Department for Transport

CONGESTION DEPENDENT VALUES OF TIME IN TRANSPORT MODELLING

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1 PROJECT BACKGROUND

1.1 INTRODUCTION

1.1.1. WSP, RAND Europe and Mott MacDonald were commissioned by the Department for Transport to conduct a feasibility study into the incorporation of congestion multipliers in highways and other transport models. This report details the investigations carried out and conclusions of that study.

1.1.2. The report covers a range of different subject areas. It presents a 'sense check' of the congestion multipliers obtained by Arup/ITS Leeds/Accent in the recent value of time and reliability project (Arup, ITS Leeds and Accent, 2015a), before going on to explore the practical and theoretical implications of using congestion multipliers in transport modelling and appraisal.

1.1.3. Congestion multipliers are applied to car values of travel time (VTT) in free flow conditions to derive congested VTT (CVTT), for example a congestion multiplier of one implies travel time in congestion is weighted equally to free flow travel time whereas a congestion multiplier of two implies travel time in congestion is weighted twice as highly as free flow travel time.

1.1.4. The sense check review has two linked objectives, first to provide an assessment of the robustness of the CVTT estimates identified by the Arup/ITS Leeds/Accent work, and second to assess the potential for confounding of the CVTT with the reliability valuations obtained in the same study.

1.1.5. Three sets of evidence have been analysed to address these objectives. Firstly, a detailed review of the ITS Leeds report has been undertaken, considering the design of the stated preference (SP) survey in addition to the choice modelling that was employed to determine the CVTT estimates. Secondly, a literature review has been undertaken to assemble benchmark CVTT estimates from the UK and elsewhere in Europe, and to consider how congested time has been presented and analysed in other SP studies. Thirdly, tests of the route choice implications of the congestion multipliers have been made using Trafficmaster data for a small sample of OD pairs.

1.1.6. The sections on the theoretical and practical implications for modelling focus on highway assignment modelling, but also consider public transport assignment, and demand modelling. Under 'practical implications' we discuss the capabilities of a subset of currently available software packages, and the possible impact on modelling consultants. We also consider the possible effects on economic appraisal.

1.1.7. The remainder of this report is structured as follows:

- Section 2 describes the SP survey used in the Arup/ITS Leeds/Accent work, presenting first an overview of the SP survey before going on to describe in more detail the SP experiment used to determine valuations of travel time in congestion. Section 2 also presents some analysis of the extent to which the SP survey respondents were able to understand the information that was presented to them.
- Section 3 discusses the SP modelling results, considering first the overall model results before going on to consider the results related to the congested travel time experiment in more detail.
- Section 4 considers the internal quality assurance and external peer review that was undertaken at the time of the modelling work in the light of the objectives defined for this review.
- Section 5 summarises the findings from the literature review, discussing each study in turn before concluding with a summary of the CVTT evidence.
- Section 6 documents the findings from the tests of the implications of the congestion multipliers on routeing using Trafficmaster data.
- Section 7 investigates the practical and theoretical considerations associated with implementing congestion multipliers in assignment models.

- Section 8 considers similar issues from the perspective of demand modelling.
- Section 9 looks at the impact on appraisal, in terms of the practicalities in undertaking the analysis, and the possible effect on results.
- Section 10 discusses how modelling consultants and their clients might be affected.
- Section 11 contains a risk register for including congestion multipliers in modelling and appraisal and suggests how these risks could be mitigated.
- Finally, Section 12 summarises our findings and sets out recommendations for further work.

2 UK VTT STUDY STATED PREFERENCE SURVEY

2.1 INTRODUCTION

2.1.1. The Department set the following aims for the 2015 VTT study:

- Provide recommended, up-to-date national average values of in-vehicle time savings, covering business and non-work travel, based on primary research using modern, innovative methods.
- Investigate the factors which cause variation in the values (e.g. by mode, purpose, income, trip distance or duration, productive use of travel time etc.) and use this to inform recommended segmentation of the values.
- Improve our understanding of the uncertainties around the values, including confidence intervals around the recommended values.
- Consistently estimate values for other trip characteristics for which values are derived from the values of in-vehicle time savings.

2.1.2. It can be seen from these objectives that providing up to date national VTT estimates was a primary focus for the study. While congested car time was to be estimated as part of ‘other trip characteristics’ there was not a requirement to provide recommended national valuations and this may have influenced the extent to which the congested car time data was subsequently analysed. This issue is discussed further in Section 3.

2.1.3. A total of 14 sets of SP (and Revealed Preference - RP) data were collected across different modes of travel and trip purposes. There are summarised in Table 1.

Table 1: Summary of surveys

Mode	Commute	Non-work	Employees’ business	Employers’ business
Car	SP	SP	SP	SP
Bus	SP	SP	n/a	n/a
Rail	SP&RP	SP&RP	SP&RP	SP
Other PT	SP	SP	SP	SP

2.1.4. The data for each mode was analysed separately and given that this review is focussed on the CVTT estimates we have only considered the data and analysis relating to the car SP surveys. For business, it is possible to calculate CVTT from both the employee and employer datasets, in the end it was decided that the employee values should be used, this issue is discussed further in Section 3.

2.1.5. Approximately 80% of respondents were recruited using an intercept approach, which for car involved sampling at motorway and A-road service stations and at petrol stations in towns or in local high streets. The remaining circa 20% of respondents were recruited by phone. This balance was arrived at to ensure sufficient long-distance trips, supplemented by short distance trips from the telephone recruitment approach. The target number of car interviews was 3,000, with targets of 1,000 for commute, employees’ business and other non-work.

2.1.6. This recruitment strategy resulted in a sample with a much higher than average proportion of long distance trips. This bias was explicitly controlled for by adding distance, time and cost elasticities to the estimated models which directly capture variations in VTT with distance, time and cost over and above the other terms represented in the models.

2.1.7. To generate nationally representative VTT a sample enumeration process was applied to a 2010–2012 sample of National Travel Survey data, and representative VTT estimates were calculated by applying the models to the trips in that sample and averaging the VTT.

2.1.8. For respondents recruited using the intercept approach, details of the journey they were making when they were intercepted were used to form the reference trip for the SP choice experiments. For respondents recruited by phone, details of a 'recent and typical' trip were recorded and used as the reference trip.

2.1.9. For the reference trip the amount of time spent in three traffic levels was recorded: free flow, light traffic and heavy traffic. The definition of these three levels is discussed further below. The cost of the journey was also recorded, in addition to fuel costs any parking, toll and car hire costs were recorded. No information about the perception of reliability for the reference trip was recorded.

2.1.10. Three SP experiments were presented to respondents:

- Time/money (SP1).
- Time/money/reliability (SP2).
- Time/money/quality[1] (SP3).

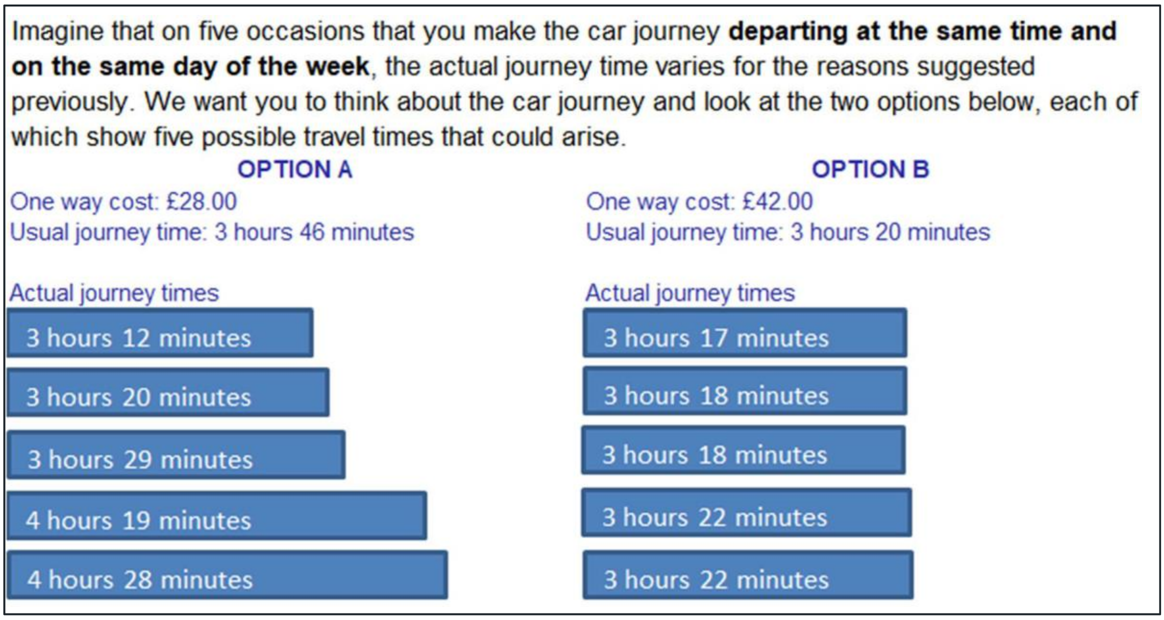
2.1.11. The SP1 experiment was always presented first, and then the order of SP2 and SP3 was determined randomly. Thus approximately half of respondents completed the reliability experiment, SP2, before completing the quality experiment, SP3. This may play a role in confounding between reliability and CVTT, this issue is discussed further in Section 3.

2.1.12. In SP1, the preamble instructed respondents to imagine free-flow conditions for car, and the experiment offered a choice between unlabelled alternatives, where the alternatives are described by differences in cost and time alone. The values of cost and time that were presented were pivoted around the values for the respondent's reference trip.

2.1.13. In SP2, a range of travel times was presented to respondents to represent the impact of reliability in journey times on individual's travel choices. In the absence of reliability information about the individual's reference trip reliability was not pivoted around the reference trip, however time and money were pivoted around the reference trip. For each alternative, five possible travel times were presented to respondents, as illustrated in Figure 1, which shows a choice between a cheaper but less reliable option (Option A) and a more expensive but more reliable option (Option B).

[1] Where quality is measured by level of congestion for car, and level of crowding for public transport.

Figure 1: SP2 experiment for car



Source: Arup, ITS Leeds and Accent (2015a).

2.1.14. It is noted that no probability was associated with each of the five travel times presented and so it was assumed that respondents interpreted each of the five travel times to be equally likely. Presenting probabilities was considered but in the end the Arup/ITS/Accent team decided against to avoid an over-complex presentation of information.

2.1.15. It is from the third quality experiment (SP3) thatvaluations of congested travel time have been obtained. This experiment is discussed in more detail in Section 2.2.

2.1.16. Five choice pairs were presented to respondents in each of the three experiments and therefore a total of 15 choice pairs were presented.

2.1.17. The designs[2] used for all three experiments are 'Bayesian D-efficient designs', reported by Arup/ITS Leeds/Accent to be state of the art in the field. D-efficiency is a specific error measure used to optimise the designs that result in reliable and unbiased parameter estimates when used properly. Efficient designs are optimised based on prior coefficient values selected by the analyst, reasonable priors are required but in this context these could be calculated drawing on experience from previous VTT studies. Bayesian designs allow for uncertainty in the prior coefficient values which optimises the design for a broader range of values of the coefficients and therefore makes the design more robust.

2.1.18. For the SP1 experiment the choice pairs presented to respondents were based around their reference trip. Therefore different priors were calculated for a set of representative trips, and then for a given trip the priors from the representative trip closest to the respondent's trip were used. Note that the characteristics of the

[2] The SP designs specify, for each of the 15 choice pairs, the levels of the attributes presented. For some of the attributes, the levels presented are based on changes relative to the respondent's reference trip to ensure that the choice pairs presented are as realistic as possible.

reference trip were deliberately not presented to avoid actively inducing reference effects whereby individuals exhibit a strong preference for their current trip. Dominant alternatives have been removed from the design[3], with dominance calculated using a regret measure.[4]

2.1.19. In addition to the information presented in the three SP experiments, a number of covariates were collected:

- Income, both personal and household, in bands.
- Distance and duration.
- Productive time.
- Trip type (urban, inter-urban, rural for car).
- Group size and composition.
- Driver versus passenger in the group size information.
- Trip frequency.
- Time of day.

2.1.20. Sixteen focus groups were undertaken in 2014 to help develop the SP survey. However, while the focus groups explored how best to present reliability to respondents (SP2), they did not explore how to best present congested travel time information to respondents.

2.1.21. A pilot survey was undertaken which is reported to have worked well with the three experiment format, and with little evidence of excessive cognitive burden on respondents. The relative valuations of VTT for commute, business and other non-work, and between time, reliability and quality (congestion/crowding) were as expected.

2.2 CONGESTION EXPERIMENT

2.2.1. It is the third quality experiment, SP3, which has been used to produce estimates of sensitivity to car travel time under different travel conditions, which are in turn used to calculate CVTT multipliers.

