). If the only random term in the model is the logistic error (i.e. no random heterogeneity is included), the derivation of the mean is not clear, as it requires additional assumptions and simulation (see chapter 3). As it was argued in the previous section, this is not the scope of this work and, therefore, in models where the standard deviation of the VTTC distribution is not estimated, only the median is reported[19]. Columns 3 to 13 provide the estimates of the relevant coefficients for each model. Columns 14 and 15 report the number of observations and individuals on each sub-sample, and the final column gives the Log-Likelihood of each model.

The last column shows that the model fit of a RV model is very superior to the RU model, for any range of BVTTC. Overall, coefficients in all models are estimated with the expected sign based on theory and previous evidence on this dataset (see chapters 2 and 3), and all levels of significance are reasonable. The only issue found was the estimation of the mean VTTC in the first part of table 9 (random heterogeneity) for the fourth sub-dataset (BVTTC=(10,25]). In that particular case, the standard deviation (σ) was very high, leading to an unrealistic mean VTTC of 41 pence per minute. However, the estimated σ was only slightly significant and very imprecise. It is probably an issue related to capturing random heterogeneity within a small dataset where the VTTC is not well spread to follow a lognormal distribution. This does not influence the other results and analysis. For ease of exposition, the results will be interpreted in several steps as follows.

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[19] The median will coincide with the mean if the logistic error is not part of the preferences, i.e. white noise. This, however, is contrary to expectations based on empirical evidence (e.g. Borjessön and Eliasson, 2014). If the VTTC follows a distribution and there are not specific random terms to capture it, it can be partially captured by the logistic error.

Table 9. Data split by BVTTC - Estimation results RV model (Standard errors in parentheses)

	RV model + Random heterogeneity														
BVTTC range	Est. VTTC p/min	β_{wtp}	β_{wta}	β_{el}	β_{eg}	$\boldsymbol{\beta_I}$	$\boldsymbol{\beta_{BC}}$	$\boldsymbol{\beta_{BT}}$	$\boldsymbol{\beta_{\Delta T}}$	$\boldsymbol{\beta_{\Delta C}}$	μ	σ	obs	Indiv.	LL
[1,2]	4.29	0.403 (0.17)	2.75 (0.58)	1.11 (0.24)	1.44 (0.36)	0.502 (0.14)	0.274 (0.1)	-0.236 (0.15)	0.704 (0.3)	-	0.743 (0.17)	-0.248 (0.38)*	3452	1846	-2049.9
(2,5]	4.77	1.2 (0.06)	2.08 (0.17)	1.35 (0.04)	1.57 (0.09)	0.231 (0.06)	0.299 (0.08)	-0.239 (0.09)	0.284 (0.15)	-	1.72 (0.4)	0.16 (0.24)*	3468	1839	-2025.6
(5,10]	4.73	0.818 (0.34)	2.51 (0.13)	1.19 (0.23)	1.68 (0.09)	0.291 (0.09)	0.311 (0.1)	-0.317 (0.13)	0.336 (0.21)*	-	1.14 (0.3)	0.0884 (0.27)*	3238	1742	-1875.5
(10,25]	41.8	-0.522 (1.14)*	1.97 (0.35)	0.0932 (0.98)*	1.58 (0.47)	0.475 (0.2)	0.586 (0.25)	-0.473 (0.27)	0.334 (0.35)*	-	3.36 (1.32)	2.43 (0.87)	2547	1465	-944.7
ALL data	6.93	0.276 (0.08)	2.29 (0.07)	0.763 (0.07)	1.29 (0.06)	0.452 (0.05)	0.429 (0.06)	-0.417 (0.08)	0.664 (0.07)	-	1.03 (0.04)	1.25 (0.06)	12705	1874	-6856.1
ALL data	6.05	0.985 (0.06)	2.2 (0.04)	1.28 (0.04)	1.6 (0.04)	0.272 (0.03)	0.258 (0.04)	-0.251 (0.05)	-	0.399 (0.02)	1.72 (0.08)	0.753 (0.04)	12705	1874	-6856.1
	RV model ($\beta_{\Delta C}$ = 0)														
[1,2]	2.91	0.0431 (0.14)	2.39 (0.45)	0.747 (0.14)	1.09 (0.22)	0.502 (0.14)	0.274 (0.1)	-0.235 (0.15)	0.703 (0.3)	-	0.737 (0.38)	-	3452	1846	-2049.9
(2,5]	4.25	1.1 (0.09)	1.98 (0.12)	1.24 (0.07)	1.47 (0.06)	0.232 (0.06)	0.3 (0.08)	-0.24 (0.09)	0.284 (0.15)	-	1.69 (0.38)	-	3468	1839	-2025.6
(5,10]	3.98	0.65 (0.43)*	2.34 (0.07)	1.03 (0.32)	1.51 (0.15)	0.291 (0.09)	0.311 (0.1)	-0.317 (0.13)	0.336 (0.21)*	-	1.14 (0.3)	-	3238	1742	-1875.5
(10,25]	2.84	-0.567 (1.11)*	2.05 (0.4)	0.428 (1.01)*	1.75 (0.49)	0.531 (0.23)	0.535 (0.24)	-0.401 (0.28)*	0.424 (0.42)*	-	0.806 (0.3)	-	2547	1465	-959.4
ALL data	3.18	0.264 (0.08)	2.3 (0.07)	0.766 (0.07)	1.3 (0.06)	0.466 (0.05)	0.426 (0.06)	-0.422 (0.08)	0.695 (0.07)	-	0.795 (0.02)	-	12705	1874	-6963.7
	RV model ($\beta_{\Delta T}$ = 0)														
[1,2]	1.81	0.873 (0.19)	2.25 (0.23)	1.29 (0.18)	1.49 (0.22)	0.295 (0.05)	0.161 (0.05)	-0.138 (0.08)	-	0.413 (0.1)	1.26 (0.12)	-	3452	1846	-2049.9
(2,5]	4.85	1.31 (0.05)	1.99 (0.1)	1.42 (0.04)	1.6 (0.07)	0.18 (0.03)	0.233 (0.04)	-0.186 (0.05)	-	0.221 (0.09)	2.17 (0.27)	-	3468	1839	-2025.6
(5,10]	4.71	1 (0.2)	2.27 (0.06)	1.29 (0.14)	1.64 (0.08)	0.218 (0.05)	0.233 (0.06)	-0.237 (0.07)	-	0.252 (0.12)	1.52 (0.22)	-	3238	1742	-1875.5
(10,25]	3.83	0.572 (0.45)*	2.05 (0.28)	0.912 (0.43)	1.84 (0.29)	0.373 (0.11)	0.375 (0.14)	-0.282 (0.14)	-	0.298 (0.21)*	1.15 (0.2)	-	2547	1465	-959.4
ALL data	4.59	0.998 (0.06)	2.2 (0.4)	1.29 (0.04)	1.61 (0.04)	0.275 (0.03)	0.251 (0.04)	-0.249 (0.05)	-	0.41 (0.03)	1.35 (0.06)	-	12705	1874	-6963.7
	* Not significant at the 90% level of confidence														

