The selection of income measures in value of travel time models and their implications for the VTT, its cross-sectional income elasticity and transport appraisal

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Abstract

This paper investigates the extent to which the selection of income variables during the estimation of choice models underlying national value of time (VTT) studies affects the cross-sectional income elasticity and the resulting VTT. Using data from the most recent GB (Great Britain) national VTT study, we focus on two contentious issues in relation to the income variable, namely taxation and within household budget allocation. Our work finds that accounting for the progressive nature of income tax and social benefits both increase the cross-sectional income elasticity. In the same vein, assumptions regarding the within-household budget allocation affect the cross-sectional income elasticity. Although the cross-sectional income elasticity is sensitive to the selected income variable, the impact on the nationally representative VTT is insignificant if the stated preference sample is representative with respect to the income variable. The observed discrepancies between the cross-sectional and the inter-temporal income elasticity of the VTT highlight that using these elasticities interchangeably influences the evaluation of future transport infrastructure decisions in terms of value for money.

***Keywords**:* value of travel time, income elasticity, income measure, appraisal, non-business

***JEL classification**:* C25; D12; R41

Competing interests: None

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1 Introduction

The value of travel time (VTT) is a key parameter in transport appraisal (Daly and Hess, 2020). Assumptions made regarding the VTT are arguably as important for the outcome of cost-benefit analyses (CBA) of transport infrastructure investments as assumptions made regarding the discount rate (Small, 2012). Most VTT studies account for variations in the VTT across different trip purposes, where the distinction between business and non-business travel (e.g. commute and leisure) is especially relevant. Travel time savings for business travellers have often been connected to the cost-savings approach (CSA) through the wage rate. The benefits of reductions in travel time accrue to the business owners as the saved time can now be used productively.[1] For non-business travel, reduced travel time allows people to use their time for alternative activities (e.g. spending more time with family and friends). It is here that we can make a connection between travel time and income. Travellers may be willing to spend more money on shorter journey times to enjoy more time with others. More formally, the VTT is defined by the ratio of the marginal utility of time over the marginal utility of income (Mackie et al., 2003, Wardman, 2001). Both the marginal utility of income and time are not considered to be constant entities because of assumed decreasing marginal utility of spending more income and (or) time on given activities. In this paper, we focus on the marginal utility of income, which is generally assumed to be decreasing with income due to the decreasing marginal utility of consumption (i.e. satiation effects). Since the marginal utility of income is placed in the denominator of the VTT, the conjecture that the VTT increases with income is widespread in the literature.

For appraisal purposes, the relationship between income and the VTT is important for two reasons. First, for deriving nationally representative VTT measures, it is important to understand how the VTT varies across the different income (and other socio-economic) segments (e.g. Börjesson and Eliasson, 2018, Mouter, 2016). Second, CBA exercises require future VTT values to quantify the benefits of travel time savings for future travellers. Due to economic growth, future travellers are expected to have higher incomes and hence higher VTT values than current generations.[2]

Economic theory only informs us about the direction of the rate of change of VTT relative to the marginal utility of income but not the size of such income effects (Fowkes, 2010, Hensher, 2011, Hensher and Goodwin, 2004, Small, 2012). Analysts are thus dependent on empirical evidence which typically comes from discrete choice models estimated on stated choice (SC) or more rarely revealed preference (RP) (Daly et al., 2014, Brownstone and Small, 2005, Varela et al., 2018). Whether SC or RP, the data used for such modelling work is typically cross-sectional, i.e. with observations at one point in time, allowing analysts to study the impact of

[1] The most recent UK VTT study (Batley et al., 2019) uses a willingness-to-pay based approach for business travel accounting for the notion that some of the benefits may arise to the business traveller himself.
[2] The Department for Transport in the UK currently adopts an intertemporal income elasticity of one and uplifts the national VTT annually based on long-term expectations in GDP growth (see DfT, 2019, TAG Data Book A1.3.2).

income differences across people, but not the impact of income changes for the same person. Many national VTT studies find significant income effects on VTT in such cross-sectional data. Even excluding outliers, empirical evidence regarding the *cross-sectional* income elasticity for non-business trips ranges from 0.25 to 0.75 (MVA/ITS/TSU, 1987, AHCG 1996, Arup/ITS/Accent, 2015, Fosgerau, 2005, Gunn, 2000, Wardman, 2001, Mackie et al., 2003, Hensher, 2011).

A factor that may explain the observed empirical variation in the cross-sectional income elasticity is the selection of the income variable in the underlying choice models. In these choice models, the income variable represents the (travel) budget of the traveller such that the estimated marginal utility of income captures the shadow price of the (travel) budget. Inaccurate representations of the budget constraint may produce biased estimates of the cross-sectional income elasticity and the VTT (Fosgerau, 2005)[3]. Four potential sources of measurement error can be identified. First, disposable income can be perceived differently by individuals depending on their knowledge of differences between net and gross income including related social benefits. Second, it is uncertain whether people consider their private or household income, or some alternative allocation of disposable income within the household. Third, it is uncertain how budget is allocated between different classes of spending, including travelling (Deaton and Muellbauer, 1980). Lastly, more data specific reasons exist. Measurement errors can be incurred as income measures are typically captured only categorically in most surveys to increase response rates, and there is ample anecdotal evidence of survey respondents falsifying the income information they provide.

This paper focuses on examining the impacts of the first and second type of measurement error. More specifically, we test the impact of using alternative representations of the income variable – based on tax implications (i.e., gross, after-tax or disposable income) and household composition and intra-household dynamics (i.e., household, equivalised household and personal income) - on the VTT and its associated cross-sectional income elasticity. We base our analysis on the SC survey collected for the 2014/15 GB[4] VTT study (Arup/ITS/Accent, 2015) and study the impact of the selected income variable on the nationally representative appraisal values.

The second part of the paper moves beyond the cross-sectional income elasticity. CBA exercises require today's and future VTT values to quantify the benefits of travel time savings of travellers during the lifespan of a transport project. Due to economic growth, future travellers are expected to have higher incomes and hence higher VTT values than current generations. Limited attention has been paid to how the cross-sectional income elasticity relates to the inter-temporal income elasticity. In theory, when preferences are not subject to change over time, the two elasticities should be closely related as non-business travellers would simply

[3] By assuming an income elasticity exists, indirect utility is implicitly assumed to be non-linear in income.
[4] The 2014/2015 study excluded Northern Ireland, hence GB instead of United Kingdom (UK).

'adopt' the preferences of the higher income segment. In practice, the cross-sectional and inter-temporal income elasticities are, however, not consistent with each other (see Börjesson et al., 2012, Hensher, 2011, Mackie et al., 2003, Small, 2012, Wardman, 2001). Empirical evidence from meta-analyses of VTT estimates indicate that the inter-temporal elasticity of the VTT with respect to GDP (per capita) points towards a unit value (Abrantes and Wardman, 2011, Wardman et al., 2016). The latter evidence base is considered as the state-of-practice for uplifting the VTT over time with applied *inter-temporal* income elasticities between 0.5 and 1, with the lower bound set out for prudency (Sartori et al., 2014, De Jong et al., 2004, Bickel et al., 2006)[5].

The disparity between the cross-sectional and inter-temporal income elasticity on the VTT can occur for three reasons. First, the growth in the VTT over time may not arise entirely due to income effects but rather emerge due to other factors including changes in preferences, socio-demographics, journey quality, productive time use during journey, or technological advances over time. inter-temporal income elasticity inferred from meta-analyses may therefore represent a combination of effects when these confounding factors are not fully disentangled from the income effect (Laird et al., 2013, Arup and Leeds ITS, 2017). Second, the cross-sectional income elasticity may not be constant across income groups. By relaxing the conventional assumption of a constant cross-sectional income elasticity, Börjesson et al. (2012) and Börjesson (2014) provide empirical evidence that the (non-constant) cross-sectional relationship between income and VTT remains stable between two repeated VTT studies. They concluded that the (non-constant) cross-sectional income elasticity by income group can be used as the inter-temporal elasticity. Thirdly, the disparity between the cross-sectional and inter-temporal income elasticity can be the result of measurement error in the income variable used in cross-sectional studies. Fosgerau (2005) highlighted that the first and third are plausible explanations for the observed disparity and that the two are not significantly different from each other after taking these factors into account. In the final part of the paper we continue on this line of research and show the implications of adopting the cross-sectional income elasticity as inter-temporal income elasticity for transport appraisal.

The remainder of the paper is structured as follows. **Section 2** reviews the treatment of income in the VTT literature and provides the essential information regarding the 2014/15 VTT estimation framework which this empirical work is based on. Research questions are also laid out in this section. **Section 3** outlines the research methodology, while **Section 4** summarises the model results discusses policy implications. Finally, **Section 5** concludes.

[5] The unit value is in line with the cost savings approach (CSA), which is used for valuing business travel time and implies a unit income elasticity since all the released travel time is assumed to be utilised for productive work (Harrison, 1974, Wardman et al., 2015).

2 Literature review and research questions

2.1 Variations in income re-distribution measures

Fosgerau (2005) is one of the rare studies to have explored the impact of the choice of income variable on the VTT and its associated cross-sectional income elasticity. His work showed that by replacing gross income with after-tax income, the cross-sectional income elasticity increases and approaches the commonly adopted unit value for the inter-temporal income elasticity. An argument in favour of this approach is that after-tax income is a more accurate representation of the budget available for consumption and travel. Fosgerau (2005) only took into account tax implications but did not specifically adjust for social benefits (e.g. unemployment, housing subsidy etc.) despite the fact that such benefits significantly affect the budget available for consumption and travel especially for lower income groups. The use of real disposable income to characterise income effects on consumer behaviour is also recommended by Ben-Akiva, McFadden and Train (2019, p.42). This paper therefore sets out to account for social benefits in the income variable. This is in sharp contrast with VTT studies that have removed observations from the lowest income group during estimation, based on the rationale that income is not a key determinant of VTT for those who rely on benefits (e.g. Börjesson et al., 2012).