2.2.2. Travel time under three sets of travel conditions was presented to respondents, free flow time, light traffic and heavy traffic. These three levels represented a consolidation of the six levels presented to respondents in the M6 toll study (free flowing, busy, light congestion, heavy congestion, stop start, gridlock) (AECOM, 2009), and it could be argued that the three levels represent an over-simplification of the range of traffic conditions respondents face in reality. In particular, as discussed further below, the information presented for heavy traffic levels is likely to have caused confusion for respondents. The time attributes presented to respondents were not pivoted around the reference trip, however cost was pivoted around the reference trip. Figure 2 shows the information that was presented.

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3 Dominant alternatives are alternatives that are superior to the other alternative for all of the attributes presented.

4 In a random regret model, individuals are assumed to choose the alternative that minimises regret. This is in contrast to the utility maximisation approach used in most choice modelling studies where individuals are assumed to choose the option that maximises utility. To calculate dominance using a regret measure, the approach set out in Bliemer *et al.* (2011) was followed.

Figure 2: Traffic conditions presented in SP3 experiment

	**Heavy traffic** – your speed is noticeably restricted and frequent gear changes are required
	**Light traffic –** you can travel close to the speed limit most of the time, but you have to slow down every so often
	**Free flowing –** you can travel at your own speed with no-problems over-taking

Source: Arup/ITS Leeds/Accent (2015a).

4.1.1. No further information was presented on the meaning of these three levels such as average travel speeds or average delay times, and in the case of heavy traffic what proportion of time is spent in stationary traffic. Therefore different respondents may have made quite different assumptions about what the heavy and light traffic levels mean which would lead to heterogeneity in their valuations of these two levels.

4.1.2. A further issue is that the visual presentation associated with heavy traffic looks like total gridlock or stop-start traffic (the cars are so close it suggests that the traffic is not moving or moving only very slowly) and this is likely to have resulted in higher valuations for travel time in heavy traffic than were intended given the text description of the level. It is further noted that in the M6 toll study, the image used for the ‘gridlock’ traffic level was identical to the image used in the Arup/ITS Leeds/Accent study for heavy traffic. It is not clear why the Arup/ITS Leeds/Accent project team decided to use an image that had previously been used to illustrate gridlock conditions to illustrate a somewhat lower level of congestion in the study. A potential improvement in any further study would be to present a short video for each traffic condition which would effectively illustrate differences in average speeds, and the percentage of time spent stationary, between the three traffic conditions.

4.1.3. In the SP3 experiment, respondents were asked to choose between two alternatives with different amounts of travel time at each of the three congestion levels alongside a travel cost. Figure 3 shows an example choice pair. Total travel time for each option is broken down into three components, time in free flow conditions, time in light traffic conditions and time in heavy traffic conditions. As noted above, five SP3 choice pairs were presented to each respondent.

Figure 3: Example SP3 choice pair

	Option A	Option B
One way travel cost	**£37.60**	**£42.00**
Traffic Conditions	1 hour and 45 minutes in heavy traffic 11 minutes in light traffic 2 hours and 53 minutes in free flowing traffic	2 hours and 11 minutes in heavy traffic 2 hours and 36 minutes in light traffic 57 minutes in free flowing traffic

Source: Arup/ITS Leeds/Accent (2015a).

4.1.4. In this example, Option B involves more travel time in light traffic and heavy traffic conditions, takes longer overall, and is more expensive. Option A is therefore dominant and we would expect it to be the preferred option. This example is for a long trip, and there is a question as to whether respondents can fully imagine the choice options presented given such high levels of travel time at different levels of congestion. If they cannot, they may use a simplified decision rule to make their choice, for example minimising cost and time in heavy traffic. This hypothesis could be tested through further analysis of the SP3 data. A further consideration is that respondents are likely to take a break during long trips and breaks were not included in the information presented to respondents. Given that the recruitment has resulted in significant fractions of long distance trips it would be worth exploring whether the sensitivities to congestion that are identified from analysis of the SP3 data vary with distance.

4.1.5. It is concerning that the example SP3 choice pair presented in the Arup/ITS Leeds/Accent report shows a dominant choice. That report states that all choices associated with dominant alternatives identified using a regret measure have been removed, however it is not clear how this regret measure was calculated and why the example in Figure 3 was not identified as a dominant choice and removed from the design. If a significant number of dominant choices have been retained in the SP3 data then these may have biased the congestion multiplier valuations, and therefore we would recommend checking how dominant choices were removed from the SP3 design.

4.1.6. To ensure that the choices presented to respondents were realistic, constraints were imposed to ensure that the total distance implied by the two options varied by no more than 25%. Distance was calculated assuming light traffic speeds to be 80% of free flow and heavy traffic speeds to be 60% of free flow. However, respondents may have associated lower speeds with the light and heavy traffic levels that would imply that the total perceived distance varied by more than 25%, and this would reduce their likelihood of choosing options with higher levels of congestion.

4.2 RESPONDENT UNDERSTANDING OF MATERIAL PRESENTED

4.2.1. Two sets of analysis are presented in the Arup/ITS Leeds/Accent report which give insight into the ability of SP respondents to understand the material that was presented to them. First, cognitive depth analysis undertaken while the SP surveys were being developed and piloted, and second diagnostic testing using information collected during the main survey. These two sets of analyses are discussed below.

Cognitive Depths Interviews

4.2.2. Cognitive depths is a type of interviewing technique which focuses on respondents' thought processes in answering survey questions and uses specialised techniques such as thinking aloud, probing, observation and paraphrasing. Ten interviews were undertaken at the pre-pilot stage and a further ten were undertaken during the pilot.

4.2.3. In terms of the survey as a whole, the questionnaire was found to work well in terms of flow and routeing. Most respondents said that they enjoyed completing the questionnaire and that they found the SP exercises either 'easy' or 'fairly easy' to understand. In general, respondents found the background travel questions to be clear and did not have issues in answering questions about the time and cost of the reference trip.

4.2.4. In terms of the SP3 congestion experiment, in the first stage the SP preamble was considered by some to be too long and detailed and it was therefore amended to be clearer to respondents. Some respondents reported that they felt SP3 to be more realistic than SP1 as it included a 'comfort' factor. Overall, the respondents reported that they understood the SP exercise and were able to make informed choices. Note that these findings relate to the SP3 experiments for all modes rather than the car experiment alone.

4.2.5. In summary, there is no evidence from the cognitive depths interviews that respondents had difficulties in understanding the SP3 congestion experiment.

Diagnostic Testing

4.2.6. The diagnostic questions were collected as part of the main SP survey. For each of the three choice experiments respondents were asked to indicate the extent to which they agreed or disagreed with a set of four questions. The following set of four tables summarise the results from the diagnostic questions that relate to the SP3 experiments. Note that these numbers include rail, bus and other PT respondents as well as car respondents.

Table 2: I was able to understand the choices I was presented with

	Total	CATI interviews	Online interviews
Strongly disagree	2%	1%	2%
Somewhat disagree	3%	2%	3%
Neither agree nor disagree	12%	12%	11%
Somewhat agree	32%	23%	34%
Strongly agree	51%	62%	49%
Mean	4.27	4.43	4.24
Base	8,486	1,380	7,098

4.2.7. Over three-quarters of respondents either somewhat agreed or strongly agreed that they were able to understand the choices that they were presented with, and over half strongly agreed. These responses indicate a good level of overall understanding of the SP3 choices. However, the car results are not presented separately from the all-mode figures and it is possible that the level of understanding of the car SP3 experiment was significantly different from the overall figures.

Table 3: I found the options that I was presented with realistic

	Total	CATI interviews	Online interviews
Strongly disagree	4%	3%	4%
Somewhat disagree	9%	4%	10%
Neither agree nor disagree	20%	17%	20%
Somewhat agree	34%	24%	36%
Strongly agree	34%	51%	30%
Mean	3.84	4.16	3.78
Base	8,486	1,380	7,098

4.2.8. Overall, just over two-thirds of respondents somewhat or strongly agreed that the options they were presented with were realistic, though only 13% disagreed that the options were realistic as one-fifth of respondents neither agreed nor disagreed. Thus, while respondents were less positive about the realism of the SP3 choices than they were about their ability to understand the choices they were presented with, only a small minority found the options to be unrealistic, and furthermore it is possible to give reasonable answers to unrealistic questions. Note that while respondents may have found the options realistic this does not mean that the journey options presented to respondents related closely to their typical journeys, as discussed earlier a high fraction of long-distance journeys have been intercepted and these journeys are atypical for most respondents. These results are across all modes and we do not know from the results presented in the Arup/ITS Leeds/Accent report whether car respondents found the options to be more or less realistic than average.

Table 4: I was able to make choices as in real life

	Total	CATI interviews	Online interviews
Strongly disagree	4%	3%	5%
Somewhat disagree	7%	4%	7%
Neither agree nor disagree	17%	16%	17%
Somewhat agree	33%	22%	36%
Strongly agree	38%	55%	35%
Mean	3.94	4.21	3.89
Base	8,486	1,380	7,098

4.2.9. Over 70% of respondents strongly or somewhat agreed that they were able make choices in the SP3 experiment as in real life, and just 11% of respondents disagreed that they were able to make choice as in real life. These results suggest that the choices presented in the SP3 experiment were seen as reasonably comparable to choices that respondents make in real life. Again, these results are positive in terms of the realism of the SP3 experiment but the results are across all modes and we do not know from the results presented in the ITS report where car respondents responded more positively or negatively than average.

Table 5: I found it easy to choose between the options I was presented with

	Total	CATI interviews	Online interviews
Strongly disagree	2%	2%	2%
Somewhat disagree	6%	4%	7%
Neither agree nor	15%	14%	15%

disagree			
Somewhat agree	26%	26%	38%
Strongly agree	40%	55%	38%
Mean	4.06	4.28	4.02
Base	8,486	1,380	7,098

4.2.10. Two-thirds of respondents somewhat or strongly agreed that they found it easy to choose between the options that they were presented with, and just 8% disagreed. This suggests that in the majority of cases respondents were presented with choice pairs where they had a clear preference for one of the options over the other. Note that this does not necessarily indicate better quality information for model estimation, when estimating models close comparisons are also useful for quantifying trade-offs. Once again it is noted that these results are across all modes and we do not know from the ITS report whether car respondents responded more positively or negatively than average.

4.2.11. In summary, the diagnostic testing data collected in the main SP survey relating to the SP3 experiment suggests that the majority of respondents were able to understand the choices they were presented with, found the options they were presented with to be realistic, were able to make choices as in real life, and found it easy to choose between the options they were presented with. However, the diagnostic data was not presented separately by mode in the Arup/ITS Leeds/Accent report, and it is possible that car respondents were less positive about the SP3 experiment than average. Therefore we recommend that the responses of the car respondents to the diagnostic questions are analysed separately.

3 UK VTT STATED PREFERENCE MODELLING

3.1 MODEL SPECIFICATION

3.1.1. In a choice model, the utility function is decomposed into deterministic and random components (the error term). The 1994 and 2003 VTT studies worked with additive error structure where $U = V + \chi$, with V and ε giving the deterministic and random components of utility respectively. This is a standard error structure used in most transport applications of logit models.

3.1.2. In the 2015 study, a multiplicative error structure was used instead, and is reported as being the state of the art and the approach used in the recent Danish VTT study. In a multiplicative structure, the utility function is expressed as $U = V.\chi$ so that utility is multiplied by the error term.

3.1.3. A practical advantage of the multiplicative error structure is that it makes it easier to make an assumption of constant variance for ε. Arup/ITS Leeds/Accent (2015a) report that it is generally found that utility variance increases as utility increases and this happens automatically in the multiplicative form of the model.

3.1.4. Tests were undertaken to assess the impact of the error structure assumption on the model results. The tests for the car SP3 experiment found that the results were significantly better for the multiplicative structure model. The model fit was substantially better than the additive model and furthermore the CVTT multipliers were substantially lower and more plausible in the multiplicative model (but still higher than expected).

3.1.5. It is noted however that the 1999 national VTT study undertaken Hague Consulting Group and Accent obtained congestion multipliers using models specified with an additive error structure that were considerably lower, and more plausible compared to the evidence presented in Section 5, than both the additive and multiplicative multipliers derived in the 2015 study (Hague Consulting Group et al, 1999).

3.1.6. The result that the congestion multipliers are higher in the 2015 study additive structure suggests that long-distance trips are biasing the congestion multipliers upwards (because in the multiplicative models the higher error level associated with longer trips is captured directly), and so analysis of variation in the congestion multipliers by trip length would be valuable. The SP1 and SP2 model results were also significantly better using multiplicative models.