VTTC estimation (mean/median)

To begin with, we do not observe a tendency of the VTTC towards the BVTTC, as opposed to the exercise with a basic RU model. For the three models estimated, the VTTC still varies slightly among sub-datasets: it is always between 4 and 5 pence per minute for the two intermediate sub-datasets, and slightly lower for the extreme ones. However, it can be observed that, overall, the estimated VTTC is not highly sensitive to the range of BVTTC presented. The β_0 coefficients (i.e. β_{wtp}, β_{wta}, β_{el} and β_{eg}) have, in general, a relatively large standard deviation, suggesting that estimation is not precise when the range of BVTTC is reduced compared to the full sample. Among sub-datasets, coefficients are much more precise is the second sub-dataset (BVTTC = (2,5]). Interestingly, the estimated VTTC in almost all sub-datasets falls into this range. This could be regarded as a positive feature of the RV approach, which would be able to approximately recover the underlying VTTC in the sample regardless of the BVTTC range presented. The second most precise set of coefficients correspond to the third sub-sample (BVTTC = (5,10]). The scale of the models (μ) is also greater in those second and third sub-samples (although with the exception of the problematic four sub-sample in the model with random heterogeneity). This could be due to the underlying VTTC being actually within those ranges. This would show that offering BVTTC that are close to the true VTTC increases the precision of the estimation. Nonetheless, even if the BVTTC range does not contain the true VTTC the RV model was able to report a close estimation (although less precise).

Random heterogeneity

To analyse this element, we need to look at the first two tables (the same model with and without random heterogeneity). The use of random heterogeneity does not affect the interpretation of results above. Including random heterogeneity improves model fit considerably if all data is used. Interestingly, it does not improve model fit at all for any of the sub-datasets. The standard deviation of the underlying normal distribution assumed for u (equation 4.10) is only significant in the last sub-sample, and only affects the estimation of the coefficients for the mean of the distribution (β_{wtp}, β_{wta}, β_{el} and β_{eg}). It is known that capturing the distribution of the VTTC through a random parameter normally affects the estimated mean, because the model is allowed to capture the right tail of the distribution (Börjesson et al., 2012). On the one hand, this may be interpreted as a sign that a reasonable wide range of BVTTC is necessary in order to capture the distribution (whether lognormal or other) of the VTTC. On the other hand, another hypothesis might be that the heterogeneity that we observe in the model on the full sample is actually an artefact caused by not fully capturing size effects. While support for the first hypothesis can be found in the existing literature (e.g. Börjesson and Eliason, 2014), this does not mean the second hypothesis might not hold (it would be an interesting objective for further research, e.g. with the use of simulated data). What this exercise also shows is that the introduction of random heterogeneity does not affect any of the covariates. One might think that there could be scope for confounding between observed and random heterogeneity. However, we are not aware of any literature that looks in particular at how random heterogeneity affects the estimation of observed heterogeneity terms.

Covariates

Looking at the models estimated on the full dataset, covariates are not affected by the introduction of random heterogeneity. Across the different sub-samples of the dataset, there does not seem to be major variations in the magnitude of the estimates. A given covariate always takes the same sign but again the standard deviations of coefficients are lower for the two intermediate sub-samples. Hence, the estimation of covariates is also more precise in the middle ranges of the BVTTC. Some patterns are also observed. First, there are differences in the covariates depending on whether the VTTC is allowed to vary with Δt (higher covariates estimates) or with Δc (lower covariates estimates).

Let us focus first on the models where variation with Δt is used. The income elasticity (β_I) and current cost elasticity (β_{BC}) are both around 0.4 if all data is used, but only around 0.2-0.3 when the BVTTC range is between 2 and 10. At the same time, the current time elasticity (β_{BT}) is, interestingly, generally about the same magnitude than the β_{BC} but with the opposite sign (i.e. cost damping and time damping effects approximately compensate each other). In this context (car travel) where current time and cost are positively correlated and directly related to journey length, this suggests a lack of journey length effect (opposite to Mackie et al., 2003, who reported a VTTC that increased with journey length due to cost damping). When all data is used, the estimate on these three covariates, which operate exclusively across individuals, is somewhat an average representation of their values among sub-datasets. With respect to the influence of the size of the changes, the estimates of $\beta_{\Delta T}$ indicate that the VTTC increases with the size of the time changes, in line with most empirical evidence (e.g. De Borger and Fosgerau, 2008; Hess and Stathopoulos, 2012). However, it can be observed that this impact reduces as the BVTTC increases, and becomes non-significant on the third and fourth sub-samples. When the full dataset is used, the estimate of $\beta_{\Delta T}$ (0.695) resembles the result from the first sub-dataset ($\beta_{\Delta T}$= 0.703) where BVTTC is only either 1 or 2. It is not obvious how to interpret this result. Further research should look at whether size effects on the time domain actually only apply when low valuation thresholds (BVTTC) are considered.

If variation with Δc (instead of Δt) is used, several aspects are affected. The estimates of $\beta_{\Delta C}$ themselves have the same implications than the estimates of $\beta_{\Delta T}$: the VTTC increases with the size of cost changes and the effect vanishes as BVTTC increases. Again, when the full sample is employed, the effect of Δc ($\beta_{\Delta C}$ = 0.41) is close to what is estimated on the sub-sample with lowest range of BVTTC ($\beta_{\Delta C}$ = 0.413). Therefore, this also points out to the possibility that size effects are mainly associated with low valuation thresholds. With respect to other elements of the model, if variation with Δc is estimated, then the scale of the model increases. This leads to more precise coefficients in general. Also, the estimates on the covariates are lower (i.e. reduced effects of observed sources of heterogeneity). On the other hand, the mean VTTC is also affected. This can be seen through the models with random heterogeneity estimated on the full sample: incorporating variation with Δt gives a greater VTTC (6.93 pence/min vs 6.05 pence/min).