Statistically speaking, changing the income variable from gross income to after-tax income alters the shape of the income distribution in the sample (and population). It reduces the variation in income across respondents especially when tax rates are progressive. In terms of modelling implications, the smaller variation in after-tax income now needs to explain the same amount of cross-sectional variation in the VTT and thus explains the higher cross-sectional income elasticity observed by Fosgerau (2005). The same logic can be applied to social benefits that uplift disposable income at the lower end of the income distribution.

This paper uses the term '*gross income*' to measure the gross earnings from employment and investments only[6]. *After-tax* income accounts for tax deductions from the gross income and *disposable* income additionally takes social benefits into account. Past UK national VTT studies (including the 2014/15 GB VTT study) have used the gross household income in the non-business VTT models. Other international studies have adopted the after-tax income (Börjesson et al., 2012, Fosgerau et al., 2007, Ramjerdi et al., 2010). Within this context, we set out the following questions regarding the impacts of the use of after-tax and disposable income as opposed to gross income:

- **Question 1**: Is the cross-sectional income elasticity of VTT based on after-tax income variables higher than the one obtained using the gross income variable under a progressive tax system?

[6] This is different to the convention adopted by the UK Office for National Statistics, in which the gross income refers to the *original* income (from labour costs and take-home pay) plus the social benefits (ONS, 2015, p.4).

- **Question 2:** Is the cross-sectional income elasticity of VTT based on disposable income variables (i.e. additionally including social benefits and tax deductions) higher than that obtained using either the gross or after-tax income variables?

2.2 Variations in household composition and intra-household dynamics

It is reasonable to assume that individuals perceive their money budget differently depending on their household compositions and intra-household dynamics (Mackie et al., 2003, Wardman, 2001). Using the total household income as proxy for the travel budget assumes that household members have access to the income contributed by all household members. Alternatively, individuals can measure their travel budget based on their personal income levels or an uneven allocation of budget across household members. A common approach for dealing with the economies of scale in consumption within a household is to re-scale the household income based on the OECD (Organisation for Economic Co-operation and Development)-modified equivalence scale. The resulting 'equivalised' income measure offers a better assessment of expenditure patterns for households of different size and composition as each member of the household requires a different level of income to maintain a comparable standard of living (Anyaegbu, 2010). The 2014/15 GB VTT study made use of the household income as proxy for the travel budget for non-business trips.

In this context, this paper sets out to answer the following questions:

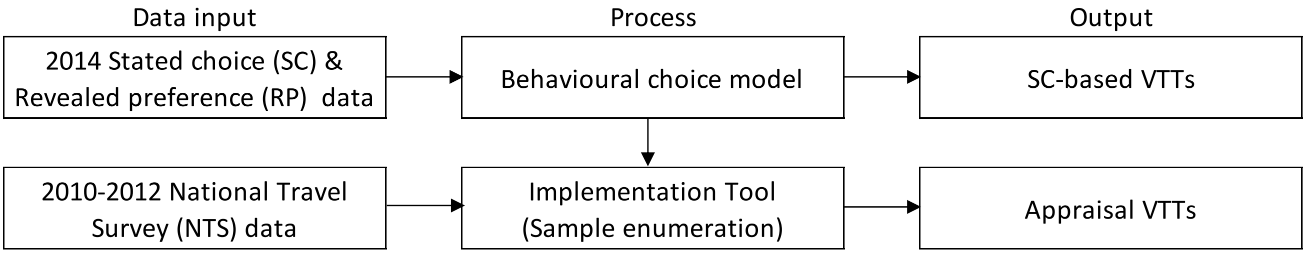
- **Question 3:** Is there a difference in the cross-sectional income elasticity of VTT when using personal income or household income?
- **Question 4:** Is the cross-sectional income elasticity of VTT when using equivalised household income different from that derived using household and personal income variables?

The potential direction of change in income elasticity is unclear from the outset for both questions since the difference between the perceived budget and respective income variable used may vary across respondents.

2.3 2014/15 GB VTT modelling framework

The 2014/15 GB VTT study produced a new set of value of travel time, reliability and other journey quality attributes for the Great Britain to be used in the appraisal of transport investment projects. To arrive at a set of nationally representative VTT measures that vary by mode-purpose segment, an elaborate data collection, estimation and implementation procedure was followed as described by **Figure 1**. Firstly, for 11 mode-purpose segments (modes: car, rail, bus, other public transport; purposes: commute, business, and leisure and other non-business travel - excluding the bus-business segment) Stated Choice (SC) data were collected supplemented by a limited amount of Revealed Preference (RP) data on rail operator choice for validation purposes. Advanced choice modelling techniques were applied to understand how the VTT values vary across various trip and traveller characteristics, including the various mode-purpose segments (see Hess et al., 2017).

Figure 1 – Overview of the 2014/15 GB VTT modelling framework



The 2014/15 GB VTT modelling framework incorporates and expands on the latest advances in VTT estimation techniques (see Hess et al., 2017 for details). First, this model framework made use of multiplicative error terms (Fosgerau and Bierlaire, 2009, Fosgerau et al., 2007), which was found to provide better performance and more reasonable results than the additive error structure during the model development. The multiplicative error structure facilities a constant variance for the error term, which is compatible with the general finding that utility variance increases as utility increases, a fact that is important in the context of studies combining short and long journeys. Second, the modelling framework also incorporates reference dependence in the form of size and sign effects relative to the 'reference' trip (De Borger and Fosgerau, 2008). This considers the common findings of the asymmetries (sign) of the VTT and also the non-linearities (size) of time or cost changes relative to the reference case (see Daly et al., 2014). Third, the impact of a wide range of trip and socio-economic characteristics on the VTT was examined alongside potential design effects as model covariates. These behavioural elements modelled include time, cost, distance and income elasticities of VTT; SP effects to consider the impact of the position of attributes and alternatives in the presentation of SC tasks; and finally covariates such as age, gender household composition and car ownership. Fourth, unobserved preference heterogeneity is incorporated in the VTT model, using flexible distributions within a Mixed Logit framework. Finally, data from all three SC games[7] were jointly estimated within a single modelling framework to increase robustness for parameters that are shared across games. The choice models directly estimated the VTT and the extent to which it varies with trip and traveller characteristics, including the cross-sectional income elasticity which is of key interest to this paper. Hence, for each observation in the sample a personal (or SC-based) expected VTT emerges as an output of the choice model.

As is commonly the case, the sampling strategy adopted in the SC survey was not nationally representative and particular segments were oversampled to better understand the key relationships for the VTT under given

[7] Three experiments are designed to collect trade-offs between time and money in SC1; time, money and reliability in SC2, and; time, money and quality in SC3 (Arup/ITS/Accent, 2015, Batley et al., 2019, Hess et al., 2017).

travel conditions (e.g. long- distance trips) (Arup/ITS/Accent, 2015, p.58). Deriving a nationally representative VTT thus requires applying the behavioural models to a nationally representative sample of trips and then averaging the trip specific VTTs using the necessary population and distance weights accordingly. Data from the National Travel Survey (NTS) over the 2010-2012 period were used for this purpose (DfT, 2014). To facilitate this procedure, a sample enumeration procedure was coded in *R* to connect the NTS data with the behavioural models and conduct the necessary averaging of trip specific VTTS. The output of this *Implementation Tool* was a nationally representative set of VTT for the different mode-purpose segments.

In this paper, we only focus on the commuting and other non-business trip (leisure) purpose segments. As explained in **Section 1,** it is in this context that a connection between the VTT and income can be made. In the business segment, the marginal utility of income is not measured when applying the cost-savings approach or the related 'Hensher-equation' (Hensher, 1977). More generally, there is potential confounding between the attribution of travel time saving benefits to the individual and the firm (see Wardman et al., 2015). The separation of the non-business trips into commute trips and 'other' non-business (non-work) trips is well-established practice in national appraisal guidelines for European countries (see Bickel et al., 2006). We limit ourselves to a single mode, namely car, to be able to present a focused discussion. Finally, we rely on estimates generated by SC1 (SC game 1, trade-offs between time and money) as used in deriving the official appraisal VTT (Batley et al., 2019). All the VTT estimates are in 2014 perceived prices, in £ (pound sterling) per hour.