3.1.7. A key feature of the models was that they were estimated by pooling the information across the three SP experiments. The main benefits of this approach are that it gives consistent estimates and increased robustness for those attributes shared across the different experiments. Multipliers are used to capture both differences in valuations that relate to different components (e.g. reliability rather than travel time) and differences in valuation of attributes such as travel time that are generic across games. Furthermore, experiment specific scale parameters were estimated to account for differences in error levels between the three experiments.

3.1.8. For the SP1 cost/time experiment, the models were specified so that VTT was estimated directly, rather than estimating separate cost and time parameters. Then for the SP3 experiment, which can be jointly estimated with SP1 and SP2 because cost is a common attribute, multipliers are used to estimate the relative valuations of:

- Free flow travel time VTT.
- Light traffic travel time VTT.
- Heavy traffic travel time VTT.

3.1.9. Thus the CVTT multipliers are directly estimated which helps to ensure plausible values and reasonable error measures, as it avoids the possibility of the denominator in a ratio estimate being close to zero.

3.1.10. Random heterogeneity was incorporated into the model specification by allowing for random heterogeneity in the base VTT in the first instance before allowing for covariates and random heterogeneity. Log-normal distributions were tested but in the end a log-uniform distribution was used. Results for the SP1 experiment estimated using log-uniform and log-normal models demonstrated that the mean VTT was almost 40% higher with the log-normal distribution. This is a result of the long tail of the log-normal distribution, by contrast the log-uniform distribution has a shorter tail.

3.1.11. An important implication of jointly estimating the models across all three SP experiments, and defining the congestion multipliers as non-random factors applied to the overall VTT distribution, is that the model specification implicitly assumes that the distribution of VTT under light traffic and heavy traffic conditions is the same as the distribution of overall VTT multiplied by constants. If in reality VTT under congestion has a more skewed distribution than overall VTT because of greater heterogeneity this may lead to upward bias to the congestion multipliers. Given the likely confusion for respondents caused by the presentation of heavy traffic conditions, and the possibility that longer-distance travellers are more sensitive to congestion, it seems quite likely that a more skewed distribution could be recovered for the heavy traffic level.

3.1.12. Arup/ITS Leeds/Accent (2015a) report that many previous VTT studies have found that the VTT estimates obtained depend on both the size and magnitude of changes relative to the reference trip, and that these findings can be related to 'Prospect Theory' in that gains are attributed a lower value than equivalent losses. In order to model reference dependence, the approach set out in De Borger and Fosgerau (2008) was used, ITS Leeds (2015a) suggest this to be the most sophisticated practical approach to date.

3.1.13. To implement reference dependence in the models, terms have been defined that express the difference in the attribute level relative to the reference level so that the impact on utility is non-linear in terms of difference in attribute level, and allow for gains to be valued differently to losses. The value functions[5] have the same functional form for changes in cost and time, but the parameters that define the functional form of the value functions are estimated separately for cost and time. In the SP3 experiment, reference values were calculated for cost but not for the three travel time components (applying reference dependence to total time worked better and seemed more consistent with Prospect Theory). Results presented in the Arup/ITS Leeds/Accent (2015a) report demonstrate that for the SP1 experiment adding reference dependence effects leads to significant increases in the fit of the models to the observed choices.

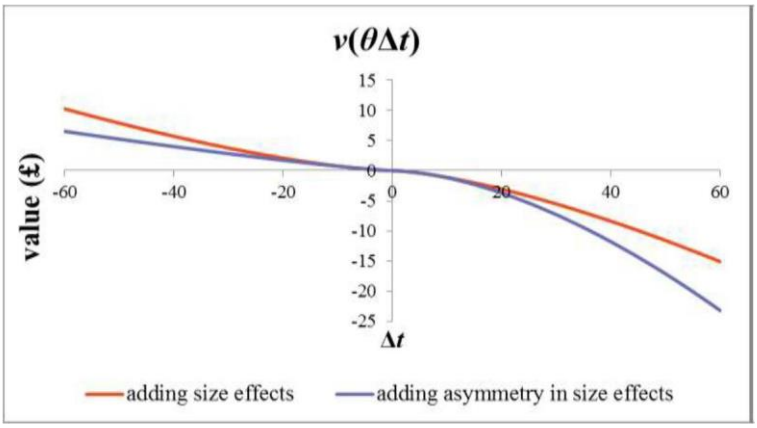
3.1.14. The reference dependent functions have three important characteristics derived from prospect theory:

- Utility changes depend on relativity to a reference point. Longer trips have a different reference point to shorter trips.
- The marginal sensitivity diminishes with distance from the reference point.
- Losses are valued more heavily than equivalent gains.

3.1.15. Figure 4 illustrates how the size, sign and asymmetric effects have been represented using a value function that expresses the impact of changes in travel time on the monetary VTT estimate. The asymmetry in the value function reflects that losses (positive Δt) are valued more highly than gains.

[5] A value function expresses the monetary value of a change in an attribute from a given base level for that attribute.

Figure 4: Impact of size, sign and asymmetric effects for changes in time



Source: Arup, ITS Leeds and Accent (2015a).

3.1.16. To account for the possible impact that congestion on the reference trip may have had on the VTT estimation, trip covariates for light congestion and heavy congestion were tested. These were specified as multipliers on VTT and were expressed relative to trips where the reference trip was undertaken in free flow conditions only. These multipliers are applied to the overall VTT estimate to account for how congestion levels on the reference trip influence an individual's VTT *at all levels of congestion*. The application of the reference trip congestion multipliers is explained in Equation form as follows:

$$VTT = \delta_{LT}^{Ref} \delta_{HT}^{Ref} \left(VTT_{base} \lambda_{FF} \lambda_{LT} \lambda_{HT} \right)$$

$\delta_{LT}^{Ref}, \delta_{HT}^{Ref}$ are the reference trip multipliers, applied if either light traffic or heavy traffic was experienced on the reference trip.

VTT_{base} is the overall average VTT (estimated across all three experiments but normalised to experiment 1).

$\lambda_{FF} \lambda_{LT} \lambda_{HT}$ are the free flow, light traffic and heavy traffic VTT multipliers (estimated from the SP3 experiment)

3.1.17. It can be seen that the effect of the model formulation is to rescale all the VTT estimates at all levels of congestion for those individuals who experienced congestion on their reference trip. The reference trip rescaling is constant for a given individual and so has no impact on the congestion (VTT) multipliers.

3.2 MODEL RESULTS

3.2.1. For business travel, separate models were estimated from the employer and employee SP samples. A comparison of the VTT estimates from the two models concluded that the values were sufficiently close that the briefcase valuations from employees can be taken to be reliable for white collar workers. For blue collar workers the SP employee sample yielded VTT estimates in line with the cost savings approach. Overall, the employee SP VTT estimates were found to be plausible and have been taken forward for VTT guidance. Therefore in this section, for business model results from the employee business SP sample are presented.

3.2.2. Table 6 presents the model results from the joint car models. The VTT multipliers estimated from the SP3 data are highlighted in green.

Table 6: Joint car models

	Commute		Employees' business		Other non-work	
Respondents	922		917		977	
Observations	13,830		13,755		14,655	
Final log-likelihood	-7,332.67		-6,933.43		-7,585.74	
Adjusted rho-squared	0.23		0.27		0.25	
Parameters of base VTT distribution	**estimate**	**t-ratio (0)**	**estimate**	**t-ratio (0)**	**estimate**	**t-ratio (0)**
$a_{\log(\theta 0)}$	-0.3559	-1.74	0.5150	3.61	-0.8840	-2.65
$b_{\log(\theta 0)}$	3.7060	15.62	3.3727	18.31	3.7141	19.16
Game specific VTT multipliers	**estimate**	**t-ratio (1)**	**estimate**	**t-ratio (1)**	**estimate**	**t-ratio (1)**
SP1 travel time	1	n/a	1	n/a	1	n/a
SP2 travel time	1.5988	4.05	1.1396	0.82	2.1875	5.52
SP2 standard dev. of travel time	0.5803	-4.75	0.8765	-1.04	0.8118	-1.48
SP3 free-flow	0.6968	-2.26	0.5718	-4.54	0.5008	-4.43
SP3 light traffic	0.9770	-0.14	0.9206	-0.74	0.8801	-0.90
SP3 heavy traffic	1.8557	2.98	1.7076	4.23	1.9955	4.05
Key elasticities	**estimate**	**t-ratio (0)**	**estimate**	**t-ratio (0)**	**estimate**	**t-ratio (0)**
income elasticity	0.5797	6.10	0.3003	3.64	0.6819	7.76
distance elasticity	0	n/a	0.2390	3.41	0	n/a
cost elasticity	0.6790	3.70	0.4511	2.63	1.0492	6.56
time elasticity	-0.6241	-2.62	-0.4538	-2.29	-0.9273	-4.72
Traveller covariates (VTT multipliers)	**estimate**	**t-ratio (1)**	**estimate**	**t-ratio (1)**	**estimate**	**t-ratio (1)**
unstated income	2.4775	0.65	0.5034	-2.41	1.0117	0.03
unknown income	1.4264	1.16	9.3098	2.90	0.2998	-5.89
refused income	0.7697	-1.30	0.5812	-1.43	0.8644	-0.77
female	1.3674	2.26				
aged 17–29	1.3645	1.76				
aged 17–39					1.4530	2.52
household with 2+ adults					0.6980	-3.47
1+car owned					2.6826	1.91
2+ motorcycles owned					0.4668	-1.65
self-employed	1.6669	1.97				
travel costs paid by company	2.2194	3.09				
company would purchase time savings come what may			1.3044	1.34		
company would not purchase time savings			0.4435	-9.51		
self-employed costs not covered			0.5629	-3.04		
self-employed			0.6767	-2.56		

	Commute		Employees' business		Other non-work	
Trip covariates (VTT multipliers)	**estimate**	**t-ratio (1)**	**estimate**	**t-ratio (1)**	**estimate**	**t-ratio (1)**
1+ nights away					1.5522	2.14
travelling with others	0.6690	-3.37				
driving on rural roads	0.8819	-1.31				
light traffic (base = free flow)	1.4026	1.57			1.3554	1.51
heavy traffic (base = free flow)	1.5604	1.78			1.4621	1.57
trip with London orig. & dest.			1.7530	1.42		
Design covariates	**estimate**	**t-ratio (1)**	**estimate**	**t-ratio (1)**	**estimate**	**t-ratio (1)**
SP1 cheap option on left	0.8842	-3.26			0.9259	-2.00
SP3 cheap option on left	0.9282	-1.37			0.9537	-0.85
SP1 time shown above cost			0.8878	-2.52		
SP2 scale if SP2 before SP3	0.8938	-2.63	1.1531	2.52		
Scale parameters	**estimate**	**t-ratio (0)**	**estimate**	**t-ratio (0)**	**estimate**	**t-ratio (0)**
μ_{SP1}	1.1975	14.71	1.7354	16.90	1.3014	16.53
μ_{SP2}	7.7383	18.05	6.3695	10.95	7.5389	16.92
μ_{SP3}	5.6636	14.65	7.2603	16.16	5.9410	17.07
Reference dependence parameters						
$\beta_{t,SP1}$	-0.4000	-3.64	-0.1141	-1.61	-0.1366	-1.91
$\beta_{t,SP2}$	-0.1564	-2.84	-0.4487	-5.10	-0.2435	-4.96
$\beta_{c,SP1}$			0.1013	1.83	0.1032	1.78
$\gamma_{t,SP1}$	-0.2127	-3.52	-0.1293	-3.58	-0.1075	-2.75
$\gamma_{t,SP2}$			-0.0627	-1.94	-0.0606	-1.79
$\gamma_{c,SP3}$			-0.1581	-2.11		
$\eta_{t,SP1}$	0.2573	4.34			0.2237	4.20
$\eta_{t,SP2}$	0.0874	1.43				
$\eta_{c,SP1}$	0.1267	2.18				
$\eta_{c,SP2}$			0.1959	2.15	0.2244	2.88
$\eta_{c,SP3}$	0.2271	1.51				

3.2.3. The SP3 VTT multipliers (highlighted in green) show the expected pattern of increasing VTT with increasing congestion. The valuations are discussed further in Section 3.3 below.

3.2.4. The key elasticities show that VTT increases with income and cost, and decreases with time, for all travel purposes. For two of the three models the cost elasticities are higher than the time elasticities implying that VTT is higher for longer trips. Only for employee's business was a significant distance elasticity observed, in this model the cost and time elasticities are similar so that the positive distance elasticity means that VTT is again higher for longer trips.

3.2.5. The traveller covariates show that respondents who refuse to provide their income have lower VTT measures, whereas a more mixed pattern is observed for those with unstated or unknown incomes. Female commuters have higher VTT, all other things being equal, as do young travellers in the commute and other non-work models. For the other non-work model, higher VTT is observed for individuals from households with one or more cars and from households with two or more motorcycles. For both, the commute and employee business models higher VTT is observed for the self-employed. Finally, a number of covariates were added to the employee business model relating to company policy towards paying for travel time savings and travel costs.