It is unclear how one should interpret these results. Both elements of the BVTTC can be used as an explanatory variable and give the same model fit. At the same time, the choice of one or the other is not innocuous, since it seems to affect the final estimates of all other covariates, the mean VTTC and the scale of the model. The reasons for this are unknown, but for appraisal, this would have the following implications. If VTTC variation with Δt is preferred, policy makers would have to decide which level of Δt could be used for a representative VTTC. If VTTC variation with Δc is preferred, a given cost change (Δc) would have to be used to choose a representative VTTC. In first instance, variation with Δc may be less straightforward and could be controversial due to nature of money (50 pence now are not the same than 50 pence in the future). However, it may be an alternative way forward to avoid the stronger influence on the final VTTC estimate of having to choose a level of Δt. Ultimately, the target should be to control for the impact of any design variable (regardless of whether they are a design artefact or a true feature of respondents' valuation), as these are unlikely to be used as sources of variation for appraisal. Nonetheless, we are forced to agree with Börjesson and Eliasson (2014) in their belief that "size effects" are the most important unresolved issue in VTTC estimation.

In the next two exercises, the data will be analysed again partially, but now in relation to the two components of the BVTTC separately.

4.5.1.2 Exercise 2 – Data split by Δt

In the case of Δt , there are only five levels for this variable in absolute terms (3,5,10,15 and 20). Hence, a more interesting analysis is to subdivide the data into five sub-samples, one for each level of Δt, rather than using ranges by quartiles. It is worth pointing out that this is possible with a RV model, but not with a RU model. One advantage of the RV approach is that, as long as there is variation in the BVTTC, the model can be estimated even if there is no variation in one of its two components (i.e. Δc or Δt). The RU approach requires variation in the levels of both time and cost changes to estimate the VTTC. Results are shown in table 10 together with those from the next section (exercise 3 explained in section 5.1.3).

The results show that the VTTC increases consistently with the level of Δt. Note, however, that sample size is much greater for two of the intermediate levels of Δt (Δt=5 and Δt=10). Therefore, only a small part of the sample observed the higher levels and other effects (e.g. personal/trip characteristics) may be at play in determining the higher values when Δt=15 and Δt=20. As it is expected, due to sample size, the precision of coefficient estimates is higher in those sub-samples with greater number of observations. However, the scale does not vary significantly across sub-samples, indicating that choices are made with a similar degree of certainty/uncertainty in all cases. The estimated covariates suggest that income and journey length effects take a similar magnitude for any level of time changes considered: income elasticity is around 0.4-0.5 and the effects of current time and current cost on VTTC approximately compensate each other so there is no journey length effect overall, in line with the previous exercise in section 5.1.1. Interestingly, the covariates used to approximate the journey length effect, β_{BC} and β_{BT} are both much greater when Δt=20, and of the same exact magnitude on average but opposite sign. This means that the effect of the base levels of cost and time are much greater when Δt=20, i.e. the effect of a trip characteristic is influenced by the choice scenario. In other words, some VTTC elasticities may not be constant. Additionally, there is also a sampling issue: only 286 individuals in the sub-sample for Δt=20. Therefore, it cannot be said whether base levels play a bigger role when changes (Δt) are higher or when the sample of individuals mainly comprises long and expensive trips (higher C and T). The fact that the effects of current cost and current time always compensate each other in every sub-sample provides strong evidence that journey length effects do not exist in this dataset, regardless of the levels of time changes. This exercise reinforces the idea that

Table 10. Data split by Δt and Δc - Estimation results RV model (Standard errors in parentheses)

	RV model ($\beta_{\Delta T} = 0$, $\beta_{\Delta C} = 0$)												
Δt	Est. VTTC p/min	β_{wtp}	β_{wta}	β_{el}	β_{eg}	β_{I}	β_{BC}	β_{BT}	$\beta_{\Delta T}$	μ	obs	Indiv.	LL
3	1	-0.597 (0.405)	-	-	0.602 (0.205)	0.519 (0.145)	0.488 (0.142)	-0.231 (0.19)*	-	0.65 (0.09)	2141	1100	-1067.9
5	2.89	0.285 (0.145)	2.13 (0.107)	0.487 (0.132)	1.34 (0.108)	0.389 (0.074)	0.365 (0.079)	-0.265 (0.104)	-	0.841 (0.05)	4485	1369	-2102.8
10	3.45	0.181 (0.125)	2.26 (0.088)	0.963 (0.084)	1.55 (0.103)	0.505 (0.071)	0.395 (0.085)	-0.446 (0.11)	-	0.834 (0.042)	4343	1565	-2440.6
15	4.89	0.0451 (0.51)	3.26 (0.34)	1.37 (0.16)	1.67 (0.21)	0.437 (0.15)	0.37 (0.2)	-0.534 (0.24)	-	0.967 (0.15)	684	298	-348.99
20	7.6	1.58 (0.27)	3.12 (0.29)	1.51 (0.25)	1.9 (0.32)	0.493 (0.17)	1.38 (0.3)	-1.38 (0.39)	-	0.766 (0.1)	1051	286	-628.88
ALL data	3.45	0.288 (0.08)	2.43 (0.07)	0.99 (0.06)	1.24 (0.06)	0.448 (0.05)	0.454 (0.06)	-0.22 (0.07)	-	0.827 (0.02)	12705	1874	-7034.3