3 Methodology

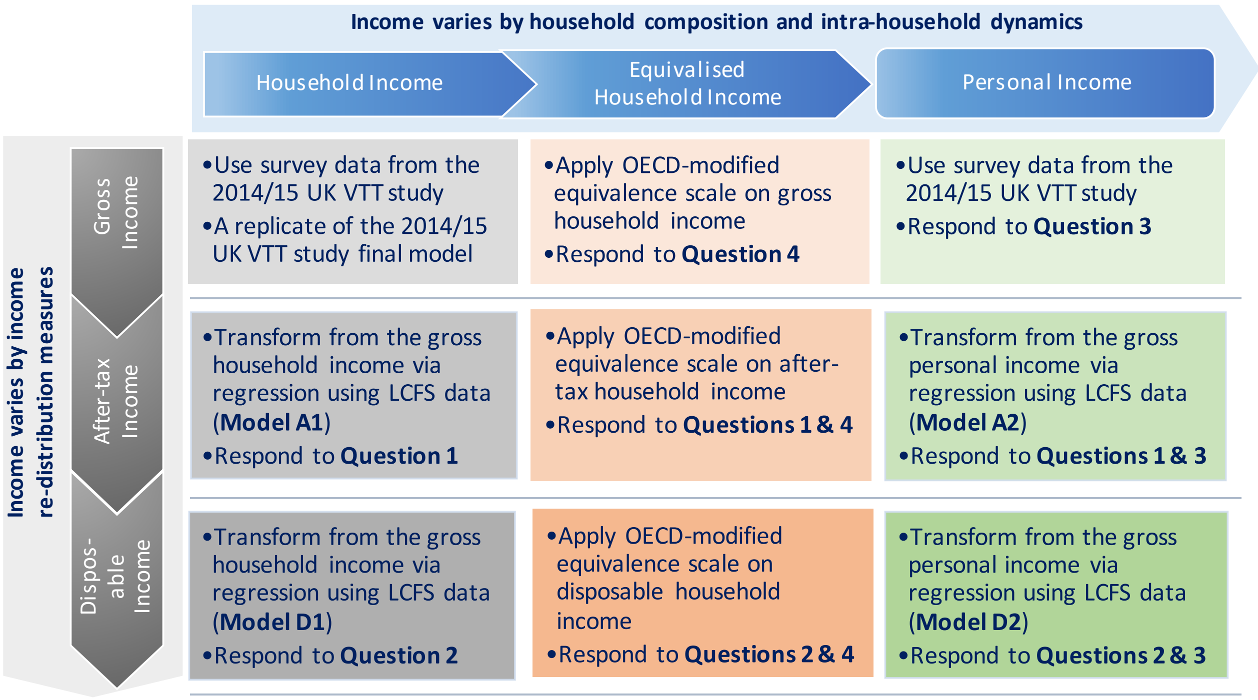
We re-estimated the behavioural models as used in the 2014/15 GB VTT study (Batley et al., 2019, Hess et al., 2017) on two mode-purpose segments, respectively car-commute and car-other non-business. The key variations that are introduced in this paper are associated with the income variable (nine combinations of gross, after-tax, disposable income; and private, household and household equivalised income, respectively). We will examine the impact of these income variables on the estimated cross-sectional income elasticity, the VTT derived in the SP sample and the appraisal VTT. The latter makes use of the Implementation Tool using the updated model specification and relevant income variables. The remainder of this Section will set out the nine alternative income variables used.

Figure 2 provides an overview of the nine alternative income variables and their connections with the research questions to be examined (See **Section 2**). The vertical axis depicts the transformation from the gross income to after-tax and disposable income, respectively. These three income measures vary depending on whether tax deductions and provision of social benefits are considered. The horizontal axis presents the variations in the assumption of within- household budget allocation. Notably, the income variable implemented in the

2014/15 GB VTT study for the two mode-purpose segments under considerations was the gross household income (top left).

The 2014/15 GB VTT survey only collected gross household and gross personal income, which was implemented by converting the categorical responses into actual income levels [8]. The transformations of these original income variables into after-tax and disposable income and equivalised household income for the purposes of this paper was more involved. **Appendix A** provides a full description of the necessary transformations, where we only provide a high-level discussion in this section.

Figure 2 - Overview of the income measurement approaches and the corresponding research questions



The conversion from gross income to after-tax household income is straightforward as the amount of tax deduction depends largely on the income level. Income is, however, taxed at the personal rather than household level in the UK. Hence, we rely on a regression analysis on data from the *Living Cost and Food Survey* (LCFS) to establish conversion factors for each household income band between gross and after-tax income. LCFS is the primary data source in the UK for assessment of the effects of tax and benefits on household income (ONS, 2015, p.26). The LCFS dataset is also used to transform the gross personal income into after-tax personal income, instead of applying the official income tax rates directly to gross personal income as in Börjesson et al. (2012) and Fosgerau (2005). This allows us to derive a realistic representation of the combined

[8] 'Midpoints' of each income category are assumed when converting categorical income variables to continuous variables, with the exception of £130K for the upper bracket, and £7.5K or £5K for the lowest category in the case of household income or personal income, respectively (Arup/ITS/Accent, 2015, p.126). A total of 8 categories were used.

tax deductions applied to taxpayers, which includes different types of direct taxes including income tax, council tax and Employees' National Insurance (NI).

The LCFS is also used to establish conversion factors to move from gross household and personal income (i.e. the top row in **Figure 2**) to disposable household and personal income (i.e. the bottom row in **Figure 2**). In determining the conversion factors, socio-economic information beyond income is also used to establish whether households or individuals are entitled to social benefits (e.g. child benefits). Households from the lowest income group are estimated to receive 112% additional income (£8.4K approx.) on top of their gross income from cash benefits on average while the top earning households are anticipated to pay 25% of income for tax deduction on average. Again, full details can be found in **Appendix A**.

In moving from the left to the middle column in **Figure 2**, the OECD-modified equivalence scale was applied. The measure falls in between household and personal income and assumes that household income is not distributed equally amongst all household members. Instead, the distribution depends on household composition and dynamics. In the UK, the OECD-modified equivalence values for the first adult, additional adult, child aged 14 and over, and child aged 0 to 13 are typically assumed to be 1.0, 0.5, 0.5 and 0.3, respectively (Anyaegbu, 2010, Howell et al., 2015, p.44). These values for children are simplified in our analysis since the number of children by age category is unavailable in the survey data. We therefore rely on the midpoint between the two equivalence values for children, i.e. 0.4. For instance, a family comprising two adults produces an equivalence household size of 1.5 (i.e. 1 + 0.5). Two additional children will push up the equivalence household size to 2.3 (i.e. 1 + 0.5 + 0.4*2). The equivalised income is the total household income divided by the equivalised household size. We apply this conversion factor to gross, after-tax and disposable income.

Figure 3 shows that for the car-commute sample the distribution of after-tax household is relatively skewed to the right, corresponding to the progressive tax system. Provision of social benefits, on the other hand, increases the available money budget for the lower income groups and thereby increases the lower bound of the disposable income distribution. Overall, the disposable income variable retains the shape of the gross household income variable but is squeezed inward at both ends, representing a reduced level of income variation within the car-commute sample. Similar effects are observed for other non-business trips.

The reduction in income variation when after-tax income is used can also be articulated through the calculation of the residual income progression (RIP) for measuring the degree of tax progression (Musgrave and Tun Thin, 1948; Jackobsson, 1976), which yields a weighted average elasticity of after-tax income of 0.879 with respect to gross income for the car-commute sample. A RIP value lower than 1 indicates a progressive tax system in GB. Accordingly, if we find a positive income elasticity of the VTT with respect to gross income, than due to RIP being lower than 1 but positive, the income elasticity of the VTT with respect to after-tax income will be higher than the one based on gross income. This argument is also used by Fosgerau (2005).

We have further expanded the RIP calculations to take into consideration disposable income rather than after-tax income. Accounting for income transfers, including social benefits, further reduces RIP from 0.879 to 0.736. Applying the same logic as in the previous paragraph, we can accordingly expect a higher cross-sectional income elasticity of the VTT with respect to residual (or disposable) income compared to its gross-income and after-tax income equivalents.

Figure 3 – Distribution of the household income to reference income ratio for commuters

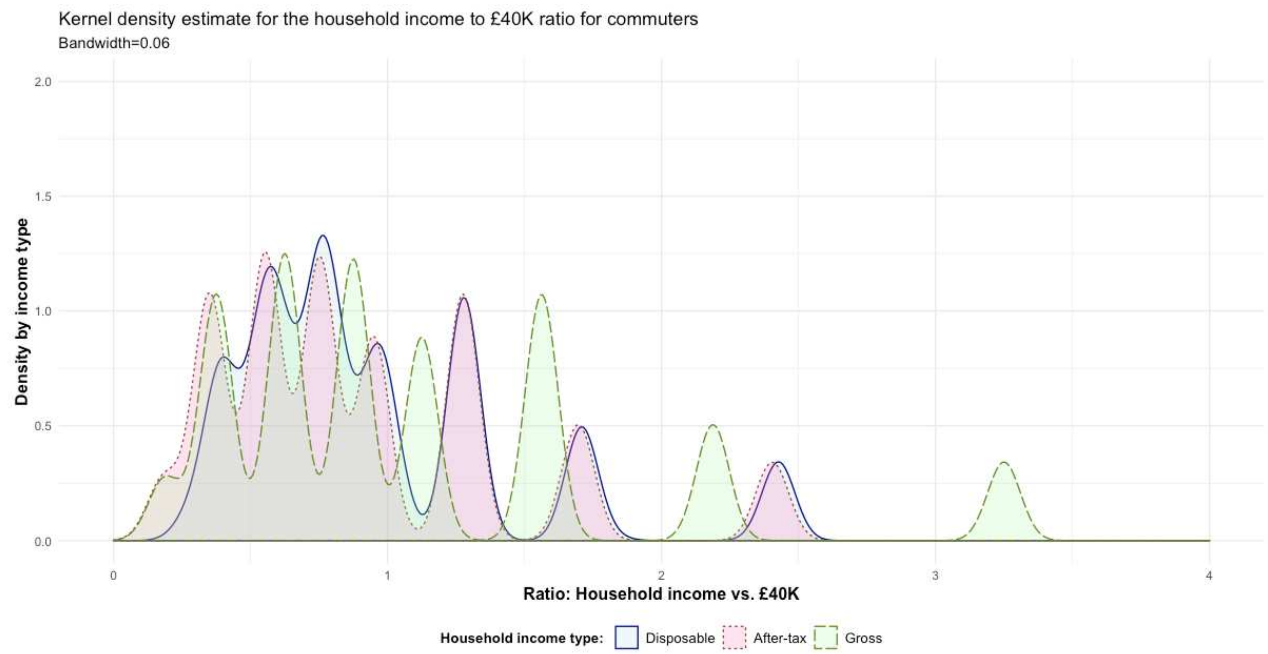
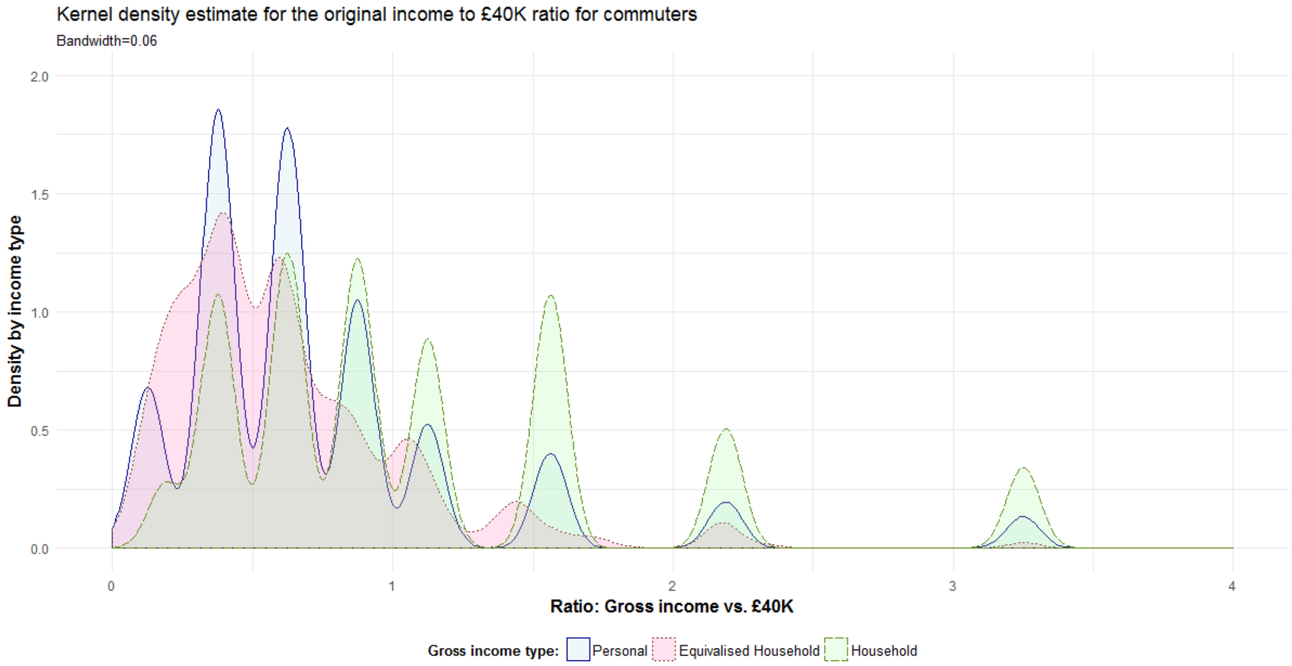