3.2.6. The trip covariates include multipliers to account for the impact of congestion on the reference trip on the *overall* VTT estimates, estimated across all three experiments. There is no need to apply these multipliers to congestion multipliers calculated from the SP3 experiment because they apply equally to travel under free flow, light traffic and heavy traffic levels and therefore cancel out when the light and heavy traffic levels are expressed relative to free flow time. The reference trip multipliers were not significantly identified in the employees' business model, but in the other two models significantly higher VTTs were observed for individuals who experienced congestion on their reference trip. It is noted that the preamble to SP1 instructed respondents to imagine free-flow conditions when responding to the choices, but these results suggest that conditions on individuals' reference trips influenced the choices they made in the SP1 experiment, as the VTT estimates are 35% to 56% higher for individuals in the commute and other non-work models who experienced some level of congestion on their reference trip.

3.2.7. Hess (2017) has run some additional analysis where the model specification has been extended so that the multipliers that account for the impact of congestion on the reference trip are estimated separately for the three experiments. His analysis demonstrates that there are differences in these multipliers that result in significant differences in the VTT by congestion level identified in the SP3 experiment, with higher VTT estimates identified for commute and other non-work. However, the congestion multipliers are not reduced by his analysis and therefore the extension to the model specification does not overcome the issue of the very high congestion multipliers that is discussed in Section 3.3.

3.2.8. The design covariates illustrate that the model specification has taken account of statistically significant variation in VTT according to whether the cheap option was presented on the left and whether time was shown above cost. It is noteworthy that the scale for SP2 is lower for commuters if SP2 is shown before SP3, and higher for employees' business. Thus there is evidence that the responses to the SP2 experiment were impacted by the SP3 experiment, and therefore it is likely that the responses to the SP2 experiment in turn impacted on SP3 for those respondents where SP2 was shown first.

3.2.9. It is noted that the scale parameters should not be compared between SP1 and SP2/SP3 because of the different modelling approach that was used for SP1. No consistent patterns emerge in terms of relative levels of error in the SP2 and SP3 experiments.

3.2.10. Sign effects have been identified for time in SP1 and SP2 for all three purposes, and for cost in SP1 for employees' business and other non-work. The models capture asymmetric damping[6] for time in SP1 across all three purposes, and in SP2 for employees' business and non-work. For cost, asymmetric damping is observed for the SP3 employees' business experiment only. Finally, there are sign effects (gain-loss asymmetry) for

[6] Asymmetric damping is where the degree of damping for a given cost or time change varies depending on whether the change is a gain or a loss.

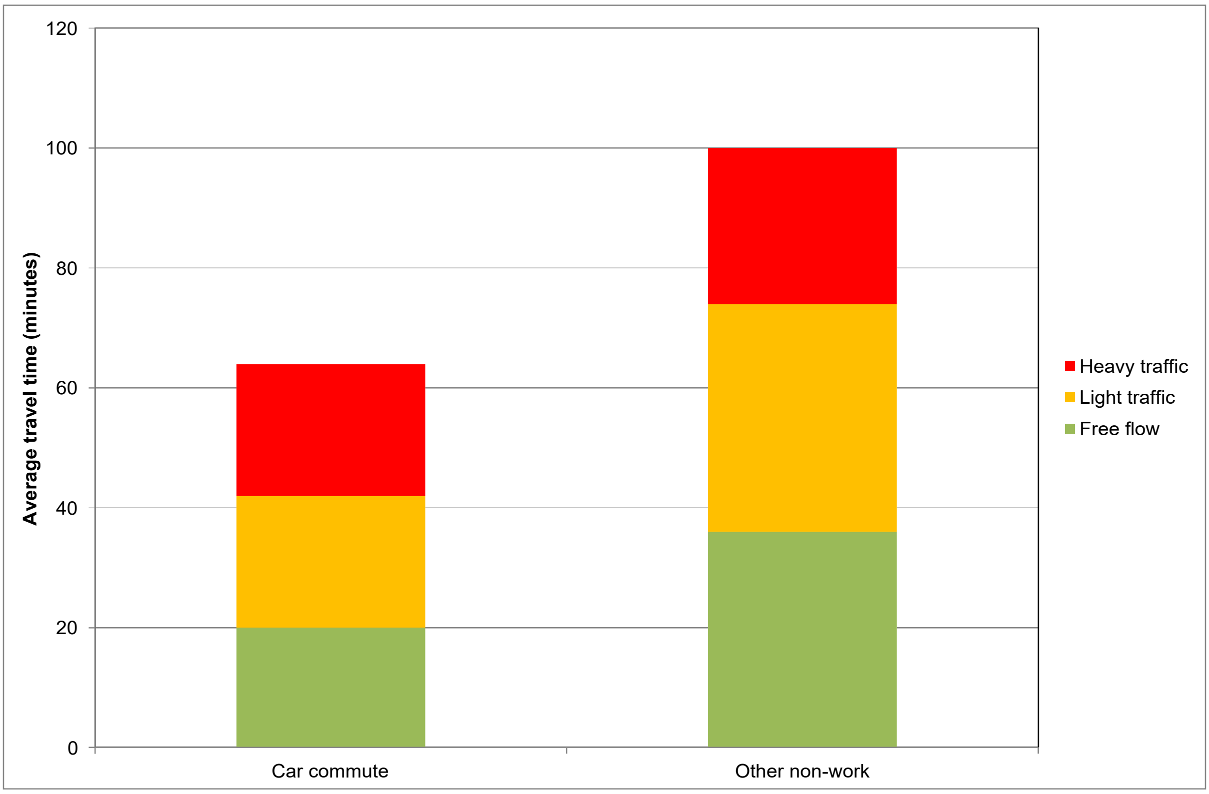
time in the commuter SP1 and SP3 experiments, and for costs in the SP2 experiments for employees' business and other non-work.

3.2.11. In summary, VTT estimates from a comprehensively specified model were obtained that take account of variation in VTT with travel purpose, SP experiment, key elasticities, traveller covariates, trip covariates, design covariates, scale parameters and reference dependence parameters. CVTT estimates have been directly estimated as VTT multipliers. The estimated values are discussed further in Section 3.3.

3.3 CONGESTION EXPERIMENT MODEL RESULTS

3.3.1. Before discussing the results from the congestion experiment, it is useful to analyse information that was collected in the surveys relating to respondent's reference trip. Individuals were asked to report how much time was spent at each of the three congestion levels. The average time by congestion level is presented in Figure 5. Note that this figure was taken from the Arup/ITS Leeds/Accent report, and that report does not present the average time by congestion level for business travel.

Figure 5: Reported time at different levels of congestion (reported minutes)



Source: Arup, ITS Leeds and Accent (2015a).

3.3.2. It can be seen that there is a fairly even distribution across the three congestion levels for commute where the relatively high fraction of trips spent in free-flow conditions is likely to reflect the substantial fraction of long distance trips in the sample, whereas for other non-work travel most time is spent in free flow and light traffic. The overall average travel times are high, but it should be noted that 80% of the SP sample was recruited via intercept methods to ensure a sufficient sample of longer trips. By comparison, the average all-mode trip travel time in 2015 NTS data was 24 minutes, i.e. one-quarter of the other non-work value in Figure 5[7].

3.3.3. There is no record of what type of carriageway was used by respondents for their reference trip under the different the different levels of congestion. The image used in Figure 2 to illustrate the three conditions implies a motorway for travel under all three conditions. However, in reality a lot of congestion occurs on roads in urban areas and the congestion valuations for these may vary from those for motorways. Variations in the valuations of congestion with road type have not been investigated in this study.

3.3.4. The SP3 VTT multipliers presented in Table 6 are expressed relative to the overall VTT estimate which is the VTT estimate in SP1 because of the way the scaling is applied. For all three purposes the free flow VTT estimate from SP3 is significantly lower than one. This suggests that individuals factored in congestion when responding to the SP1 experiment, such that the VTT estimates relate to travel time incorporating average levels of congestion encountered on respondents' reference trips.

3.3.5. To make the variation in VTT with congestion level clearer, the SP3 congestion multipliers have been rescaled relative to a value of one for free-flow time because some of the free-flow parameter estimates were significantly lower than one. The rescaled values are presented in Table 7. For each purpose the estimated congestion multipliers are presented on the left and the associated t-ratios are presented on the right, with the t-ratios expressing the significance of each multiplier relative to value of one.

Table 7: SP3 congestion multipliers

	Commute		Employees' business		Other non-work	
	multiplier	t-ratio	multiplier	t-ratio	multiplier	t-ratio
Free flow time	1	n/a	1	n/a	1	n/a
Light traffic time	1.40	1.71	1.61	3.25	1.76	2.85
Heavy traffic time	2.66	4.04	2.99	6.79	3.98	6.08

3.3.6. These valuations are high in comparison with values quoted in the literature, which in the UK are around 1.5 on average and rarely exceed two (see Section 5). This is particularly true for other non-work, where heavy traffic time is weighted nearly four times as highly as free flow time.

3.3.7. Section 7.6.2 of the Arup/ITS Leeds/Accent (2015a) report does acknowledge that the heavy traffic time valuation for other non-work appears extremely high and illustrates the route choice implication of this result. The illustration assumes a free-flow speed of 70 mph and a heavy traffic speed of 25 mph. A heavy traffic / free flow ratio of 4 implies that drivers would be willing to take a free flow diversionary route 11 times as long to avoid congestion, which seems unreasonably high. It is noted that the factor of 11 only considers time costs, if distance-based vehicle operating costs are included – and this is the standard modelling approach – then the factor reduces to around 4.5 which is still high but is much more plausible than a value of 11. If a higher mean speed for heavy traffic is assumed, then lower diversion distances are obtained but this does not explain why the heavy traffic multipliers are so high. The high valuation for heavy traffic time seems to imply that respondents perceived this to be gridlock conditions associated with high journey times that they strongly

[7] https://www.gov.uk/government/statistical-data-sets/nts01-average-number-of-trips-made-and-distance-travelled#table-nts0101, accessed 15/11/17.

wanted to avoid. The Arup/ITS Leeds/Accent report suggests the possibility that having been asked to focus on the three levels of congestion, respondents may have over-reacted to them.

3.3.8. A likely contributor to the high valuations for heavy travel time is the pictorial presentation of traffic at this level. As discussed in Section 2.2, this looks like gridlock conditions which is at odds with the accompanying text description of 'your speed in noticeably restricted and frequent gear changes are required'. If the pictorial presentation has had a greater influence on respondents than the text descriptions this is likely to have contributed to the high valuation of heavy travel time.

3.3.9. Another possible explanation for the high valuations for heavy traffic travel time is confounding between reliability and congestion, i.e. that individuals reacted to the congested travel times presented in SP3 on the basis of both congestion and a perception that congested journeys would be unreliable[8]. One possibility is that individuals who participated in SP2 before SP3 have different SP3 VTT multipliers to individuals who participated in SP3 first, this analysis is not presented in the Arup/ITS Leeds/Accent report but email correspondence with the ITS analysis team has confirmed that the order of SP2 and SP3 had little impact on the SP3 results. Nonetheless respondents may still have confounded congestion and reliability, an issue that is not discussed in the Arup/ITS Leeds/Accent (2015a) report.

3.3.10. In future SP studies, the potential for confounding between congestion and reliability could be reduced by instructing respondents in the reliability and congestion experiments to assume that the other attribute does not vary across choice pairs. For example, the choice pairs presented in the congestion experiment could additionally state to the respondent that they should assume that the level of reliability associated with each trip is the same. However, a fraction of respondents will view congestion and reliability as inseparable and so completely eliminating this effect is not possible.

3.3.11. As discussed in Section 3.1, the model formulation assumes that the VTT distribution for the three traffic levels presented in SP3 is the same as the overall VTT distribution. Another potential explanation for the high heavy traffic time valuations is that the underlying VTT distribution is significantly more skewed for travel under congestion than for free flow time, which might be in part due to inconsistency between the text description and pictorial illustration for the heavy traffic level, and that this more skewed distribution combined with the assumption that VTT at all congestion levels has the same distribution caused upward bias to the congestion multiplier. Developing separate models for the SP3 dataset would allow this hypothesis to be investigated. Furthermore, there may be outlier individuals in the SP3 data who are very averse to congestion, but are not non-traders. Excluding outliers may help reduce the high congestion multiplier values. In summary, there are a number of hypotheses for the high congested time multipliers that could be explored through further analysis of the SP3 dataset.

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[8] While the interpretation of the SP results depends on how respondents *perceive* the relationship between congestion and reliability, regardless of the actual relationship in reality, it is worth noting that there is extensive research that confirms that reliability (as measured by the standard deviation of travel time) generally gets worse as congestion increases. For example, the research underpinning Appendix C of [TAG Unit A1.3](), and the inter-urban functions used in MyRIAD (see, for example, Mott MacDonald (2008)). The relationship between congestion and reliability is, however, complex and in congested conditions the nature of queue formation and dissipation leads to a non-linear and dynamic relationship.