	RV model ($\beta_{\Delta C} = 0$)												
Δc range	Est. VTTC p/min	β_{wtp}	β_{wta}	β_{el}	β_{eg}	β_{I}	β_{BC}	β_{BT}	$\beta_{\Delta T}$	μ	obs	Indiv.	LL
(5-15]	2.89	0.054 (0.16)	2.36 (0.46)	0.721 (0.16)	1.12 (0.33)	0.46 (0.13)	0.246 (0.1)	-0.2 (0.14)*	0.748 (0.36)	0.722 (0.15)	3593	1523	-1989.3
(16-35]	3.82	0.544 (0.23)	2.44 (0.42)	0.986 (0.14)	1.39 (0.11)	0.556 (0.16)	0.562 (0.2)	-0.478 (0.16)	0.558 (0.48)*	0.713 (0.21)	3455	1773	-2102.8
(35-75]	4.85	1.06 (0.26)	2.32 (0.12)	1.24 (0.19)	1.7 (0.12)	0.298 (0.09)	0.35 (0.11)	-0.338 (0.1)	0.252 (0.27)*	1.29 (0.31)	2972	1586	-1552.1
(75-300]	2.3	-0.44 (0.63)	2.11 (0.19)	0.303 (0.5)	1..37 (0.28)	0.469 (0.14)	0.669 (0.19)	-0.755 (0.22)	0.825 (0.35)	0.774 (0.14)	2685	1214	-1278.2
ALL data	3.18	0.264 (0.08)	2.3 (0.07)	0.766 (0.07)	1.3 (0.06)	0.466 (0.05)	0.426 (0.06)	-0.422 (0.08)	0.695 (0.07)	0.795 (0.02)	12705	1874	-6963.7
	* Not significant at the 90% level of confidence												

attention should also be paid to the design variables in relation to the estimation of covariates.

4.5.1.3 Exercise 3 –Data split by Δc

The data is split based on the quartiles of Δc for the last exercise. The results are also shown in table 10 above. The results from this exercise are close to those observed for the first exercise, where the data was split according to the BVTTC (which makes sense, since BVTTC= Δc/Δt). The VTTC varies slightly among sub-samples in a similar way. Initially the VTTC seems to increase with the level of Δc, but it falls again for the sub-sample with the highest Δc. Overall, the estimated VTTC is greater for the two intermediate sub-samples, where Δc is between 16 and 75. There is also one sub-sample, where Δc = (35,75), which gives higher scale and slightly more precise coefficients. As in section 5.1.1, this could be because this sub-sample mostly comprises values of the BVTTC which are close to the underlying VTTC of respondents.

In relation to observed heterogeneity, precisely in that particular sub-sample the estimates of all covariates are generally smaller. This is another sign that covariates estimates are sensitive to the values of the design variables. Additionally, the association of lower covariates with greater scale and estimation precision (this was also found in the first exercise) could be interpreted as a sign that those covariates estimates are probably more reliable. Therefore, the covariates estimates derived from models on the whole sample may be overestimated. Again, as in the previous exercise, the income effect is the most stable across sub-samples. For current level effects, both β_{BC} and β_{BT} increase in magnitude (with the exception of that sub-sample Δc = (35,75]), suggesting that the impact of current trip conditions may be greater for higher levels of Δc. Hence, again the elasticities are affected by design variables, and the same interpretation that in section 5.1.2 can be applied. Finally, the VTTC increases with Δt in the two extreme sub-samples and for the full sample ($\beta_{\Delta T}$ is not significant on the two intermediate sub-samples, perhaps due to lack of variation on Δt).

4.6 Conclusions

This chapter has investigated the role of the variables used in the SC experiment on the estimation of the set of VTTC (i.e. mean and covariates). In the simplest VTTC experiment, the design variables are time changes (Δt) and cost changes (Δc). Our aim is to increase our understanding of the reality of the distribution of the VTTC in a given population. For this, we used partial data analysis. A large dataset of individuals' responses from the last national VTTC study in the UK was employed. This dataset was split according to different levels of the design variable of interest (three exercises were carried out for the three different design variables: BVTTC, Δt and Δc). The estimation of the same model on each sub-sample provides insights into potential effects of the variable of interest. To increase the meaningfulness of our results, state-of-the-art model specifications were employed.

In the set of exercises conducted, we have observed that model estimates can be sensitive to the levels of the design variables analysed. This is also the case for a sophisticated model that could be regarded as part of the state-of-the-art in the field of VTTC estimation. Whether the influence of these variables on the estimates is part of individuals' true preferences is unknown. In any case, if model estimates (including the VTTC and covariates) are different in different settings, then by focussing the survey on specific settings, our sample level results will be affected accordingly. SC designs should be constructed bearing this in mind. At the modelling stage, good practice should at least try to control for those influences.

Splitting the data according to the valuation threshold (BVTTC) showed that, fortunately, the BVTTC does not have a direct and predictable impact on the estimated VTTC if the RV model is employed. The basic RU model employed at the beginning of the exercise did provide a VTTC which tended to the BVTTC, in line with Fosgerau (2014). However, the accuracy of the estimation did vary: more precise results are obtained the closer the levels of BVTTC are to the underlying VTTC. The estimates of covariates suggested, quite consistently, that: i) income effects are always present in a relatively similar magnitude, and ii) journey length effects do not seem to exist in the car context, since the VTTC seems to increase with current cost but decreases with current time always in a similar magnitude. This has major implications for appraisal, since it would suggest a move from the current recommended set of VTTC in the UK (which increases with journey length significantly; see Mackie et al., 2003). The inclusion of random heterogeneity (more in particular, the assumption of a lognormal distribution for the VTTC) improves greatly the model only if the full sample is analysed, but has no positive effect for the sub-samples. This is logical and it simply confirms that a wide range of BVTTC values is needed to capture the whole VTTC distribution (e.g. Börjesson et al., 2012). Another interesting finding is that the introduction of random heterogeneity does not seem to alter any conclusions in relation to the covariates included, i.e. deterministic heterogeneity.

The roles of Δt and Δc were treated in all exercises in different ways. Using a RV model, it is possible to account for variation with only one of the two variables simultaneously, since they are multicollinear with the BVTTC, already in the model. This also implies that goodness of fit cannot be used to determine which effect should be used in a RV model. Independently, they both seem to have a positive relationship with the VTTC, in line with the literature (see De Borger and Fosgerau, 2008). However, the selection of one or the other is not obvious and seems to have important implications. According to the first exercise, if Δc is selected as an additional covariate instead of Δt, the mean VTTC is different (lower if random heterogeneity is accounted for, higher otherwise), all other covariates have reduced effects and the scale of the model is higher. The impact on covariates implies that, if Δt is used as a covariate, the estimated set of VTTC will be much wider. In principle, Δt may seem more intuitive as an explanatory variable of the VTTC and is widely used (see Börjesson and Eliasson, 2014), but Δc is a potential alternative that should be considered by policy makers. Since both variables are technically capturing the same effect (identical model fit), it is not possible to decide based on empirical evidence. More research would be recommendable in order to approach the travellers' underlying VTTC and VTTC elasticities.