Figure 4 presents the income distributions for the gross household, equivalised household and personal income in the car commute sample. Overall, these three income distributions embody different shapes and there is no clear conclusion as to how the household budget allocation assumptions would affect the income elasticity, as previously. This explains the neutral formulation of research questions 3 and 4 in **Section 2**.

Figure 4 – Distribution of the gross income to reference income ratio for commuters



All the 9 income measures that differ in income measurement approaches are incorporated in the 2014/15 GB VTT modelling framework for estimation of (SC-based) VTTs, followed by the compilation of the nationally representative VTTs for appraisal, as described in **Section 2.3**. Further details on the interaction between income and the base VTT specified in the behavioural modelling framework and the VTT re-weighting by NTS trips are provided in **Appendix B**.

4 Empirical findings

4.1 Variations of income elasticities

Table 1 reports the eighteen estimated income elasticities based on the nine alternative income variables for the car-commute and car-other non-business samples. The discussion presented here focuses on the commuter trips as similar findings are observed for other non-business trips. The use of gross household income yields an income elasticity of 0.58. This is equivalent to the official income elasticity for commuting car trips recommended in the 2014/15 GB VTT study and forms our basis for comparison. The cross-sectional income elasticity increases as we progress vertically down **Table 1**, i.e. from gross income to after-tax income, and then further down to disposable income. When tax payments and social benefits are accounted for in the income variable, the cross-sectional income elasticity increases considerably to 0.64 and 0.78, respectively. This finding supports our hypotheses related to research questions 1 and 2. A similar pattern is observed for the use of equivalised and personal income. For other non-business trips, the income elasticity increases from a higher base of 0.68 to the near-unit elasticity of 0.93.

Table 1 – Income elasticities of VTT and final LL on the 2014/15 GB VTT data

Income Measure	Household Income				Equivalised HH Income				Personal Income			
	Final LL	Income Elasticity			Final LL	Income Elasticity			Final LL	Income Elasticity		
		Est	*t*-stat *vs 0*	*t*-stat *vs 1*		Est	*t*-stat *vs 0*	*t*-stat *vs 1*		Est	*t*-stat *vs 0*	*t*-stat *vs 1*
Commuting *(n=922)*												
Gross	-7332.67	0.58	*6.10*	*-4.42*	-7344.37	0.45	*4.84*	*-5.84*	-7356.05	0.32	*3.19*	*-6.80*
After-tax	-7332.74	0.64	*6.09*	*-3.38*	-7346.19	0.47	*4.60*	*-5.17*	-7356.29	0.35	*3.15*	*-5.87*
Disposable	-7332.06	0.78	*6.08*	*-1.71*	-7346.95	0.57	*4.43*	*-3.30*	-7351.96	0.54	*3.78*	*-3.18*
Other non-business *(n=977)*												
Gross	-7585.74	0.68	*7.76*	*-3.62*	-7595.96	0.59	*6.89*	*-4.76*	-7608.36	0.44	*5.96*	*-7.73*
After-tax	-7585.82	0.75	*7.77*	*-2.55*	-7597.58	0.63	*6.78*	*-3.90*	-7608.53	0.48	*5.94*	*-6.49*
Disposable	-7589.81	0.93	*7.35*	*-0.58*	-7598.97	0.83	*6.52*	*-1.29*	-7606.65	0.70	*6.12*	*-2.65*

The observed increase in the cross-sectional income elasticity using after-tax and disposable income can be explained by the fact that we have effectively tightened the income variations to explain the same VTT variations (i.e. trade-offs between time and cost). Empirical evidence in **Table 2** also supports this proposition, which shows that changes in the income elasticity of VTT estimates, relative to the gross income-based estimates, are relatively close to the inverse of the residual income progression values. Such finding supports hypotheses 1 and 2 that a reduced level of income variation, as in the after-tax and disposable income relative to gross income, will lead to increase of the income elasticity of VTT. Provided that the elasticity of disposable income is higher than after-tax income, income elasticity of VTT estimated by using disposable income will be higher than using after-tax income.

Table 2 – Change in income elasticity of VTT and residual income progression relative to gross income-based measure

Income Measure	Household Income			Equivalised HH Income			Personal Income		
	Income elasticity		Inverse of RIP	Income elasticity		Inverse of RIP	Income elasticity		Inverse of RIP
	Est.	vs. gross income		Est.	vs. gross income		Est.	vs. gross income	
Commuting									
Gross	0.58			0.45			0.32		
After-tax	0.64	111%	114%	0.47	104%	114%	0.35	109%	114%
Disposable	0.78	135%	136%	0.57	126%	136%	0.54	170%	135%
Other non-business									
Gross	0.68			0.59			0.44		
After-tax	0.75	110%	113%	0.63	107%	114%	0.48	110%	114%
Disposable	0.93	136%	145%	0.83	141%	135%	0.70	160%	154%

Comparing the final LLs vertically in **Table 1**, it is shown that the model fit remains stable. Indeed, the three behavioural models that incorporate different income measures all explain the same VTT variations but do so by using different income variables. Since the shape of the income distribution is largely retained except for being squeezed by the income transformation as shown in **Figure 3**, the behavioural model gains no additional explanatory power and thus the final LLs remain the same.

Household income consistently produces the highest income elasticities of VTT while personal income gives the lowest income elasticities of VTT overall. Such a finding of a lower elasticity of VTT generated by the use of personal income is contrary to the Scandinavian experience (Algers et al., 1995, Fosgerau et al., 2007, p.29, Ramjerdi et al., 1997, p.57). However, this finding still adheres to our hypotheses 3 and 4, which state that income elasticities can go either way depending on how respondents within the sample perceive their budgets provided the possibility of budget allocation within households.

4.2 Impacts on SC-based VTTs

Table 3 presents the average SC-based VTT for the car-commute and car-other non-business samples in the SC surveys based on the models associated with each of the nine income variables. We see that the average SC-based VTTs do not differ significantly across these nine income measurement approaches, with a range from £12.25/hr to £13.16/hr for commuters and similarly small variation for the other non-business segment. As we progress vertically down **Table 3**, the average VTT estimates remain largely unchanged, despite the increasing cross-sectional income elasticities when tax implications and social benefits are additionally accounted for in the income measurement as described earlier. Comparing the VTT estimates horizontally across **Table 3**, the personal income based VTTs are approximately 6% lower for car commute trips compared to the household income based values, which is not significant given the confidence intervals for the VTT[9]. Overall, the small variation in SC-based VTTs indicates that the measurement error due to assumed income variable is limited. For the car-other non-business trips, the average SC-based VTT estimates are comparable across the nine income measurement approaches, also shown in **Table 3**.

[9] The 95% confidence intervals for car-commute and car-other non-business journeys are 33% and 70%, respectively. The range of confidence intervals are also results from the flexibility given in behavioural models in terms of preference heterogeneity and functional form (Arup/ITS/Accent, 2015, p.249).