3.3.12. In summary, significant VTT multipliers for travel in light traffic and heavy traffic have been identified for all three travel purposes. However, the valuations are high, particularly for heavy traffic time. There are a number of possible explanations for the high valuations of congestion.

3.3.13. First, the visual presentation for the heavy traffic option appears like gridlock conditions, and that may have biased how individuals respond.

3.3.14. Second, having been asked to focus on congestion levels in the SP3 experiment individuals may have over-reacted to them.

3.3.15. Third, there may have been confounding between reliability and congestion that resulted in inflated valuations of heavy traffic time. However, lower reliability is an inherent feature of car travel in more congested conditions and so it is hard to imagine how respondents could react to a congestion experiment without giving some consideration to reliability.

3.3.16. Fourth, it is possible that respondents making long distance trips are more sensitive to congestion and that their valuations are biasing the overall congestion multipliers.

3.3.17. Finally, assuming that the congested VTT distributions were the same as the overall VTT distributions may have biased the congestion multipliers upwards. The SP3 data could be analysed further to explore these hypotheses, however limited sample sizes may be an issue.

3.3.18. To provide more insight into the relatively high congestion multipliers, we concluded that that the route choice implications of the multipliers presented in **Error! Reference source not found.** should be investigated using a simple test network. This analysis is presented in Section 6.

4 UK VTT STUDY QUALITY ASSURANCE AND AUDIT FINDINGS

4.1 INTRODUCTION

4.1.1. Two sets of checks were undertaken to provide reassurance that the VTT estimates have been correctly estimated, internal quality assurance checks and an external peer review exercise. These two sets of checks are summarised in Sections 4.2 and 4.3 respectively.

4.2 QUALITY ASSURANCE

4.2.1. A separate note was provided by Arup/ITS Leeds/Accent (2015b) to document the quality assurance (QA) procedures that were followed during the VTT savings and reliability project, this section briefly summarises that note.

4.2.2. Seven stages of QA checks were employed during the model development process, these are summarised below.

Stage 1: Data checking, cleaning and diagnostics

4.2.3. The raw SP data received from Accent was subject to checking, and then the data was cleaned and some exclusion criteria were employed, documented in the final report. Tests of alternative exclusion criteria were undertaken to investigate the impact on the model results. For consistency, if a given choice was removed then all other choices for that respondent were also removed. The final stage was to employ diagnostic testing for non-rational SP choices, non-trading, and so on. These diagnostic tests are documented in the final report.

Stage 2: General specification search

4.2.4. The main focus of this stage was to undertake comparative testing of additive and multiplicative model forms, these tests provided clear empirical evidence for the multiplicative model for all three SP experiments. Next, the benefits of size and sign effects were demonstrated. It was noted that all tests were made by making specification changes incrementally so the benefit of each individual element could be distinctly identified.

Stage 3: Detailed covariate search

An iterative specification search was followed, gradually building up the level of model complexity. The starting point was models without covariates, and then elasticities were added, followed by sign and size effects, and then the remaining covariates. Parameters were added in batches, with insignificant parameters moved before introducing additional ones.

Stage 4: Model estimation

The model estimation started with the development of base Ox code[9] that was then subject to internal model audit. Next, some additional coding was undertaken to investigate the impact of different starting values. This additional coding was checked by another member of the modelling team to confirm that it had been implemented correctly. Following this the modelling time decided upon the final model specification and made the final estimation run. A sense check of the final estimation run was undertaken by two senior modellers from outside of the modelling team involving assessing the plausibility of the model results, such as whether

[9] Ox is a programming language that is increasingly being used to estimate discrete choice models.

variations by travel conditions and purposes were intuitive, and checking whether the results were consistent with DfT's appraisal needs.

Stage 5: Methodological review

4.2.5. Methodological review and challenge was undertaken in parallel with Stages 1 to 4, in particular for key decision points in the modelling. This work was led by John Bates. Six technical notes were produced by John in this review role. Technical advice and challenge was also obtained from other technical experts in the team (Bliemer, Börjesson, etc.).

Stage 6: External model audit

4.2.6. The external model audit was undertaken by SYSTRA, Imperial College London and the Technical University of Denmark, and is documented in Section 4.2. Arup/ITS Leeds/Accent (2015b) report that to the best of their knowledge the audit work did not reveal any significant concerns regarding the rigour of the modelling process and the robustness of the resulting outputs. The external model audit is summarised in Section 4.3 below.

Stage 7: Internal model audit

4.2.7. To provide additional reassurance on the accuracy and reliability of the behavioural modelling, Andrew Daly (who was not involved in the model coding) audited the car commute and rail employee business models. Daly summarised his findings as follows 'The issues I have found were minor and have largely been resolved by the project team, so that, as far as I can see, nothing of consequence remains to be corrected in the code.' Arup/ITS Leeds/Accent (2015b).

4.2.8. In summary, a number of QA checks have been employed throughout the model development process, both by the project team and by qualified people outside of the project team. These checks include detailed QA checks of the final car commute model code which was used to estimate CVTT for commute. We cannot be certain that there is not an error with the coding for the SP3 experiment that contributes to the high CVTT estimates, but the level of QA checking applied throughout the model development process means that this is unlikely.

4.3 AUDIT

4.3.1. The independent audit was undertaken by a team of market researchers and VTT experts from SYSTRA, Imperial College London and the Technical University of Denmark. The aim of the audit was to provide external and independent verification of the methodology and interpretation of results, to establish if the survey data has been collected in the way that it has been reported, and the analysis was accurate and unbiased.

4.3.2. The auditors set out five main concerns with the Arup/ITS Leeds/Accent work:

- A minority of respondents expected to trade between complex choices without visual stimuli, for these respondents the interviewer read out the choice option over phone. It is believed c. 10% of total sample was collected in this way. It does not seem to be able to identify which respondents were interviewed in this way and therefore the impact of these responses on the model results in unknown.
- Plausibility of the SP experiments presented to respondents. All three SP experiments presented journeys that were both faster and more expensive that the other journey option. However, in general

faster journeys would be expected to use less, not more, fuel[10] and so the risk is that respondents see the choice as implausible. To deal with this issue respondents were told that time and cost may be different due to changes in fuel cost, congestion levels, breakdowns or unplanned roadworks. This helps deal with plausibility issue but the risk then of confounding of these influences with time and cost, for example individuals might then choose a shorter more expensive journey in order to avoid roadworks.

- In the SP2 experiment, no information was provided as to what probability respondents should attach to each of the five travel times that were presented in ascending order, and the concern is that respondents may have assigned all sort of different patterns of probabilities to the five outcomes and that this may bias the resulting valuations of reliability which assumed that each of the five outcomes presented was equally likely.
- Some members of the review team expressed a concern that the implications of adopting a reference dependent approach have not been sufficiently investigated or thought through. While reference dependence was significantly estimated no attempt was made to determine whether it was an artefact of the SP experiment rather than real behaviour, either in the initial qualitative work or in the subsequent modelling work.
- The final concern relates to the balance of effort in the study between model development and model implementation. The concern was that the study team had developed the most comprehensive choice modelling specification possible, and then make a number of simplifying assumptions at the implementation stage to generate VTT estimates for national use. The auditors suggest that more sensitivity and uncertainty analysis could have been used to consider different conditioning variables and imputation methods.

4.3.3. Overall the auditors were satisfied with the way the study implemented most of their planned programme of surveys and modelling, but expressed reservations about some of the data collected and the degree of emphasis on what they term ‘ambitious modelling’ rather than more thorough investigation of data quality issues and more measured development of hypotheses and model testing.

4.3.4. None of the auditors’ five main concerns relate directly to SP3, nor do any of the more detailed points they raise in their report. The first main concern on the telephone surveys may have had some impact on SP3 but would only apply to around 10% of the data.

4.3.5. In summary, there is no evidence from the auditors of particular problems with the SP3 experiment and analysis. A number of the issues raised by the auditors affect all of the VTT estimates that have been estimated, however none would be expected to specifically impact on the congestion multiplier estimates. Furthermore, the auditors do not comment on the high CVTT estimates that emerge from the modelling.

[10] The exact variation of consumption with speed varies according to where you are on the fuel consumption curve.

5 LITERATURE REVIEW

5.1 INTRODUCTION

5.1.1. The literature review was undertaken to obtain congestion multipliers estimates from the UK and elsewhere in Europe. The literature review omitted North American evidence on the basis that fuel costs are higher and mean trip lengths lower in Europe than in North America, and these differences may give rise to differences in the congestion multipliers.

5.1.2. The literature search was undertaken using a combination of strategies. First, a snowball approach was followed starting with the references given in the Arup/ITS Leeds/Accent study, and the recent VTT studies in Sweden Denmark and the Netherlands. The majority of the literature reviewed was identified from the snowball search. Second, key word searches were undertaken for 'value of time' in a number of transport journals, namely Transportation Research Part A, Transportation Research Part B, Transportation Research Record, Transport Policy, Transport Reviews, Journal of Choice Modelling, and Journal of Transport Economics and Policy.

5.1.3. The standard approach in the SP studies reviewed is to present to respondents minutes of free flow time and minutes of congested time, in some cases segmented by level of congestion, alongside cost (though some studies have presented trip time alone). It should be noted that the free flow and congested times sum to total travel time. This differs from most highway assignment contexts where 'congested time' means total travel time including congestion and free flow time is the total travel time in the absence of any congestion. This should be noted when interpreting the congestion multipliers estimated in the SP studies.

5.1.4. This Section presents the UK evidence identified from the literature review first before going on to summarise other European evidence.

5.2 UK EVIDENCE

Abrantes and Wardman (2011) Meta-analysis of UK values of travel time: an update

5.2.1. This paper presents the findings from a meta-analysis of 226 UK studies undertaken between 1960 and 2008 that yielded a total of 1,749 VTT estimates. These valuations are sources that have calculated VTT using either SP or Revealed Preference (RP) data. The majority of sources are unpublished, e.g. reports by consultancies, and as such unavailable from other public sources.

5.2.2. The definition of congestion used in this study was simply congested time. The majority of valuations come from SP studies where congested time is presented alongside free flow time, and then a congestion multiplier is calculated from the ratio of the two. So congested time in this context is total travel time in congested conditions rather than delay time (i.e. time in excess of free flow time).

5.2.3. The authors note that a number of more recent SP studies have presented reliability choices to respondents but that there were insufficient reliability studies to include it as an outcome variable in the meta-analysis.

5.2.4. The review identified nine studies that provided a total of 29 congestion multiplier values. The overall mean valuation for the congestion multiplier is **1.54±0.06**. Interestingly there was little difference in the valuations obtained from SP and RP data, which were **1.55±0.06** and **1.51±0.28** respectively. It should be noted however that the RP multiplier was calculated from a sample size of 4 valuations.

5.2.5. Abrantes and Wardman went on to fit a meta-model to all their VTT data. In this model, congested time was valued 34% higher than free-flow conditions with a t-ratio of 2.4. The model also included terms for headway, departure time shifts, walk time, wait time, income, distance, purpose, mode, data type, SP presentation and area. Interestingly, while there was no difference in the congestion multipliers with data type, the meta model identified RP in-vehicle time valuations to be 22% higher on average than SP valuations. Another interesting finding in the context of this study is that the meta-model could identify no significant differences in the valuations of free flow time and of generic car time. This is in contrast to the findings from the ITS SP analysis, where the time information presented in SP1 seems to have been interpreted by respondents as travel in average conditions with a valuation close to the light traffic level presented in SP3. The meta-model included terms for journey purposes, however these are expressed as adjustments to overall VTT and so the model formulation does not test whether the congestion multipliers vary with purpose.

5.2.6. It is noteworthy that the meta model results imply a congestion multiplier of 1.34, whereas the average multiplier from the studies used in the meta model is 1.54. Abrantes and Wardman suggest that this may be because the meta-model valuations are relative to IVT in general rather than to free-flow time, this is consistent with the 1.34 multiplier from the meta model being significantly lower than the 1.54 average multiplier in the input data. The low significance of the term (t=2.4) also suggests the effect is not strongly estimated. Given these issues we believe the 1.54 value taken as the average of the input values to be more reliable than the output multiplier of 1.34.

5.2.7. As noted above, reliability was not included in the meta-model. There was no discussion in the paper of possible confounding between congestion and reliability in the CVTT estimates that were used in the meta-analysis.