Given the existing issues and controversies around the roles and modelling of Δt and Δc in VTTC experiments, new ideas would be welcomed.

For example, one possibility could be to use, for the SC survey, only the value of Δt that is going to be used for appraisal. That is, relate the SC experiment to policy. After all, it seems that a decision is always made post-estimation. Therefore, if policy makers know that they would be interesting in knowing the VTTC of a population for changes of 10 minutes, this information could be used in the SC experiment. The consequence would be a simplification of the estimation process. Each person would consider different scenarios, each with a different price (Δc would vary across scenarios) for an homogenous good: a saving (or a loss) of 10 minutes of travel time. Fewer assumptions would have to be made, and the results would potentially be more reliable, only at the expense of not collecting information on valuation of other kind of goods (i.e. greater or smaller changes) which, nowadays, does not seem to be used in appraisal anyway.

Chapter 5

Conclusions

5.1 Concluding remarks

Understanding and approaching valuation of goods by human beings is not an easy task. Human minds are complex, valuations are never precise and/or unique. Our own human obsession with measuring everything numerically may take us through very complicated paths. Nevertheless, the existing conception of transportation policy makes it necessary to have some measures of how people value changes in travel time. The research carried out in this thesis is an attempt to take a step forward in this path.

The review of the existing literature on valuation of travel time changes revealed that more research would be welcomed in several respects, including the understanding of how valuation varies for different people or even for the same person, the nature and impact of data collection methods and new developments in modelling and estimation techniques. The current state of research in the area is outlined in Chapter 1 as an introduction to our work. Throughout the whole thesis, the work has greatly benefited from having been granted access to two datasets of travellers' choices from two major national VTTC studies: the last UK national study (ACHG, 1994; Mackie et al., 2003) and the last Danish national study (Fosgerau et al., 2007).

Chapter 2 analysed how the value of travel time changes (VTTC) varies in the population, including inter-individual and intra-individual sources of variation, from the angle of standard microeconomic theory. Some important insights and evidence from alternative behavioural theories were also considered. A key contribution of Chapter 2 is the development of a general picture (map) that brings together four important sources of VTTC variation: the size and sign of the changes considered (in both travel time and travel cost), journey length effects (through the assumption that journey length is correlated with current level of time and cost incurred by the traveller) and income effects. Based on this framework, we suggested that potential confounding between some of these sources of variations is likely to exist in practice. The empirical work, carried out on the dataset from the last national VTTC study in the UK, proved this to be true. In particular, the analysis revealed that the size of travel cost changes highly influences the VTTC. Nevertheless, this source of variation has not been included in almost all national VTTC studies in Europe (the only exception is the last Dutch national study, Significance et al., 2013). As a result of this omission , several recurrent popular findings in the literature may have been misleading. These have relevant implications for appraisal and transport policy-making. Among these findings are low valuation of small time changes and cost damping. First, chapter 2 concluded that the VTTC, *ceteris paribus*, cannot be said to be higher for longer journeys with the data available. This has also been found using more sophisticated models in chapters 3 and 4. Accounting for the different impacts of the SC design variables, together with the modelling of time damping rather than only cost damping, led to the disappearance of the journey length effect.

If we do believe that the VTTC should indeed increase with distance, there is a plausible explanation for not finding such result. This explanation lies in the data collection process. The respondents, in most VTTC studies, are interviewed about a trip they have recently made. Herein, the fact that is often forgotten is that respondents, in their regular life, must have made some choices that led them to undertake that trip (e.g. residential location choice, job location choice, mode choice, etc.). We may expect that people with high VTTC would tend to make life choices that lead to short trips. Therefore, to some extent it may be that the underlying VTTC explains the current conditions of the trip, and not the other way around. If we want to know how the VTTC varies with the distance of a trip (ceteris paribus) for a given person, then ideally we should be looking for individuals' choices under different trip contexts (e.g. offer each respondent few SC scenarios under each of the next three contexts: i) short distance trip, b) medium distance trip and c) long distance trip). We expect this "*previous-choices* effect" to be playing a role, and it would be impossible to disentangle it with existing data.

Secondly, the results in chapter 2 indicate that the typical finding of low value of small time savings, allowing the VTTC to vary with Δt (but not Δc), may be biased. Variation with Δc also plays a role. It is unclear how the VTTC truly varies with Δt when considering both SC design attributes in light of the overall findings of the thesis. Chapter 2 certainly highlighted this issue, leading to the subsequent analysis of chapters 3 and 4. In relation to income effects, these were are also affected by confounding, being found to be less relevant than in previous analyses of the same dataset. Additionally, loss aversion was found to be present in the cost domain, in line with the theoretical expectations, while inertia effects (i.e. the possibility that people may dislike changes per se) completely disappeared when all the sources of variation studied were accounted for simultaneously. These results have major implications in practice. The set of recommended VTTC currently used in the UK, which includes significantly greater VTTC for longer journeys and higher income groups, would be remarkably different. Before policy-makers continue to recommend appraisal VTTC values that vary with distance, we would highly encourage more research on what the true journey length effects are.

In chapter 2, all the analysis has been restricted to the use of one modelling framework. Random Utility (RU) model was used as the main framework, in line with the experience over the last four decades (see Daly et al., 2014) and allowing us to provide results that were comparable with the current recommended model in the UK, based also on RU. We are aware that this modelling approach is not the only option, and over the last few years a solid alternative approach has been used in other national studies in Europe. Hence, the natural continuation of this chapter was to explore these possibilities.