Table 3 – SC-based VTTs (2014 perceived prices, £/hr)

Journey Type	Income Type	Household Income		Equivalised HH Income			Personal Income		
		Mean VTT	Diff vs. Gross HH Inc	Mean VTT	Diff vs. Gross EqvHH Inc	Diff vs. Gross HH Inc	Mean VTT	Diff vs. Gross Pers Inc	Diff vs. Gross HH Inc
Commuting *(n=922)*	Gross	13.09	-	12.76	-	-2.5%	12.25	-	-6.4%
	After-tax	13.09	0.0%	12.70	-0.4%	-3.0%	12.25	0.0%	-6.4%
	Disposable	13.16	0.5%	12.75	-0.1%	-2.6%	12.33	0.6%	-5.8%
Other non-business *(n=977)*	Gross	9.29	-	9.17	-	-1.2%	9.17	-	-1.3%
	After-tax	9.28	0.0%	9.16	-0.2%	-1.4%	9.16	0.0%	-1.3%
	Disposable	9.33	0.4%	9.22	0.5%	-0.7%	9.23	0.7%	-0.6%

4.3 Impacts on appraisal VTTs

The nine behavioural models were next applied to the 2010-2012 NTS data to calculate the VTT for each trip within the NTS sample. The sample sizes in the NTS for the car-commute and car-other non-business are 95,758 and 413,198, respectively. Following the specification in the 2014/15 GB VTT study, the appraisal VTTs presented here are derived by weighting each trip by its corresponding expansion factors provided by the NTS survey[10] and by trip distance. The weighted averages as summarised in **Table 4** thus provide a nationally representative appraisal VTT for each mode-purpose segment[11].

Table 4 – Mean appraisal VTTs (weighted by NTS expansion factors and trip distance) (2014 perceived prices, £/hr)

Journey Type	Income Type	Household Income		Equivalised HH Income		Personal Income	
		Mean	St. err. Mean	Mean	St. err. Mean	Mean	St. err. Mean
Commuting *(n=95,758)*	Gross	11.70	*1.96*	11.20	*1.79*	8.97	*1.15*
	After-tax	11.70	*1.95*	11.02	*1.72*	8.97	*1.14*
	Disposable	11.79	*2.03*	11.20	*1.83*	9.23	*1.20*
Other non-business *(n=413,198)*	Gross	4.91	*1.74*	5.19	*1.79*	3.77	*1.17*
	After-tax	4.89	*1.72*	5.18	*1.77*	3.77	*1.17*
	Disposable	5.02	*1.89*	5.58	*2.02*	3.98	*1.25*

[10] The NTS expansion factors are provided to re-weight the trip rates to match the frequency of reporting long and short trips in NTS travel diaries to a nationally representative sample; it additionally accounts for non-response and drop-off in reporting trips (Lepanjuuri et al., 2017, Section 5).

[11] The income effect incorporated for deriving appraisal VTTs reflect income distribution of the travelling population, an approach which is recommended for appraisals of all sizes (for small, medium sized and major schemes and policies) in general for the UK (Batley et al., 2019).

The UK's official appraisal VTT of £11.7/hr for car commuting trips was derived using household income and acts as the point of reference. It can first be seen that all appraisal VTTs presented in **Table 4** are lower than their corresponding SC-based VTTs (see **Table 3**). For our reference case, the SC-based VTT reduces from the £13.1/hr to £11.7/hr based on the NTS data. Again, we observe that the VTT hardly changes when we move from the gross household income to the after-tax and disposable income despite the increase in the estimated cross-sectional income elasticity. This picture is consistent across the different assumptions made about the distribution of income within the household. In fact, the equivalised household income case results in highly comparable VTT values to the household income case. The largest discrepancy is, however, observed when applying the personal income variable, where the appraisal VTT drops somewhat unexpectedly to approximately £9/hr, which represents a 22% decrease relative to the official VTT for car commuters. This disparity is also observed for the other non-business trips.

It is not surprising to see that VTT differs between the stated choice and NTS samples, and hence the difference between the SC-based and appraisal VTTs. As noted in **Section 2.3**, the socio-demographics and travel characteristics for the SC sample cannot be fully representative, despite considerable effort put into representative sampling. Also, some market segments are purposefully oversampled to ensure recruitment of adequate samples of specific groups of target respondents (e.g. long-distance car and rail travellers). These residual biases in the sampling are anticipated to be corrected at the implementation stage to re-weight the SC-based VTTs for national representativeness. Given the limited variations in SC-based VTTs across all income measurement approaches, however, one would not expect such large differences in appraisal VTTs across the different income variables. The large difference in appraisal VTTs between the use of personal income and household income warrants further investigation below.

We trace back the potential causes of this discrepancy by providing a breakdown of the appraisal VTT calculation for the different income measures. The final model specification for commuting trips accounts for deterministic heterogeneity in traveller and trip covariates by estimating multipliers on the VTT, one of which is the income effect associated with the selected income variable. By comparing the average multipliers on VTT across the model specifications, we can pinpoint the specific multiplier that causes the disparity in appraisal VTTs.

Table 5 – Mean VTTs and mean VTT multipliers and commuting trips by using gross income (2014 perceived prices, £/hr)

	Gross Household Income			Gross Equivalised Household Income			Gross Personal Income		
	SC	NTS	Diff from SC	SC	NTS	Diff from SC	SC	NTS	Diff from SC
Base underlying VTT	10.19	10.19	0%	12.46	12.46	0%	10.20	10.20	0%
VTT multipliers - traveller covariates									
Aged 17–29 (vs. 30+)	1.07	1.06	-1%	1.06	1.06	-1%	1.06	1.06	-1%
Female (vs. male)	1.17	1.14	-2%	1.16	1.14	-2%	1.20	1.17	-3%
Self-employed (vs. any other)	1.05	1.04	-1%	1.05	1.04	-1%	1.05	1.04	0%
Travel costs paid by company (vs. respondent or other paid)	1.19	1.13	-5%	1.18	1.13	-5%	1.18	1.13	-5%
VTT multipliers - trip covariates									
Travelling with others (vs. travelling alone)	0.94	0.92	-2%	0.94	0.93	-2%	0.94	0.93	-2%
Light / heavy congestion (vs. free flow)	1.31	1.30	-1%	1.33	1.31	-1%	1.35	1.33	-2%
Driving on rural roads (vs. urban or motorway)	0.94	0.94	0%	0.95	0.95	0%	0.96	0.96	0%
VTT multipliers - key elasticities									
Time	0.99	1.52	54%	0.98	1.45	48%	0.98	1.44	48%
Cost	0.96	0.39	-60%	0.95	0.40	-58%	0.96	0.39	-59%
Income	**1.00**	**1.16**	**16%**	**0.76**	**0.89**	**16%**	**0.86**	**0.84**	**-2%**
SC-based VTT in SC / appraisal VTT in NTS (unweighted)	13.23	9.03	-32%	12.87	8.66	-33%	12.43	6.87	-45%
Appraisal VTT in NTS (weighted)		11.70			11.20			8.97	

Table 5 shows the mean values of the multipliers associated with each of the explanatory variables in the model. Multipliers on VTT for deriving the appraisal VTTs are grouped into 3 categories for presentation: traveller covariates, trip covariates, or elasticity-based multipliers. We first compare the average VTT multipliers for traveller and trip covariates between the SC and NTS data. The covariate effects that relate to the characteristics of travellers and trips are not significantly different between the two data sources and for different income measures. The decrease in average VTT multipliers in the NTS results is consistent amongst income measurement approaches that use gross household, equivalised household and personal income.

With respect to the elasticity-based multipliers, changes in the VTT multipliers for the travel time and cost between the SC and NTS data are quite large, but again consistent across income measures. This is because the commuting journeys in the NTS sample are shorter and cheaper on average. This finding is common in practice and reflects the difficulty in capturing shorter trips in field surveys. As a manifestation of the negative elasticity on travel time, the decrease of travel time pushes up the average VTT multiplier for travel time by 54%, from 0.99 to 1.52. In contrast, the decrease in average travel cost in the NTS sample leads to a 60%

reduction of the average VTT multiplier for travel cost, from 0.96 to 0.39, which is a direct result of reduced cost damping. Combining these two contrasting effects leads to a net decrease of the VTT in the NTS results relative to the SC results.

We finally look at the last remaining elasticity-based multiplier presented in the table. The income effect appears to have positive influence (+16%) on the base VTT by applying household and equivalised household income to NTS trips while it has limited impact (-2%) when personal income is in use. Given that other VTT multipliers are comparable between different income measurements, we conclude that the income effect is the driving force between the observed discrepancy between the NTS VTT based on household (and equivalised) income and personal income.

A further investigation shows that the differential income effects that affect the appraisal VTTs are a direct result of sampling bias. As shown in **Figure 5**, the SC survey appears to be under-representing household income in general. The mean household income in the NTS data is £56,650, which is 30% higher than the mean household income for SC respondents. The increase of household income translates into a 16% increase of the average VTT multiplier, from 1.0 to 1.16. In contrast, the personal income distribution does not change substantially between the NTS and SC data as shown in **Figure 6**. The mean personal income decreases by 2% only, which translates into a 2% decrease in average VTT multiplier, from 0.86 to 0.84.

The mismatch of the household income distribution between the SC and NTS sample raises an important question of which income variable should be used as the basis for the appraisal VTT computation. Economic theory does not provide any guidance as to which income measure is more justified. At best, an assumption can be made on what best represents the travel budget of the traveller. Indeed, there may be a mismatch between the two samples in the household income measure which does not rule out the latter as long as each income category is sufficiently covered in the SC sample. Hence, what we observe here is that the income measure in the SC survey is not sampled representatively and hence leads to diverging appraisal values, but we are unable to make a decision on which income measure is most appropriate, especially not without a new specification search with different income measures where model specifications that hinge on the choice of income variable are evaluated based on statistics including Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC). For completeness, the weighting does not contribute to the disparity between appraisal VTTs as shown in **Table 5**.