Wardman and Ibáñez (2012) The congestion multiplier: variation in motorist' valuations of travel time with traffic conditions

5.2.8. The paper quotes a 1986 ITS Leeds study that they believe to be the first SP application to route choice, and furthermore the first study to estimate congestion multipliers. The congestion multipliers were significantly estimated at the 1% level with values of **1.39, 1.46** and **1.28** for commuting, other and business trips respectively. This study was then repeated by Hague Consulting Group and Accent (1999) as part of the national VTT study undertaken at that time, yielding higher valuations of **1.70, 2.04** and **1.90** for the same three purposes.

5.2.9. The authors believed that the most sophisticated previous piece of UK evidence was a 2004 Steer Davies Gleave Study that explored the possible contribution of road congestion to strong growth in rail demand. This study differentiated six levels of road conditions:

- Free flowing: you can travel at your own speed with no problems over-taking.
- Busy: you can travel pretty much at the speed limit, but you are forced to change lanes now and then.
- Light congestion: you can travel close to the speed limit most of the time, but you have to slow down every so often for no apparent reason.
- Heavy congestion: your speed is noticeably restricted with frequent gear changes required.
- Stop start: you are forced to drive in a stop start fashion.
- Gridlock: you are only able to move at a crawl at best, and spend a lot of time stationary.

5.2.10. Two SP exercises were undertaken, the first exercise was a car-rail mode choice and the second exercise presented unlabelled route choice alternatives. The following table summarises the estimated multipliers and the exercise that was used to estimate the valuation. No purpose specific results are reported.

Table 8: Congestion multipliers from 2004 SDG study

Traffic condition	SP exercise	Congestion multiplier
free flowing	both	1.00
busy	first exercise	1.20
light congestion	second exercise	1.11
heavy congestion	both exercises	1.46/1.47
stop start	both exercises	1.69/1.61
gridlock	first exercise	1.96

5.2.11. Thus valuations range from just over one at light congestion levels up to a maximum of 2 in gridlock conditions. It is noteworthy that the heavy congestion valuation of 1.46–1.47 is in the same range as the SP valuation for congested time in the Abrantes and Wardman meta-analysis.

5.2.12. A number of congestion multipliers from studies across the world are then quoted. Table 9 quotes the multipliers identified from European studies.

Table 9: Congestion multipliers cited by Wardman and Ibanez

Study	Context	Time	Multiplier	Data	Purpose
MVA (1997)	Nottingham	congested	1.18	mode choice car users	non-business
			1.57	mode choice P&R users	commute
			1.75	mode choice P&R users	other
Nielsen *et al.* (2002)	Copenhagen	congested	1.31	SP route choice	commute
			1.64		business
			2.16		other
Eliasson (2004)	Stockholm	slow queue	1.42	SP unlabelled alternatives	morning
			1.53		afternoon
			1.44		business
Nielsen (2004)	Copenhagen	congested	1.61	SC route choice and SC 2 unlabelled alt.s	all
Fosgerau (2006)	Denmark	congested	1.52	SC 2 unlabelled alt.s	non-business
Rich and Nielsen (2007)	Copenhagen	congested	1.15	SC 2 unlabelled alt.s	commute
			1.65	SC 2 unlabelled alt.s	business
			2.00	SC 2 unlabelled alt.s	leisure
Murphy (2009)	Riga, 2005	stop-start	1.00	SC 2 route choice	commute
			1.07	SC 2 route choice	business
			1.07	SC 2 route choice	other
Murphy (2009)	Serbia, 2007	stop-start	1.73	SC 2 unlabelled alt.s	commute
			1.14	SC 2 unlabelled alt.s	business
			1.05	SC 2 unlabelled alt.s	other

5.2.13. These European valuations are broadly consistent with the value of 1.5 that was the mean of the 29 values used by the UK meta-analysis study. Only one of these 20 European valuations is greater than two.

5.2.14. Wardman and Ibáñez note that some analysts take the view, first raised by MVA et al in the 1987 UK VTT study, that congestion multipliers contain an element relating to unreliability and that reliability should therefore be presented alongside the different congestion levels. To investigate this hypothesis, the authors included a term in a meta-analysis model estimated from all the data that they assembled[11] that was applied if the congestion multiplier was from a model that included reliability. However, this term was insignificant and so no impact of reliability on the congestion multipliers was identified.

5.2.15. The authors went on to develop a new SP study using the six levels of road conditions used by the 2004 SDG study, namely free flow, busy, light congestion, heavy congestion, stop-start and gridlock. Various SP exercises offered a choice between two unlabelled alternatives, one with a mix of good and bad travel conditions (option A) and one offering a single set of travel conditions somewhere between the two (option B). As per the Arup/ITS Leeds/Accent congestion game, the text descriptions of the different congestion levels were supplemented by pictorial representations. The descriptions and images presented for three of the six levels are reproduced in Figure 6. It is noted that no reliability information was presented.

Figure 6: Traffic conditions presented in unlabelled SP experiment

	**Busy traffic** – you can travel close to the speed limit most of the time, but you have to slow down every so often for no apparent reason
	**Gridlock –** you are able to move at a crawl at best, and spend quite a lot of time stationary
	**Heavy congestion –** your speed is noticeably restricted and frequent gear changes are required

Source: Wardman and Ibáñez (2012).

5.2.16. It is noted that the images are from the same set of images that was used for the Arup/ITS Leeds/Accent study (see Figure 2). However, different images have been associated with a given traffic level. In particular, the heavy traffic text description in the Arup/ITS Leeds/Accent study was presented together with the gridlock image presented in Figure 6. The text descriptions given in Figure 6 better match the corresponding images than those in the Arup/ITS Leeds/Accent study congestion experiment, where an image implying gridlock was presented alongside text suggesting heavy but moving traffic. As discussed earlier, it is possible that the images presented in the Arup/ITS Leeds/Accent congestion experiment contributed to the very high valuations of heavy traffic time.

[11] The data they assembled included studies undertaken in the UK, the rest of Europe and the rest of the world.

5.2.17. It is noted that the choices presented in the SP experiment were described by differences in travel time only and so no monetary costs were presented. This is in contrast to the Arup/ITS Leeds/Accent congestion game where time by congestion level was presented together with cost, and may raise an issue of fungibility whereby the valuations of travel time in a given SP experiment vary depending on whether cost is presented. That said, the congestion multipliers identified from this study are consistent with those identified in other studies where both time and cost were presented.

5.2.18. On the issue of the potential for confounding between reliability and congestion multipliers, the authors suggest that their presentation helps to mitigate this by presenting options where it is not immediately obvious which option would be more unreliable.

5.2.19. The data was collected in 2006 as part of the M6 toll study. A total of 8,462 choice observations were collected from 956 individuals. A jack-knife procedure was used to deal with the issue of correlation between an individual's choices. Table 10 summarises the time multipliers that were obtained, and compares them to the 2004 SDG valuations. As per the SDG study the models were estimated across all trip purposes.

Table 10: Congestion multipliers from M6 toll SP data

Travel time conditions	M6 toll SP, 2006	SDG1, 2004	SDG2, 2004
free flow	1.00	1.00	1.00
busy	1.14	1.20	
light congestion	1.23		1.11
heavy congestion	1.31	1.46	1.47
stop-start	1.45	1.67	1.61
gridlock	1.78	1.96	

Source: Wardman and Ibáñez (2012).

5.2.20. The M6 toll study valuations are slightly lower than the values obtained by SDG, but overall there is a good level of correspondence between the two sets of values. The authors make the point that we might expect time spent in gridlock conditions to be similar to waiting for public transport services, and that the valuations in Table 10 are consistent with the widespread practice of applying a multiplier of two to waiting time to convert to generalised time. The congestion multipliers are significantly lower than those identified from the 2015 Arup/ITS/Accent study. One potential contribution to these differences is that the study successfully avoided confounding between reliability and congestion.

5.2.21. Wardman and Ibáñez suggest four areas where further research would be valuable:

- Tests based around driving simulators.
- Tests based upon motorists' physical reactions to different driving conditions.
- Tests based upon statements of the perceived difficulty of driving in different conditions.
- Analysis which addressed whether it is realistic to offer distinctly different types of travel time in SP experiments or whether realism requires that many more types of traffic condition are offered along the lines of those typically experienced through a journey.

5.2.22. These areas are worth considering in any further congested time multiplier research.

5.3 OTHER EUROPEAN EVIDENCE

5.3.1. The first set of studies reviewed are recent national studies that estimate VTTs using SP data. Studies from Denmark, Sweden, the Netherlands and Switzerland have been reviewed. The second set of studies reviewed are studies that estimate VTTs using city-level data. The first is from Stockholm and uses SP data, the second is from Copenhagen and uses RP GPS data.

Fosgerau et al (2007a) The Danish Value of Time Study: Final report, Fosgerau et al (2007b) The Danish Value of Time Study: Results for experiment 2

5.3.2. Business trips were excluded from the Danish VTT study as a pre-study had concluded that VTT for these trips were better calculated based on the direct costs to the employer.

5.3.3. A total of 6,000 SP interviews were collected. Respondents were presented with four experiments, with eight choices presented per experiment:

- SP1, abstract time-cost exercise.
- SP2, disaggregated time components, including congestion for car, presented alongside costs.
- SP3, cost-time trading for an alternative mode.
- SP4, transfer price questions.

5.3.4. No reliability information was presented.

5.3.5. In the SP2 experiment, alternatives were described in terms of cost, free flow time, congested time, parking search time and egress walk time. If any of the last three were unfamiliar to respondents they were dropped from the attributes presented.

5.3.6. In the car SP2 experiment, 32% of all choices were dominant choices as a result of a design error, and these choices were removed from the analysis. A few more observations were excluded with unrealistically high parking search times, egress walk times and levels of congestion on their reference trip.

5.3.7. In contrast to the UK study, SP1 and SP2 were analysed separately. The analysis of the car SP2 experiment took into account reference dependence, and furthermore the VTT estimates were obtained separately for trips less than and greater than 25km in length. VTT was assumed to following a log-normal distribution, and a multiplicative rather than additive error structure was used. The reference dependence parameter for congestion was not significant and so was dropped from the model.

5.3.8. The key result from the SP2 experiment was that the estimate of congested VTT expressed as a multiplier relative to free flow time VTT was less than one with an estimate of 0.88 with a 95% confidence interval of 0.81–0.97. Given that a value less than one is undesirable the authors recommended a value of one on the basis that it does not take account of travel time variability due to congestion. Later the report notes that standard Danish practice is to use a value of 1.5 as a congestion multiplier to take account of travel time variability, and that this practice is not contradicted by the study findings given that the lower study estimates for the congestion multiplier do not take account of travel time variability. So the study authors suggest that the accepted Danish congestion multiplier value is greater than one because of lower reliability associated with congestion rather than a higher valuation of travel time spent in congested conditions. No explanation is given for the low congested time multiplier valuation obtained from the analysis of the SP2 experiment.

5.3.9. Like the ITS study, the Danish study used a multiplicative error structure, took account of reference dependence, and presented options varying by both time and cost in the congestion experiment, yet despite the similarities in the analytical approach very different valuations for the congestion multiplier were obtained. The key difference between the two sets of analyses is that the ITS study pooled the data across all three experiments whereas in the Danish work the congestion experiment was analysed separately. However, we do not believe that pooling across all three experiments in the Arup/ITS Leeds/Accent study explains the high congestion multipliers that they identified because their model specification took account of differences in scale between the three experiments and of the impact of levels of congestion on the reference trip on the VTT estimates, and because the three relevant multipliers are estimated from SP3 data alone.

Börjesson, M. and Eliasson, J. (2014) Experiences from the Swedish Value of Time Study

5.3.10. Consistent with the Danish study, no employer's business data was collected in the Swedish VTT study.

5.3.11. SP data was collected using two surveys carried out in 2007 and 2008. In the 2007 survey, only car drivers were interviewed, they were recruited from their number plate registration details and then interviewed by telephone. In the 2008 survey, car, long and short distance train and bus users were interviewed, with car drivers recruited using a random sample from the population register, and public transport users recruited on-board vehicles. Both car and public transport users could choose between internet or call-back telephone interviews. A total of 1,440 car interviews were collected across the two surveys.

5.3.12. The models developed in the SP analysis represented VTT using a log-normal distribution with careful investigation of the 'tail' effects. The models took account of reference dependence by incorporating terms for both size and sign effects. The models assumed an additive, rather than multiplicative, error structure which is a key difference with the Arup/ITS Leeds/Accent and Danish studies. Like the Arup/ITS Leeds/Accent study the models were estimated in VTT space, rather than with separate cost and time terms, which provided direct estimates of VTT. Covariates were added to the model to take account of variation in VTT with travel purpose and by socio-economic variables, specifically whether the individual was employed, whether there were children in the household, whether they lived in Stockholm and the log of income.