The focus of the analysis is diverted in Chapter 3 to look at new modelling developments. Until the last decade, it was common practice to estimate models assuming RU. The last national VTTC study in Denmark (Fosgerau et al., 2007) implemented a new modelling approach to estimate the VTTC that differs substantially from what was considered to be current practice: it assumed that the randomness mainly relates to valuation. This approach is based on early work by Cameron and James (1987), and although terminology is unclear, it could be referred to as Random Valuation (RV) approach. RV has become popular over the last years, being subsequently implemented in the last Swedish and Norwegian VTTC studies. In Chapter 3 we explored the relationship between these two popular approaches (RU and RV) and provided new empirical evidence on their comparison. To begin with, the new approach is only applicable if the choices of travelers were only based on a simple cost-time trade-off (i.e. two options-two attributes choice scenarios). However, in this simple context, it is a powerful alternative to RU. RU and RV approaches can be both derived from microeconomic theory, since they are equivalent in the deterministic domain: RU and RV only differ in the main assumption regarding the introduction of the error term. Therefore, none of them is theoretically preferred to the other. The comparative empirical work was carried out at four different levels of modelling sophistication. This analysis also allowed us to disentangle other effects that, in practice, may have been playing a role in the comparison (the RV approach, in the existing studies, has always been applied using logarithms and normally accounting for random heterogeneity). It seemed essential to disentangle those components which were not necessarily a part of the RV approach. RU and RV could then be compared in fair manner. The analysis was carried out for both the UK and the Danish datasets. The results showed that the RV approach fits the data better in both datasets, in line with the existing literature (e.g. Börjesson and Eliasson, 2014) and for all four levels of comparison. This suggests that the form of error heteroskedasticity assumed in the RV approach should be preferred. In general, the VTTC mean values do not differ significantly across approaches. However, the calculation of the mean VTTC requires the use of simulation in the RV approach unless some specific form of random heterogeneity (e.g. such that VTTC follows a lognormal distribution) is introduced, due to the specification of the logistic error term (related to the VTTC and the BVTTC). The use of logarithms also provides a better model fit than a linear specification in both datasets, although there are in-between options (e.g. Box-Cox specification) that has not been explored in this thesis and could provide better fit to the data (Daly and Tsang, 2009). When observed and random heterogeneity are included in the models, the VTTC do subsequently increase, possibly because they enable the models to capture the typically long right tail of the distribution (e.g. Börjesson et al., 2012). The results on the estimation of observed heterogeneity are not significantly different between approaches for the variables explored (income and base levels of time and cost). However, this was a restricted set of covariates, and further tests with a more complete set of covariates would allow for an interesting additional comparison of the RU and RV approaches. Finally, it was observed that the main model estimates and the pattern of comparison between approaches were surprisingly similar in the two different countries analysed. Since individuals in both countries and their travelling conditions should not, in principle, be identical, the similarities might be related to the data collection process: these two studies employed a very similar stated choice design. Overall, several questions were left open: e.g. why is the VTTC, in general, systematically lower with the RV approach? Does that mean that the current VTTC in the UK has been overestimated due to the use of a RU model? Why do preferences seem so similar in two different countries? In relation to the current VTTC for appraisal in the UK, we would argue that, even in the case that they were overestimated from the use of a RU model, they would have also been underestimated from the lack of random heterogeneity in the models in Mackie et al. (2003). Therefore, luckily these effects might have counteracted each other to some extent. In general, the analysis of the RV approach with its implications and possibilities constitutes an area which is increasingly attracting the interest of researchers. Much more could be investigated. For example, what can be said about the underlying individuals' choice behavior in light of the disparity between the approaches? We suggest the use of simulated data in order to get more insights into the relationship between RU and RV. It is crucial to remember that the only difference between the approaches, in practice, is the specification of the error term. With simulated data, precise assumptions can be made on the underlying behavior that lead to a dataset of choices.

Within the scope of this thesis, Chapter 3 encouraged us to explore the key question of how the VTTC varies across and within a population making use of the RV approach. Additionally, together with the results from Chapter 2, it also encouraged us to have a closer look at the impact of the stated choice design in VTTC estimation. In particular, the impact of the design variables that are present in the type of SC experiments that has been explored in the thesis: i.e. simple binary time-cost trade-offs. Those design variables are the boundary VTTC (BVTTC), Δt and Δc. First, the change in travel cost (Δc), which was identified as a key source of VTTC variation based on the results from Chapter 2, is a variable that is defined in the design. The same applies for the change in travel time (Δt). The researcher creates these variables for the experiment. Secondly, Chapter 3 showed the importance of the boundary VTTC on the travel choices that constitute the base of VTTC estimation. The change in travel cost and the change in travel time are the components of the boundary VTTC ($BVTTC = \Delta c/\Delta t$) . Consequently, research efforts in Chapter 4 were directed towards the design and the role of the boundary VTTC, Δt and Δc. Ultimately, the aim of this work has always been to understand and approximate the individuals' underlying set of VTTC of a population.

Hence, to complete this thesis, Chapter 4 investigated the role of the design variables on both the mean VTTC and the covariates estimates. The analysis included simultaneously, where possible, all relevant sources of variation mentioned throughout the thesis: income effects, journey length effects, sign and size effects and random heterogeneity. The research approach was based on Fosgerau's (2014) work, to which we refer to as partial data analysis. Using all car travelers responses from the UK study (Mackie et al., 2003), the dataset was split into four or five sub-samples based on the levels of a design variable of interest. Since we had three design variables, three different exercises were conducted: i) BVTTC, ii) Δt, and iii) Δc. To increase the meaningfulness of our results, state-of-the-art model specifications (taking as a base a RV model in logarithmic form) were employed. The estimation of the same model on each sub-sample provided valuable insights. It was observed that model estimates (both mean VTTC and covariates) can be sensitive to the levels of the design variable. The main result is that, regardless of whether preferences vary with the design variables in real life (something which is impossible to answer with the data available), model estimates are different in different design settings. Therefore, if a SC survey is focused on particular settings, our sample level results for the set of VTTC will be affected accordingly. The obvious implication is that the construction of SC designs should be taking this into account, while modelling specification should try to control for the influence of the design variables. However, this could instead be seen as a temporary solution given the current state of practice. The evidence found in this thesis suggests that issues around design variables and, in particular, Δt, will require plenty of innovative and creative thinking in order to move forward in the field. Several potential directions will be suggested in the final 5.2 section.

All the analysis and the evidence obtained throughout the thesis have allowed us to achieve our global target: increasing our understanding of the underlying set of VTTC in a population. A series of policy recommendations, some of which have already been suggested so far, is provided as a result. Many questions remain still unresolved, pointing towards avenues for further research.