Figure 5 – Gross household income to reference income ratio for commuters (SC vs. NTS)

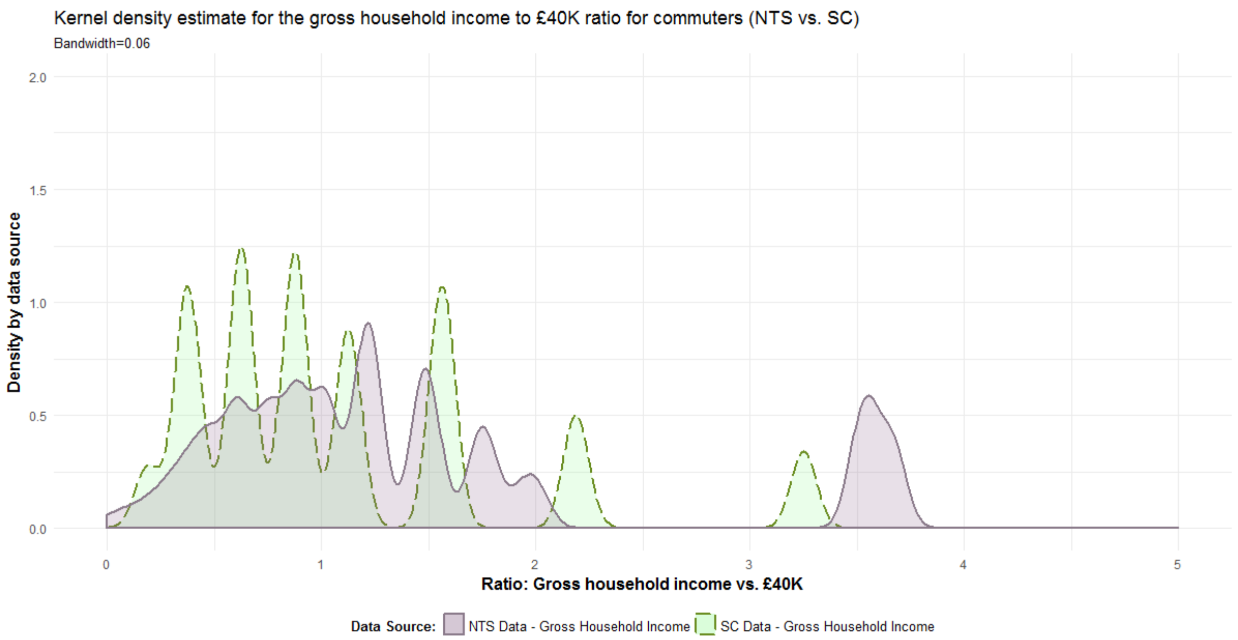
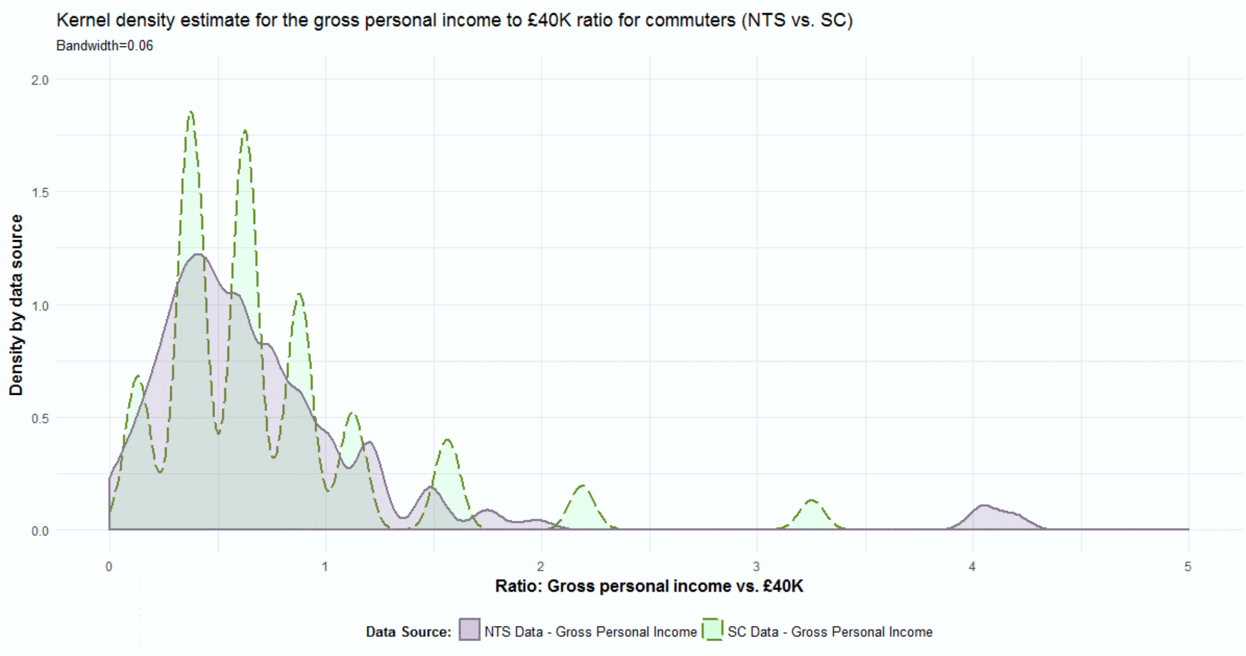


Figure 6 – Gross personal income to reference income ratio for commuters (SC vs. NTS)



4.4 Choice of inter-temporal income elasticity and implications for transport appraisal

The preceding results highlight that the VTT (based on the SC and on the NTS sample) for the base year 2014 shows little variation with respect to the income variable selected - provided the SC survey is sampled representatively. The cross-sectional income elasticity, however, does vary substantially across selected income variables. Indeed, this may be a direct and intuitive result based on the smaller cross-sectional variation in income when taxes and social benefits are considered. Nevertheless, the discrepancy between the cross-sectional and inter-temporal income elasticity prevails in most instances but varies in size. As argued in Section 1, unless preferences change over time, there is no direct reason to assume a difference between the cross-sectional and inter-temporal income elasticity of the VTT. The argument of using the cross-sectional income elasticity as the inter-temporal income elasticity is supported empirically by Börjesson et al. (2012). Although we are not able to confirm the argument of Börjesson et al. (2012) due to not having repeated (identical) SC surveys at our disposal and not having tested the non-constant cross-sectional income elasticity of the VTT, we display the impact of deviating from the unit inter-temporal income elasticity in the worked example below.

The inter-temporal income elasticity induces differences in the VTT over the span of the appraisal period. Impacts of transport investments are typically assessed over a standard 60 years of economic life in the UK (DfT, 2018, TAG A1.1). As a common starting point for all scenarios, we use the UK's official appraisal VTT of £11.7/hr for car commuting trips in the base year 2014. The first scenario adopts the official unit value for the inter-temporal income elasticity. Scenarios two-five adopt the cross-sectional income elasticities found in **Table 1** for respectively gross and disposable; and household and personal income (ranging between 0.32 and 0.78). **Figure 7** illustrates how the VTT for commuting in the UK increases over a 60-year appraisal period and diverges with the assumed inter-temporal income elasticity. Please note that income is assumed to grow based on forecasted GDP growth rates (DfT, 2019, TAG Data Book Annual Parameters). By 2074, the appraisal VTTs for commute based on a unit income elasticity is expected to be more than double than that when income elasticities of 0.32 or 0.54 are applied (i.e. the personal income based models).

The divergence in the VTT over time will lead to significant differences in the Benefit-Cost-Ratio (BCR). Assuming that a project is built between 2014-2017, each year incurring £5 million in investment cost. Once the project is finished, 100K hours of annual travel time savings for commuters will be realised in 2018; and these time savings are assumed to increase at 2% p.a. from 2018 onwards. Based on this simple worked example, we can apply the different time paths for changes in the VTT over time. Conventional assumptions on discounting are assumed. A BCR of 2.46 is computed based on the unit income elasticity assumption. The BCR, however, drops well below 2 in **Table 6** once the lower income elasticities are applied (1.48 and 1.75 respectively). In terms of the Department for Transport's Value for Money framework[12], this implies that the project drops from 'High' to 'Medium' in terms of its evaluation and hence may lead to significantly different policy conclusions.

[12] https://www.gov.uk/government/publications/dft-value-for-money-framework

Figure 7 – Mean appraisal VTTs for the commuting trip purpose from 2014 to 2074 (2014 prices)

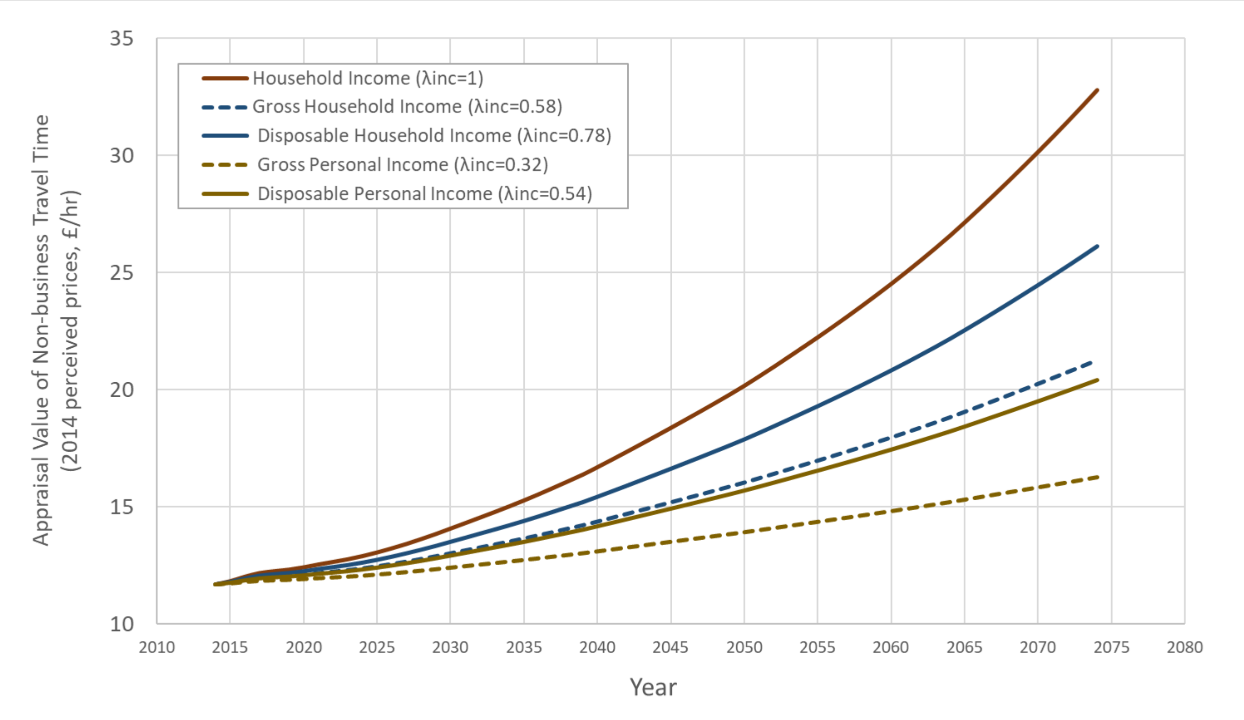


Table 6 - Benefit-to-cost ratios by different income elasticity assumptions (£, 2014 prices)