5.3.13. Congested time was not presented separately in the study and therefore there are no direct estimates of congestion multipliers. However, VTTs were found to be significantly higher than average in Stockholm compared to the rest of the country by a factor of 1.3 (note that this result is after taking account of variation in VTT with income, employment and presence of children). The authors suggest that considerably higher traffic congestion and associated travel time variability in Stockholm than elsewhere may explain this high valuation given that the SP experiments did not explicitly control for these factors. Thus the Swedish study provides some evidence for the existence of a congestion multiplier greater than one.

Significance et al (2014) Values of time and reliability in passenger and freight transport in The Netherlands

5.3.14. The Dutch VTT study recruited 5,760 respondents via an internet panel in 2009, and a further 1,430 respondents via en-route recruitment after the 2009 VTT estimates were found to be significantly lower than previous studies. The conclusion was that the panel is likely to be biased and it is believed this is due to the lower than average incomes of the panel members who are willing to spend time completing questionnaires for fairly small amounts of money.

5.3.15. Two SP experiments were undertaken, SP1 was a travel time and cost experiment with six choice pairs presented, and SP2 was a reliability experiment where each option had five travel times with associated arrival times with a total of 13 choice pairs presented. Congested time was not presented to respondents and therefore no congestion multipliers were estimated.

Axhausen et al (2008) Income and distance elasticities of values of travel time savings: New Swiss results

5.3.16. The respondents in the SP surveys used in this study were recruited from the ongoing and continuous survey of the Swiss Federal Railways from which reference trip and socio-demographic information was available.

5.3.17. Two SP experiments were presented to respondents:

- SP1, a mode choice experiment (car and bus or rail) only presented to respondents who have a car available;
- SP2, a route choice experiment, where a choice between two routes on the current mode was presented.

5.3.18. In the car route choice experiment three attributes were presented, travel cost, uncongested travel time and congested travel time. No reliability information was presented. This presentation was decided on after initially testing presentations with total travel time and share of congestion, and total travel time and time in congestion, both approaches were found to overestimate the congested time multiplier. A total of 2,838 choices were collected in the car route choice experiment.

5.3.19. In terms of model specification, error components were added to the model specification to capture individual-specific effects, however these were not significant suggesting that correlation between an individual's choices had been captured in the observed part of utility. Sign and size effects were not represented in the model specification. Distance and income elasticities were represented.

5.3.20. The SP1 and SP2 models were estimated jointly with scale parameters used to capture differences in the error level between the two experiments. The key result in the context of this study was that there was little difference in model results when car time was segmented into congested and uncongested car time, and therefore no significant estimate for a congestion multiplier was derived. The authors suggest that the low share for the uncongested part for the reference trips (<10%) explains this, in contrast in the Arup/ITS Leeds/Accent data on average more than half the time of the reference trip is spent in traffic with some degree of congestion.

Eliasson (2004) Car drivers' valuations of travel time variability, unexpected delays and queue driving

5.3.21. An SP survey was undertaken with car drivers in and around central Stockholm. Drivers were recruited by collecting registration numbers and then contacting them by telephone to see if they would be willing to complete a survey. In the telephone interview a few screening questions were asked and then in-scope drivers were mailed a survey. Just over 200 completed surveys were obtained for each of the three segments, morning, business and afternoon.

5.3.22. The SP experiment collected information about attitudes to delays and so on, as well as socio-economic information. Three SP experiments were undertaken, with four choice pairs presented in each:

- SP1 was a time-cost trade off with a range of total travel times presented for each option;
- SP2 introduced occasional delays into the time-cost trade-off exercise, and so was a reliability experiment;
- SP3 was a time-cost congestion experiment, with time presented as X minutes of which Y minutes are spent in queue.

5.3.23. Thus models were developed to investigate the impact of journey time reliability on VTT estimates, but reliability was not presented alongside congestion to allow the effect of the two factors to be separated.

5.3.24. The models were estimated jointly across the three sets of responses. The utility function for the SP3 congestion experiment had a total time term, a cost term and a time spent in queue time term. No reference dependence terms were specified. The following valuations for the time spent in a queue relative to total travel time were obtained:

- Morning, 1.42.
- Business, 1.44.
- Afternoon, 1.53.

5.3.25. The authors note that these valuations are stable across other segmentations not presented in the paper.

Prato et al (2014) Estimating Value of Congestion and of Reliability from Observation of Route Choice Behaviour of Car Drivers

5.3.26. In contrast to most of the other studies reviewed, this study used RP data to estimate congestion multipliers in models which directly accounted for the impact of reliability. Route choice information was collected in 2011 from 169 car drivers living in the Greater Copenhagen area using cars equipped with GPS devices that collected traces of their routes. These traces were then matched to a highway network taken from the Danish National Model. After some map-matching and filtering an initial dataset of 17,115 routes was generated.

5.3.27. A choice set generation process was then run to generate alternative routes for the 17,115 observed routes. A double stochastic method was applied to do that that accounted for heterogeneity in the two components of total travel time, time in free flow conditions time in congested conditions, and error in length. The parameters of the time components were assumed to be log-normally distributed and the error term was assumed to be gamma distributed.

5.3.28. The route choice model fitted to the GPS data included terms for free flow time, congested time, travel time reliability, cost, number of left turns and number of right turns. Models were estimated with and without log-normally distributed parameters.

5.3.29. The models without log-normally distributed parameters yielded congestion multipliers of 1.46 in the peak and 1.25 in the off-peak, and the model with log-normally distributed parameters yielded congestion multipliers of 1.50 in the peak and 1.26 on the off-peak.

6 SIMPLE NETWORK TESTS

6.1 OVERVIEW

6.1.1. One concern regarding the use of congestion-dependent VTT was whether they would have a significant impact on route choice, and if so whether the routes chosen would be realistic (though as noted in paragraph 3.3.6 above, the inference that drivers would be willing to travel 11 times as far to avoid congestion is unlikely to be correct). The answer to both of these questions could influence the recommendation whether to include congested-dependent VTT in transport models.

6.1.2. To test this, a simple GIS-based analysis was carried out. This used Trafficmaster journey time data for two locations and a GIS-based routeing algorithm to explore the impact of congested-dependent VTT on optimum (i.e. minimum generalised costs) routes.

6.2 METHODOLOGY

Data

6.2.1. Trafficmaster data was obtained for two counties, Hampshire and Leicestershire. These locations were chosen because (a) the data was already held by the project team in a format suitable for this analysis (i.e. mapped to the OS Integrated Transport Network (ITN) layer in MapInfo) and (b) they offer both urban and inter-urban origin-destination (OD) pairs with a number of alternative routes available.

6.2.2. The Trafficmaster data has the following properties:

- Cars only.
- Hourly data, averaged over Monday to Friday (excluding bank holidays) for a whole year.
- Leicestershire data covers the period 01-Jan-2016 to 31-Dec-2016.
- Hampshire data covers the period 01-Sep-2014 to 31-Aug-2015.

6.2.3. The following link attributes from the merged ITN/Trafficmaster data were used:

- Road type.
- Length.
- Travel time.
- Speed.
- Number of Trafficmaster observations[12].

[12] i.e. the number of vehicles recorded using the link during the course of the year in each weekday hour. If the same vehicle uses the link on, for example, 10 occasions during the year then that would count as 10 observations.

6.2.4. Free-flow times for each link were estimated by finding the minimum observed travel time over all time periods. The delay for each link and time period was then calculated as the difference between the observed travel time and the free-flow time[13].

6.2.5. Initial analysis revealed that a large number of links in the ITN network had no Trafficmaster observations. These tended to be links with an ITN road type of 'local streets'[14]. They were therefore excluded from the analysis. This resulted in a reduced network that was more akin to the level of detail that would typically be included in a detailed urban transport model, compared to the full ITN network.

Generalised cost function

6.2.6. To test the impact of congestion-dependent VTT it was necessary to define an appropriate generalised cost function that was compatible with the GIS-based route-finding tool. The implications of different cost functions are discussed in detail in Section 7.2 below. For the purposes of this analysis, the following function was used:

$$GC = VTT_{FreeFlow} \times T_{FreeFlow} + VTT_{Delay} \times T_{Delay} + PPK \times D \qquad (1)$$

Where

$T_{FreeFlow}$	is the free flow travel time (minutes)
T_{Delay}	is the delay time (minutes)
D	is the travel distance (kms)
PPK	is the vehicle operating cost in pence per km
$VTT_{FreeFlow}$	is the value of time in free-flow conditions (pence per minute)
VTT_{Delay}	is the value of time for delay (pence per minute)

6.2.7. As discussed in Section 7.2 this cost function has the key properties that the average value of time increases with the level of congestion (here measured by 'delay') and can be implemented using readily available software tools (in this case MapInfo and RWNet[15]).

6.2.8. The coefficients for testing were defined as follows:

[13] Throughout Sections 6 and 7 'free-flow time' refers to the travel time that would be experienced if there was no other traffic (i.e. no congestion). This is *not* the same as the time spent in free-flow conditions when other traffic is present and there is a mixture of free-flow and congested conditions on the route.
[14] The ITN user guide (https://www.ordnancesurvey.co.uk/docs/user-guides/os-mastermap-itn-layer-user-guide.pdf) describes the 'local street' road type as "*A public road that provides access to land and/or houses, usually named with addresses. Generally not intended for through traffic*".
[15] http://www.routeware.dk/rwnet4/rwnet.php

Table 11: Cost coefficients used for testing

Coefficient	Value(s) tested	Notes
PPK	5.52p/km	Commute value taken from Highways England's VTT and VOC spreadsheet, consistent with July 2017 WebTAG databook[16].
$VTT_{FreeFlow}$	14.3p/min	Commute VTT of 20.59p/min taken from HE spreadsheet (weekday average) with a factor of 0.6968[17] applied to convert from "average" VTT to "free-flow" VTT.
VTT_{Delay}	14.3p/min, 21.5p/min, 43.0p/min	Multipliers of 1,1.5 and 3 applied to $VTT_{FreeFlow}$.

2017 values in 2010 prices

6.2.9. Values for VTT_{Delay} of 1, 1.5 and 3 times $VTT_{FreeFlow}$ were chosen to cover the full range of congested VTT multipliers (relative to free flow) estimated in previous studies, accounting for the fact that we have used a different definition of 'congestion' compared to those studies (as discussed in more detail in Section 7.2).

6.2.10. All coefficients are costs per vehicle. We have implicitly assumed that the same congestion multipliers apply to car drivers and car passengers, although the evidence reviewed relates to the former.

OD pairs

6.2.11. One OD pair was tested in each of the two counties:

- Leicestershire: urban OD pair in Leicester, between the junction of A563 and A6 to the south east of the city to the junction of the A607 and Leicester Western Bypass to the north of the city.
- Hampshire: inter-urban OD pair between Alton and J8 of the M27, offering strategic route choice alternatives between the A32, M3/M27 and A3/M27.

6.2.12. Minimum cost routes were found for each direction of travel, for each time period (AM, IP, PM) and for three different values for the delay coefficient VTT_{Delay}.

6.3 RESULTS

Leicester

6.3.1. Maps showing the minimum cost routes for each OD pair, direction and time period are shown in A. Each map shows the three routes chosen for each value of VTT_{Delay} (C1 means that VTT_{Delay} has the same value as $VTT_{FreeFlow}$; C2 means it is 1.5 times as high; C3 means that it is three times as high.)

[16] "VTT_and_VOC_from_WebTAG_Databook (July 2017) - release040817v2.xls"; NB: this uses the July 2017 version of the WebTAG data book, which was superseded in December 2017, after this work was originally completed.

[17] Value taken from VTT SP3 experiment as shown in Table 7 above, which has a multiplier of 0.6968, relative to the SP1 multiplier of 1. For the purposes of this test we have assumed that the SP1 VTT corresponds to average conditions and is equivalent to the WebTAG VTTs.

6.3.2. Table 12 sets out the characteristics of each optimum route (by direction, time period and the multiplier on VTT_{Delay}) in terms of the distance, free-flow time, and delay time. It also reports the average VTT for the whole journey, and the implied multiplier on this (i.e. the ratio of the average VTT to the free-flow VTT). The calculation of the average VTT is discussed in more detail in Section 7.2.

Table 12: Characteristics of minimum cost routes (Leicester).