5.2 Policy recommendations and avenues for further research

The field of valuation of travel time is still evolving. This thesis has explored a number of issues which seem crucial for the understanding of the topic. While more research would always be welcomed in some respects, some key policy recommendations can be extracted from our work. All recommendations are directly applicable to the UK case, since the last UK VTTC dataset was gently given to us to conduct our research. Some of them, if not all, are extendable to more general contexts.

Recapping on all work conducted, it seems that starting from the last chapter will create a better shape for the set of recommendations. The first recommendations relate to the data collection stage. Any VTTC study using SC experiments should bear in mind the potential influence of the design variables. If simple cost-time trade-offs are used to estimate the VTTC, then we should carefully decide the levels of the design variables: BVTTC, Δt and Δc. These variables influence model estimates. It is still unknown to what extent these variables influence real preferences, but the key fact is that, whether part of preferences or not, these variables will affect the estimated set of VTTC: both the mean VTTC and the estimated impacts of the covariates can be affected. Hence, the experimental setting should be carefully selected. Also, there is no reason to believe that this problem would not affect more complex SC experiments with more attributes (e.g. reliability). If any, the problem would be even less visible in those complex settings, where more research on the role of the design variables would be useful. In relation to the BVTTC, it is important to cover a wide range of values to capture the whole distribution (as it is pointed out by Börjesson et al., 2012), but it may also be useful to remain focused on a relatively narrower part of the range where one could expect the underlying VTTC to fall. Our research showed greater precision in all estimates the closer the range of the BVTTC was to the estimated VTTC.

In relation to the changes in time and cost (Δt and Δc), we could think of several alternative steps forward. On the one hand, one option is to continue with the current state of practice, wherein it would then be important to ensure a good coverage of values and to acknowledge that they will have to be controlled for at the modelling stage. In this sense, for modelling, there are potentially many ways of dealing with the design variables. For example, the variables could be related directly to the VTTC or they could be included in the error structure of the model. And there are plenty of ways of doing so. Our analysis shows that Δt and Δc may affect the VTTC, but their impacts change with the model specification and also with the sample used (i.e. the levels selected in the design matter). Hence, even if we make their relationship with the VTTC explicit in the model, their effect would not go away. Also, there are some recommended model specifications (RV approach) which cannot deal with both non-linear effects from both variables simultaneously due to multicollinearity. For unknown reasons, the mean VTTC and the covariates estimates may be affected by the choice of explanatory variable (i.e. Δt or Δc). Hence, a choice must be made by the researcher and this is not innocuous. We recommend the investigation of size effects on both time and cost domains.

Nonetheless, several alternative steps forward are possible. No matter what the modelling stage delivers, if design variables play a role, policy-makers would decide what to do with the set of VTTC that depends on them, e.g. Δt (and potentially Δc). So far, all European VTTC studies have led to a recommended set of VTTC based on a selected level of Δt (e.g. 11 minutes in the UK, 10 minutes in Sweden or the average over choice situations in The Netherlands). To obtain a VTTC for the selected Δt, all these studies had to rely on modelling work that analyses a sample where respondents considered a mix of Δt values. As we mentioned before, it seems that the selection of Δt is something unavoidable, given its influence on the VTTC that is always observed in practice. The first alternative step forward, given the issues with SP designs, is to move back to the use of Revealed Preference data (RP) or joint SP-RP might be seen as an option (see e.g. Daly et al, 2014). However, apart from the well-known difficulty to obtain RP data for VTTC, the observed choices would also suffer from the same size effects issue. The only advantage is that the VTTC estimations could be related to a few selected real life travel scenarios. Finally, we would like to suggest a second alternative step forward: continuing with SC designs, but relating the SC design directly to appraisal. In other words, policy-makers could consider the use of SC designs that only contain the desired appraisal level of Δt. Obviously, the question of how to select this level of Δt would remain open, while behavioural economists and choice modelers may argue that such action would reduce realism of surveys. However, we would argue that most people would still believe that there could be a reasonable level of Δt for which almost everyone would consider a time-cost trade-off (e.g. 10 minutes), irrespectively of the trip context (i.e. they can reveal a VTTC). Fewer assumptions would need to be made at the modelling stages (for example, the current need to control for the controversial size effects would disappear). Furthermore, the analysis of VTTC would become more homogenous: it would relate to one homogeneous good, i.e. 10 minutes saving (or loss), that every respondent would evaluate. In line with Börjesson and Eliasson (2014), we also believe that the study and treatment of size effects is one of the most critical unresolved issues in the field of VTTC.

Another clear recommendation for future projects on the VTTC follows from chapter 3. This relates to modelling specification. Again, where choices are made between two alternatives differing only in time and cost, the random valuation (RV) approach developed by Fosgerau et al. (2007) gives a much better explanation of the choices than a random utility (RU) model, regardless of the degree of model sophistication. This purely relates to the structure of the error term, necessary to estimate any model. The studies in the Scandinavian countries over the last years have already moved towards these modelling techniques (Daly et al, 2014). The consideration of the RV for VTTC modelling seems obvious. However, we have repeated throughout this thesis that more research (e.g. using simulated data) would be welcomed to increase our understanding of this modelling approach in relation to the more traditional RU approach. In practice, there are also different ways in which RV can be used that deserve more exploration. The particular form in which the RV is applied can be empirically chosen: logarithms seemed to fit the data better than a linear approach, but in-between alternatives could also be explored (e.g. Daly and Tsang, 2009). Also, the logarithmic form allows the estimation of a log-normal distribution for the VTTC in a straightforward way, and this distribution has been proved to be quite successful in many applications (see Börjesson and Eliasson, 2014). Another key point is that a distribution (whether lognormal or other) should be estimated as this allows the model to account for the right tail of the distribution (i.e. people with very high VTTC which could not be identified through the sample). In terms of the current VTTC used for appraisal in the UK, the use of the suggested modelling techniques has major implications. It should be noted, however, that it was not possible at the time of the study by Mackie et al., (2003) to account for random heterogeneity. Overall, using a RV model in logarithms such that the VTTC follows a log-normal distribution, the VTTC estimated using the same dataset would have been greater.