Project benefits and costs by different income elasticity assumptions (£, 2014 prices)

	λ_{inc}=1	Household Income		Personal Income	
		Gross	Disposable	Gross	Disposable
Income elasticity of VTT, λ_{inc}	1.00	0.58	0.78	0.32	0.54
Present value of costs (PVC)	£19,008,185	£19,008,185	£19,008,185	£19,008,185	£19,008,185
Present value of benefits (PVB)	£46,837,165	£34,330,965	£39,837,658	£28,195,254	£33,316,365
Net present value (NPV)	£27,828,980	£15,322,780	£20,829,473	£9,187,069	£14,308,180
Benefit-to-cost ratio (BCR)	2.46	1.81	2.10	1.48	1.75

Assumptions:

- *Project costs £5 million for the each of first 4 years (2014-2017)*
- *100K hours of annual travel time savings in 2018; increase at 2% p.a. from 2018*
- *Real GDP growth rates as in UK DfT's Transport Analysis Guidance Databook*
- *60-year appraisal period and discount rates as in the Green Book issued by UK HM Tresurary*

5 Summary and conclusions

The selection of the income variable in choice models for Value of Time models remains a contentious issue. Even across studies aimed at estimating nationally representative VTTs there is not only a discrepancy in the use of personal- and household-based income measures, but also in the application of before- and after-tax income measures. Such discrepancies have a direct impact on the derived cross-sectional income elasticity and can thereby partly explain the empirical disparity between the cross-sectional and inter-temporal income elasticity. The latter is typically found to take a value around unity, whereas the former is generally found to be lower. A better understanding of the cross-sectional relationship between income and the VTT is imperative, because economic theory only provides guidance on the sign (positive) of the cross-sectional income elasticity, but not its size. Moreover, unless preferences change over time there is no reason to assume that the cross-sectional and inter-temporal income elasticity should differ in size since lower income groups will adopt the preferences of higher income groups as income grows (e.g. Börjesson et al. 2012).

In Section 1, we argued that part of the empirical discrepancy between the cross-sectional and inter-temporal income elasticity could be caused by confounding of income changes with preference changes over time and by measurement error in the selected income variable. This paper has focused on the latter issue and studied the implications of using alternative income variables on the VTT, its cross-sectional income elasticity and the implications for transport appraisal. By adopting the modelling framework developed from the 2014/15 GB VTT study, we examined nine alternative income variables corresponding to a 3x3 matrix based on two dimensions: variation in the income re-distribution measures (gross-, after-tax, and disposable income) and variation in the assumption of within-household budget allocation (household, equivalised household and personal income).

In the first dimension, we find that the use of after-tax income rather than gross income yields higher income elasticity of VTT, a finding which is consistent with Fosgerau (2005). We extend this analysis by additionally accounting for social benefits to lower income groups. We demonstrate that the use of the latter disposable income, increases the cross-sectional income elasticity of VTT and further reduces the gap between the cross-sectional and inter-temporal income elasticity. This leads to a cross-sectional income elasticity which is not significantly different from the unit value typically assumed for the intertemporal income elasticity. Notably, accounting for measurement error in the income variable, in our case income re-distribution, does not affect the resulting VTT measures.

The observed increase in the cross-sectional income elasticity (relative to the gross income based estimates) is close to the inverse of the residual income progression (RIP). That is, the elasticity of the after-tax income and the disposable income relative to gross income is smaller than unity, and as articulated by Fosgerau (2005) one would expect a higher cross-sectional income elasticity for the VTT with respect to these alternative measures of income. In statistical terms, the progressive nature of the tax system alongside income redistribution reduces the variation in within sample income that can be used to explain the same variation in the VTT. This increases the cross-sectional income elasticity.

In the second dimension, we examine the impacts that assumptions regarding the budget allocation in the household have on the income elasticity and the VTT. The use of household income results in a higher cross-sectional income elasticity than personal income, which is followed by smaller reduction in income elasticity by using equivalised house income. Overall, household income produces the highest income elasticity amongst the income variables tested. Although this finding is contrary to findings from some Scandinavian studies, which found lower income elasticities by incorporating the household income for VTT estimation. It does, however, not contradict our proposition that changes in the income elasticity can go in either direction. Again, the VTT estimates are unaffected by using any of these 3 income variables.

Economic theory does not prefer any income measure (and hence elasticity of VTT) for non-business trips. Therefore, the answer to the question regarding the choice of income measure is not obvious. Intuitively, disposable income should be a better representation of a consumer's budget than gross and after-tax income. However, the relationship between perceived travel budget and intra-household dynamics is unclear making the choice of income variable less obvious. We therefore highlight the need for testing different income measures to understand their potential impacts on model estimation and welfare measures. The choice of income measure can in these circumstances be made on evaluation of model specifications such as the AIC and BIC statistics.

Within sample the choice of income variable may not influence the VTT. However, when additionally sample enumeration is needed over a representative sample to obtain a nationally representative VTT estimate which can be used for appraisal purposes, the choice of income variable requires additional scrutiny due to sampling bias. In the case of the latest VTT study for Great Britain, as used in this paper, the National Travel Survey (NTS) was used for sample enumeration purposes. We find that appraisal VTTs based on personal income are substantially lower than the (official) VTT based on household income. When moving from the stated choice sample to the NTS, VTTs are scaled down considerably to adjust for the shorter and cheaper trips sampled in the NTS data relative to the stated choice data. Field surveys typically struggle to capture short distance trips and these results highlight the impact this can have. More importantly, high income households are under-sampled in the stated choice survey, whereas the distribution of personal income is comparable between the two data sources. As a result, the appraisal VTT is adjusted upwards when using household income. We conclude that it is the sampling bias associated with the household income in the stated choice data that causes the disparity in appraisal VTTs and not the selected income variable. It is therefore imperative to ensure that the income distribution is sampled representatively in addition to carefully testing different income variables in the modelling. This may minimise adversarial impacts on appraisal VTTs.

Finally, turning to the inter-temporal income elasticity, there is indeed evidence preferences change over time. Increased productivity, due to technological advances and comfort improvements, may reduce the VTT alongside increases in income (ITF, 2019). As such, the observed empirical discrepancy between the cross-sectional and inter-temporal VTT is explicable but not desirable. In a worked example we showed how the VTT and the resulting Benefit-Cost ratios are affected – in terms of value for money - when replacing the unit value for the inter-temporal income elasticity with the lower cross-sectional income elasticity. Thus, despite having shown that the selection of the income variable may not be very influential for the base year VTT, the resulting cross-sectional income elasticities may have significant implications for long-term transport investments. Hence, additional empirical and theoretical research, along the lines of Börjesson et al. (2012), is needed on changes in the VTT over time and how this can be decomposed from income changes. As noted by ARUP and Leeds ITS (2017), more frequent repeat stated choice studies are needed to signal structural changes in preferences that differ from gradual changes as a result of growing income. Alternatively, we suggest that additional control variables are required to control for the difference in income measures in the derivation of the inter-temporal income elasticity.

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Appendix A Additional notes on income transformations

From gross income to after-tax income

The conversion from gross income to after-tax household income is straightforward as the amount of tax deduction depends largely on the income level. Income is, however, taxed at the personal level and not at the household level in the UK. Hence, we rely on a regression analysis on data from the *Living Cost and Food Survey* (LCFS) to establish conversion factors for each household income band between gross and after-tax income. LCFS is the primary data source in the UK for assessment of the effects of tax and benefits on household income (ONS, 2015, p.26). A simple linear regression model was developed to regress the after-tax household income on the gross household income over 5,130 income profiles in the 2014 LFCS.

$$AfterTaxInc_h = \sum_{i=1}^{8}\left(\beta_i * GrossInc_h * (GrossIncCat_h == i)\right) + C + \epsilon_h \qquad \text{(Model A1)}$$

The weekly gross income, $GrossInc_h$ represents the total gross earnings for household h before deduction of any payments of direct taxes and receipt of any cash benefits. The gross income term interacts with an indicator which is equal to 1 when the observation belongs to income group i ($h \in i$, with $i = 1, \ldots, 8$), and 0 otherwise. Weekly after-tax income, $AfterTaxInc_h$, represents the remaining income after taking into account income taxes, National Insurance (NI) and local taxes (e.g. council taxes). In this specification, β_i is the parameter estimated for income group i, C is the intercept and ϵ_h is the error term for household h. In the conversion of income in the SC data, the transformation function (i.e., β_i and C) is applied to 853 car commuters and 864 other non-business car drivers who have reported their income levels in the UK VTT sample. The results from the regression model and the income transformation in the SC data are summarised in the left part of **Table A.1**. The transformed income shows that the average tax burden rises with income, which is expected due to the progressive nature of the income tax in the UK.