Thirdly, some recommendations can be made regarding heterogeneity in the VTTC in relation to personal and trip characteristics. First of all, according to our expectations and intuition, it seems that income is the variable which influences the VTTC in the most consistent way, no matter which model specification or survey settings are employed. For any sample or sub-sample of the UK dataset, the income elasticity has always been found to be around 0.25 and 0.5. No doubts remain that this variable has a real influence on people preferences (and hence on the VTTC). The same cannot be said about journey length effects. Distance effects can be approximated through the current levels of time and cost experienced by the traveller, which are highly correlated with distance (especially in the car context). In all the three chapters, models that include both effects (current time and current cost), and for any sample of the UK dataset, showed that VTTC could increase with current cost but would always decrease with current time in a way that the effects cancel out. It is highly recommended to account for both cost and time current level effects. The last VTTC study only accounted for current cost effect and consequently provided a set of VTTC which increases with journey length. The fact that this relationship may not exist is crucial for appraisal. Projects involving longer journeys would no longer be benefited over short-distance projects on grounds on higher VTTC. Following this, a key recommendation is to record a measure of distance in any VTTC survey, something missing in the last UK study (AHCG, 1996). This would help to avoid confounding effects with the design variables, that are normally correlated with the current reported levels. Also, when interpreting any results of VTTC variation with current reported levels, it should be remembered that people would have made earlier choices (based on their underlying VTTC) that led them to make their current reported trip: i.e. VTTC may influence current reported levels, and not the other way around.

Overall, more research would be welcome in any of the topics addressed in this thesis. In particular, we would encourage more investigation on the role of the design variables, namely the size of the changes in travel time and travel cost. It would also be interesting to apply some of the analyses carried out in this thesis to different contexts. This can involve different modes, datasets from different SC surveys, different countries, etc. Within the simple time-cost surveys explored in this thesis, a great avenue for further research is to conduct in-depth analysis of the distribution of people’s responses to the different price thresholds offered. Given the possibility to observe a boundary VTTC, it is possible to explore the share of respondents rejecting the boundary VTTC. This has been done in some studies for preliminary analysis, but it is possible to go beyond that. For example, we are currently carrying out work in this direction, investigating graphically how the share of respondents rejecting the BVTTC changes with variables that can be of interest: e.g. income, current trip conditions, size of changes, etc. Another idea is to attempt the observation of the VTTC rather than modelling. For this, we suggest the implementation of SC surveys which allow the respondents to state that they are indifferent between the two travel options considered. In that way, they would be able to reveal whether their VTTC is actually equal to the valuation threshold offered. Finally, another suggestion is to broaden all the analysis conducted here in relation to how the VTTC changes across and within individuals. It would be a great contribution to look at the same issues within more realistic choice scenarios (at the expense of losing simplicity) which include more variables and/or alternatives.

Research on valuation of travel time should always remain highly active. Nothing will ever be definite in the field of valuation of goods. Valuation happens in human minds. Hence, it is likely to change and evolve over time. And time, once again, is the most valuable resource humans have. There will always be challenges for us.

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List of Abbreviations

VTTC: Value of travel time changes

BVTTC: Boundary value of travel time changes

SC: Stated Choice

RU: Random Utility

RV: Random Valuation

Appendix A
The current UK model for the VTTC

In this section, details are provided for the current (original) model employed in last UK VTTC study (Mackie et al., 2003), from which the set of VTTC that is still used for appraisal was obtained. The model was specified as follows:

$$U_i = \beta_{\Delta c}\left(\frac{y}{y_0}\right)^{\eta_y}\left(\frac{c}{c_0}\right)^{\eta_c}(\Delta c_i) + \beta_{\Delta t}(\Delta t_i)' + \beta_{Ine} * Ine_i \qquad \text{(A.1)}$$

for i =1,2

with:

$$(\Delta t_i)' = Sign(\Delta t_i) * \left[(\Delta t_i) * (|\Delta t| \geq \theta) + \theta\left(\frac{(\Delta t_i)}{\theta}\right)^M * (|\Delta t| < \theta)\right] \qquad \text{(A.2)}$$

And where:

U_i is the utility for travel option i =1,2

y is income

y_0 is a 'reference' income

C is travel cost for the current (reported) travel option

c_0 is a 'reference' current travel cost

c_i is travel cost for travel option i =1,2

$\Delta t_i = t_i - T$ is the change in travel time for options i=1,2

t_i is travel time for travel option i =1,2

T is travel time for the current (reported) travel option

$(\Delta t_i)'$ is a time "perception function" to capture misperception of small time changes.

θ is the threshold (fixed to 11 minutes) parameter distinguishing between "small" and "high" time changes.

Ine_i is a dummy variable equal to 1 when alternative i coincides with the current travel option (i.e. when both (Δc) and (Δt) equal to zero).

$\beta_{\Delta c}, \eta_y, \eta_c, \beta_{\Delta t}, M, \beta_{Ine}$ are parameters to be estimated.

$(|\Delta t| \lesseqgtr \theta)$ are dummy variables expressed as conditions, equal to 1 if the condition is satisfied.

Most of the elements of this model are also present in our generalised UK model (chapter 2) and the reader is referred to the explanation provided there. The only element that differs in this model is the treatment of size effects. For this, Mackie et al. (2003) employed a "perception function" (equation A.2). The parameter M captures size effects on the time domain in a more restrictive way than $\eta_{\Delta t_{gain}}$ and $\eta_{\Delta t_{loss}}$ in our generalized UK model. If $0 < M < 1$, the marginal disutility (sensitivity) of travel time will decrease as Δt increases (within the range $0 < |\Delta t| < 11$, where this non-linear structure is applied). For values of $M > 1$, the marginal disutility of travel time would increase as Δt increases. If M cannot be said to differ from 1, the marginal time disutility would be equal to $\beta_{\Delta t}$ for all levels of Δt (i.e. linearity would apply).

The estimated results from our own replication exercise of their model (reported in Mackie et al., 2003), are shown in the table below.

Table 11. Current UK model estimates

Parameter	Current UK model (2003)	
	Est.	t-test
β_{Ine}	0.9	18.41
$\beta_{\Delta t}$	-0.103	-15.33
M	2.09	6.55
η_c	-0.409	-8.48
η_y	-0.366	-7.00
$\beta_{\Delta c}$	-0.0244	14.72
Null Log-Likelihood	-3283.438	
Final Log-Likelihood	-2690.983	
Parameters	6	
Adjusted ρ^2	0.179	