Similar procedure is set out to transform the gross personal income to after-tax personal income. Instead of applying the official income tax rates to gross personal income as in Fosgerau (2005), and Börjesson et al. (2012), we apply the linear regression to establish the transformation function for personal income (Model A2). This allows us to derive realistic representation of the combined tax deductions applied to taxpayers, which includes different types of direct taxes including income tax, council tax and Employees' National Insurance (NI). The specification of the regression model to regress the after-tax personal income on the gross personal income for person p as follows:

$$AfterTaxInc_p = \sum_{i=1}^{8}\left(\beta_i * GrossInc_p * \left(GrossIncCat_p == i\right)\right) + C + \epsilon_p \qquad \text{(Model A2)}$$

All parameter estimates in Model A2 are significant at the 95% level of confidence, as shown in the right part of **Table A.1**. Average personal tax burden is estimated to increase from 4% for individuals who earn less than

£10K to 31% for the highest income group. Both R-squared values for Models A1 and A2 are very high at 0.98, which is not surprising for a society with progressive tax rates that closely link to income level.

Table A.1 – Regression results - After-tax income

Income group i		Model A1: After-tax household income (*AfterTaxInc$_h$*) — Regression (LCFS data *n=5,310)* Est	*t*-stat	Implied average tax burden (UK VTT SC data)** Commute *(n=853)*	Other NB *(n=864)*		Model A2: After-tax personal income (*AfterTaxInc$_p$*) — Regression (LCFS data *n=5,310)* Est	*t*-stat	Implied average tax burden (UK VTT SC data)** Commute *(n=845)*	Other NB *(n=851)*
	C	11.2617	4.18			C	1.7991	2.84		
1 <£10K	β_1	0.9047	35.12	2%	2%	β_1	0.9375	127.38	4%	4%
2 £10K-£20K	β_2	0.8956	80.67	7%	7%	β_2	0.8724	281.75	12%	12%
3 £20K-£30K	β_3	0.8631	124.17	11%	11%	β_3	0.8245	381.14	17%	17%
4 £30K-£40K	β_4	0.8434	164.33	14%	14%	β_4	0.7995	414.63	20%	20%
5 £40K-£50K	β_5	0.8307	193.11	16%	16%	β_5	0.7823	420.10	22%	22%
6 £50K-£75K	β_6	0.8072	281.31	18%	18%	β_6	0.7578	455.51	24%	24%
7 £75K-£100K	β_7	0.7685	316.11	22%	22%	β_7	*0.718**	-	28%	28%
8 >£100K	β_8	*0.735**	-	26%	26%	β_8	*0.686**	-	31%	31%
	R-squared: 0.9758					*R*-squared: 0.9816				

** Interpolated due to top-coding of LCFS data (GSS, 2014, p.22)*
***Average tax burden =1-After-tax Income ⁄ Gross Income*

From gross income to disposable income

Another set of regression models is estimated to transform the gross income to disposable income. In contrast to the after-tax income model (Models A1 and A2), where only the gross income is used as a regressor, the eligibility to social benefits depends also on socio-demographics. The linear regression models developed to relate the disposable income to the gross household income is specified as follows:

$$DispoInc_h = \sum_{i=1}^{8}\big((\alpha_i + \gamma_i Kid_h + \theta_i Old_h) * GrossInc_h * (GrossIncCat_h == i)\big) + C + \epsilon_h \quad \text{(Model D1)}$$

where Kid_h represent the number of children within household h; Old_h refer to the number of seniors (65+) within household h; α_i, γ_i and θ_i are the parameters estimated for income group i; C is the intercept and ϵ_h or ϵ_p refer to the error term for household h and person p, respectively. The regression results for disposable income are shown in the left part of **Table A.2.** By applying the transformation function (with α_i, γ_i, θ_i and C) on the SC data, it is shown that households which earn less than £20K are estimated to receive net gain in salary due to the receipt of social benefits. Households from the lowest income group are estimated to receive 112% additional income (£8.4K approx.) on top of their gross income from cash benefits on average while the top earning households are anticipated to pay 25% of income for tax deduction on average.

Table A.2 – Regression results – Disposable income

Income group i			Model D1: Disposable household income ($DispoInc_h$)					Model D2: Disposable personal income ($DispoInc_p$)			
			Regression (LCFS data *n=5,310)*		Implied average tax burden (UK VTT SC data*)***			Regression (LCFS data *n=5,310)*		Implied average tax burden (UK VTT SC data*)***	
			Est	*t*-stat	Commute *(n=850)*	Other NB *(n=861)*		Est	*t*-stat	Commute *(n=842)*	Other NB *(n=849)*
		C	255.10	57.99			C	132.50	79.45		
1	<£10K	α_1	-0.2511	-4.15	-112%	-93%	α_1	0.2057	8.28	-79%	-82%
2	£10K-£20K	α_2	0.1538	6.89	-23%	-20%	α_2	0.4781	50.40	1%	-1%
3	£20K-£30K	α_3	0.3755	27.91	2%	1%	α_3	0.5643	83.30	16%	13%
4	£30K-£40K	α_4	0.4883	50.01	11%	12%	α_4	0.6105	116.04	19%	18%
5	£40K-£50K	α_5	0.5525	67.40	13%	14%	α_5	0.6317	125.09	21%	20%
6	£50K-£75K	α_6	0.6010	114.86	18%	18%	α_6	0.6409	142.16	25%	24%
7	£75K-£100K	α_7	0.6293	155.86	22%	22%	α_7	0.636*	-	29%	29%
8	>£100K	α_8	0.645*	-	25%	25%	α_8	0.629*	-	32%	32%
Effect on disposable income as per the number of children within household h (Kid_h)											
1	<£10K	γ_1	0.6761	20.31			γ_1	0.3025	19.05		
2	£10K-£20K	γ_2	0.3087	22.56			γ_2	0.0694	9.15		
3	£20K-£30K	γ_3	0.1170	13.13			γ_3	0.0145	2.57		
4	£30K-£40K	γ_4	0.0444	6.69			γ_4	-	-		
5	£40K-£50K	γ_5	0.0239	3.90			γ_5	-	-		
6	£50K-£75K	γ_6	0.0071	2.22			γ_6	-	-		
Effect on disposable income as per the number of seniors (65+) within household (Old_h)											
1	<£10K	θ_1	0.1112	1.91			θ_1	0.4399	20.87		
2	£10K-£20K	θ_2	0.0737	4.85			θ_2	0.2031	20.88		
3	£20K-£30K	θ_3	0.0413	4.62			θ_3	0.1442	16.54		
4	£30K-£40K	θ_4	0.0396	5.03			θ_4	0.1167	12.01		
5	£40K-£50K	θ_5	0.0332	4.30			θ_5	0.1297	12.79		
6	£50K-£75K	θ_6	0.0422	8.54			θ_6	0.0827	7.32		
7	£75K-£100K	θ_7	0.0185	2.39			θ_7	0.082*	-		
			Adjusted R-squared: 0.9205					Adjusted R-squared: 0.8442			

** - Interpolated due to top-coding of LCFS data (GSS, 2014, p.22)*

*** - Disposable income vs. original income; (+): tax burden; (-): net benefits received*

A similar model specification is set out for transforming the gross personal income to the disposable personal income:

$$DispoInc_p = \sum_{i=1}^{8}\left((\alpha_i + \gamma_i Kid_h + \theta_i Old_h) * GrossInc_p * (GrossIncCat_p == i)\right) + C + \epsilon_p \quad \text{(Model D2)}$$

As shown in the right part of **Table A.2**, the R-squared value of 0.84 indicates that the regression model provides a lower fit by using personal income to predict amounts of social benefits, compared to the use of household income (with an adjusted R-squared value of 0.92). This finding is reasonable since eligibility of many types of social benefits including the housing benefits and child benefits, are dependent on household income rather than personal income

Appendix B Model estimation and sample enumeration

A continuous interaction between income and the base VTT is specified in the 2014/15 UK VTT behavioural framework to directly estimate a constant cross-sectional elasticity of VTT with respect to changes in income, given by the following functional form:

$$f(inc, VTT) = \theta_0 \left(\frac{inc}{inc_{ref}}\right)^{\lambda_{inc}} \quad \text{(B-1)}$$

where $f(inc, VTT)$ is the income elasticity formulation associated with the base underlying VTT, θ_0, as part of a range of interactions of VTT with different covariates (Hess et al., 2017, Table 2). Observed income and reference income are represented as inc and inc_{ref}, respectively; λ_{inc} refers to the cross-sectional income elasticity of VTT. Income is divided by a reference income of £40K to ensure that the base VTT corresponds to the respondent with an annual income of £40K. This specification is retained across all income measurement approaches for a fair comparison of the income elasticity estimates. The selection of the reference income does not affect the model fit or estimation of the income elasticity. For each of the 9 income measurement approaches, the designated income measurement for modelling, either collected by the 2014/15 UK VTT survey or generated by the income transformation, replaces the income variable inc in **Equation B-1**. Valuations of time for each respondent are averaged across the SC data to generate an average SC-based VTT value across sample.

Sample enumeration

The Implementation Tool that make use of the sample enumeration approach is retained in our analysis to compute the mean VTT across the NTS sample and the different confidence measures across different segments. This process involved calculation of the appropriate valuations (of time, reliability, etc.) for each NTS trip in the sample while acknowledging the relevant covariates, and the weighted averages over the sample to derive a nationally representative value. The NTS trips are weighted by both the expansion factor provided with the NTS data and also the trip distance. This implies that the VTT generated by the Implementation Tool is at an average kilometre basis. This process can be generalised as follows (see Hess et al., 2017, Equation 36):

$$\overline{VTT} = \frac{\sum_i w_i l_i E(VTT_i)}{\sum_i w_i l_i} \quad \text{(B-2)}$$

where $w_i$represents the expansion factor provided in the NTS data for trip i; l_i represents a trip distance for the NTS trip i for distance weighting, and $E(VTT_i)$ is the valuation formula from the behavioural model, which is as function of covariates, including the income elasticity of VTT.