Direction	Time period	Delay multiplier value	Distance (km)	Free-flow time (mm:ss)	Delay time (mm:ss)	Total time (mm:ss)	Average VTT (p/min)	Implied VTT multiplier (Average/ Free flow)
NB	AM	1	16.6	14:34	10:42	25:16	14.3	1.0
NB	AM	1.5	16.6	15:10	10:12	25:22	17.2	1.2
NB	AM	3	16.6	15:10	10:12	25:22	25.8	1.8
NB	IP	1	13.9	10:42	09:52	20:34	14.3	1.0
NB	IP	1.5	13.9	10:42	09:52	20:34	17.7	1.2
NB	IP	3	16.6	14:56	07:36	22:32	23.9	1.7
NB	PM	1	16.6	14:44	09:02	23:46	14.3	1.0
NB	PM	1.5	16.6	14:44	09:02	23:46	17.0	1.2
NB	PM	3	16.6	15:25	08:45	24:10	24.7	1.7
SB	AM	1	13.5	12:29	13:50	26:19	14.3	1.0
SB	AM	1.5	13.3	13:22	13:10	26:32	17.8	1.2
SB	AM	3	17.4	16:44	10:22	27:06	25.2	1.8
SB	IP	1	13.5	10:31	10:04	20:35	14.3	1.0
SB	IP	1.5	13.5	10:31	10:04	20:35	17.8	1.2
SB	IP	3	16.8	14:07	07:59	22:06	24.6	1.7
SB	PM	1	16.8	14:58	09:35	24:33	14.3	1.0
SB	PM	1.5	16.8	14:58	09:35	24:33	17.1	1.2
SB	PM	3	16.8	14:58	09:35	24:33	25.5	1.8

6.3.3. In almost all cases there is some variation in the optimum route as the value of VTT_{Delay} increases, with only PM peak southbound producing the same route regardless of the value of VTT_{Delay}.

6.3.4. It can be seen from the maps that in the inter-peak (both directions) and the AM peak southbound, the optimum route for C1 is a relatively direct route reasonably close to the city centre (between 13.3 and 13.9 km long depending on the time period and direction). As the value of VTT_{Delay} increases the optimum route changes to a longer route (16.6-16.8km) further from the city centre which avoids the worst of the congestion.

6.3.5. For other time periods and directions there is less variation in routeing as VTT_{Delay} increases, with the longer route the optimum (with minor variations) even with relatively low values for VTT_{Delay}.

6.3.6. Table 12 shows that, as would be expected, as greater importance is attached to delay time the delay on the optimum route reduces, while the other components of generalised cost, free flow time and distance, increase. For example, for the NB direction in the inter-peak, when VTT_{Delay} is at its maximum value, the optimum route is 2.7km longer (16.6 vs 13.9) and has 4m14s extra free flow time, but delay decreases by 2m16s.

6.3.7. Total travel time and distance tend to increase as VTT_{Delay} increases.

6.3.8. Overall, all of the routes identified look reasonable, in the sense that they do not force drivers to make unrealistically long detours to avoid congested conditions[18]. There are some instances of the chosen route using rat-running to avoid junctions. This may be realistic, or it may be an artefact of the Trafficmaster data. In particular, low or zero sample sizes in Trafficmaster will result in high standard errors for the journey times used, and may be introducing a bias towards these links.

Hampshire

6.3.9. Maps showing the minimum cost routes for each OD pair, direction, and time period are shown in B.

6.3.10. Table 13 sets out the characteristics of each optimum route (by direction, time period and the multiplier on VTT_{Delay}) in terms of the distance, free-flow time and delay time.

[18] In principle it would be possible to analyse the raw Trafficmaster GPS trace data to identify the routes actually used and compare to those reported above. However, this is beyond the scope of the current study.

Table 13: Characteristics of minimum cost routes (Hampshire).

Direction	Time period	Delay multiplier value	Distance (km)	Free-flow time (mm:ss)	Delay time (mm:ss)	Total time (mm:ss)	Average VTT (p/min)	Implied VTT multiplier (Average /Free flow)
NB	AM	1	45.3	29:48	17:21	47:09	14.3	1.0
NB	AM	1.5	45.3	29:48	17:21	47:09	16.9	1.2
NB	AM	3	46.5	33:20	15:53	49:13	23.5	1.6
NB	IP	1	51.8	25:15	13:09	38:24	14.3	1.0
NB	IP	1.5	53.6	25:02	12:42	37:44	16.7	1.2
NB	IP	3	53.6	25:02	12:42	37:44	23.9	1.7
NB	PM	1	51.8	25:44	14:18	40:02	14.3	1.0
NB	PM	1.5	53.6	25:27	14:01	39:28	16.8	1.2
NB	PM	3	53.6	25:29	14:00	39:29	24.4	1.7
SB	AM	1	45.2	30:01	13:46	43:47	14.3	1.0
SB	AM	1.5	45.2	30:01	13:46	43:47	16.5	1.2
SB	AM	3	45.2	30:01	13:46	43:47	23.3	1.6
SB	IP	1	53.8	25:31	12:40	38:11	14.3	1.0
SB	IP	1.5	53.8	25:31	12:40	38:11	16.7	1.2
SB	IP	3	53.8	25:31	12:40	38:11	23.8	1.7
SB	PM	1	46.1	28:44	14:29	43:13	14.3	1.0
SB	PM	1.5	46.1	28:44	14:29	43:13	16.7	1.2
SB	PM	3	46.1	28:44	14:29	43:13	23.9	1.7

6.3.11. For this OD pair there is much less variation in the optimum route as VTT_{Delay} changes. There is some variation in the optimum route as the value of VTT_{Delay} increases in the northbound direction; in the southbound direction for each time period the same route is chosen as optimum regardless of the value of VTT_{Delay}. This is despite the fact that the optimum route does vary between time periods and direction, with a tendency to avoid using the M3 in the peaks.

6.4 CONCLUSIONS

6.4.1. It would be unwise to generalise too much from looking at just two example OD pairs. Nevertheless, the results presented above indicate:

- Increasing the value of time in congested conditions does affect route choice in some cases.
- The routes chosen appear reasonable.

6.4.2. An important caveat is that the generalised cost function used in these tests is not the same as that used in previous studies to estimate congested VTT multipliers. The reasons for this are discussed in more detail in Section 7.2 below. This means that it is not possible to exactly translate the “multipliers” reported in previous studies, to the value of VTT_{Delay} used in these tests.

6.4.3. Nevertheless, by using values of VTT_{Delay} that are up to three times the value of $VTT_{FreeFlow}$ we are confident that we have used relative values for congested and free-flow times which are broadly in line with the range suggested by the literature (with the exception of the multiplier of 3.98 for the Other journey purpose, from the 2015 UK study).

7 IMPLICATIONS FOR ASSIGNMENT MODELS

7.1 OVERVIEW

7.1.1. In this section we consider some of the theoretical and practical issues that might arise from including congestion-dependent VTT in assignment models. This is based on a combination of the literature review, the experience of setting up the highway-based GIS analysis described above, and expert opinion from experienced practitioners and assignment software programmers on the theoretical and practical issues.

7.1.2. The focus is very much on highway assignment models. The issues covered are:

- The definition of congestion and the generalised cost function.
- Interaction with distance-dependent VTT.
- Implications for minimum cost path finding algorithms.
- Implications for finding supply-side (assignment) equilibrium.
- Microsimulation and dynamic assignment models
- Segmentation.
- The current capabilities of key software packages.

7.1.3. We also consider, briefly, the implications for public transport (PT) assignment.

7.2 DEFINITIONS OF CONGESTION AND GENERALISED COST

7.2.1. These two issues are inextricably linked. How we define ‘congestion’ directly affects how we represent congestion-dependent VTT in the generalised cost function.

Standard Definition of Generalised Cost

7.2.2. In transport models the generalised cost for car travel can be expressed, in money units (pence) as[19]:

$$GC = VTT \times T + PPK \times D + C \qquad (2)$$

Where

T	is the travel time (minutes)
D	is the travel distance (kms)
C	is the ‘charge’ (road toll and/or parking charges) (pence)
PPK	is the vehicle operating cost in pence per km
VTT	is the value of time (pence per minute, implicitly an average over congested and uncongested conditions)

[19] Generalised costs are often expressed in units of generalised time, particularly in demand models. Money units are used here as it simplifies the presentation.

7.2.3. Generally, VTT is a fixed coefficient (apart from varying between demand segments and user classes[20]).

Extension to Include Congestion-dependent VTT

7.2.4. For this current project we are considering the situation where *VTT* varies according to the level of congestion (the precise definition of which we discuss later)[21]. We can then write *VTT* as *VTT(cong),* i.e. the value of time is a function of congestion. Our updated definition of the generalised cost function is therefore:

$$GC = VTT(cong) \times T + PPK \times D + C \quad (3)$$

7.2.5. For consistency with the evidence, this function implicitly applies at the route level (as opposed to OD, or individual links). We discuss below how route costs and link costs need to be related to each other.

Definition of Congestion

7.2.6. In all of the studies we have reviewed, *cong* is a categorical variable, i.e. *VTT* takes one of a number of discrete values according to the category of congestion[22]. In the recent UK study (Arup, ITS Leeds and Accent, 2015a) three categories were used:

- Heavy traffic.
- Light traffic.
- Free-flowing.

7.2.7. Other studies, such as that carried out for the M6 toll, used up to six categories. However, most of the studies reviewed distinguished between just two categories, free flow and congested time.

7.2.8. Using a categorical definition of congestion would therefore have the advantage of being consistent with recent studies, and allowing appropriate congestion-dependent values of time to be used without the need to re-analyse existing data or undertake further primary research. However, as discussed below there are considerable practical and theoretical difficulties in doing so within a highway assignment model.

Problems with Congestion as a Categorical Variable

7.2.9. The use of a categorical variable to define congestion has two significant problems for modelling and appraisal.

7.2.10. The first of these is that the categories are not well-defined. For modelling purposes, we would need to look at a particular route or link in the model and to be able to identify to which category of congestion it should be allocated, based on characteristics such as free flow travel time and delay. As noted in our earlier review

[20] For clarity, this segmentation is not shown in the notation.

[21] We have generally avoided the use of the term ‘multiplier’ when defining congested VTT as this pre-supposes a particular way of representing the effect in the generalised cost function (albeit in a way that is consistent with most of the evidence reviewed).

[22] In some studies this is expressed in terms of a multiplier for VTT in congested conditions, to be applied to the free flow VTT, but it amounts to the same thing.

however, in the recent UK study there is considerable uncertainty about how respondents interpreted the categories presented to them, and therefore how they could be implemented in a modelling context.

7.2.11. This problem could be resolved with further work. This could include:

- Making a number of assumptions about how respondents have interpreted the information presented.
- Collecting and analysing further SP data using a more rigorous and objective definition of congestion.
- Using RP data in conjunction with a rigorous and objective definition of congestion.

7.2.12. We do not explore these options any further as there is a second, less tractable, obstacle that we believe is insurmountable.

7.2.13. This second problem is similar to the issue associated with using distance-banded VTT in modelling, namely the potential for 'boundary effects' to cause implausible and unstable behavioural responses as a particular route or OD moves from one category of congestion to another. These are discussed in DfT's response to the consultation on the value of travel time savings in October 2015[23]. To quote from that document:

"A range of respondents were critical of the proposed implementation of three discrete distance bands for employers' business VTTS. The chief reasons cited for this were:

- *there appears to be no clear empirical or theoretical justification for sudden changes in the values around the discrete boundary cut-off points;*
- *appraisal results could be highly sensitive to the banding of values, especially where trip distances are close to one of the boundaries; and*
- *there is potential for instability in models where distance changes across a boundary between the without-scheme and with-scheme cases."*

7.2.14. DfT's response goes on to say that these concerns have been addressed by recommending VTT as a continuous function of distance for use in appraisal. We are aware that this continuous function has been used in demand modelling, but are not aware of any successful implementations in highway assignment models (for reasons discussed above)[24]. We are not aware of any implementation of discrete distance-banded VTT in either demand or highway assignment models.

7.2.15. Our conclusion is that it would *not* be appropriate to use a categorical definition of congestion in modelling.

Continuous Definitions of Congestion

7.2.16. Given the problems described above it would be preferable, for implementation, to replace discrete categories of congested VTT with a version of *VTT(cong)* that is a continuous function of congestion. This would require:

- Defining congestion to be a continuous variable.

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[23] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/544165/understanding-and-valuing-the-impacts-of-transport-investment-values-of-travel-time-savings-consultation-response.pdf

[24] We are aware of at least one attempt to approximate this using distance banding, with each distance band allocated to a separate user class, but this was abandoned due to the difficulty of interfacing with a demand model and the risk of the boundary effects noted earlier.

- Re-estimating *VTT(cong)* as a continuous function of congestion, either from existing data or from newly-collected data[25], since none of the previous studies we reviewed used a continuous function.

7.2.17. Candidates for a continuous definition of congestion include:

- Congestion index: this is the ratio of actual travel time to free-flow travel time (where 'free-flow time' is the travel time that would be experienced in the absence of any congestion). This is an already-established variable. For example it is used in the estimation of travel time variability in urban areas.
- Delay: either the absolute value, or expressed as a proportion of total travel time (the latter is closely related to the congestion index). Delay is usually defined as the difference between actual travel time and free-flow time. In modelling terms, it can be further partitioned between link-based delay (i.e. as defined by link-based speed-flow curves) and time spent queuing at junctions. Junction delay can further be partitioned between delay at under-capacity junctions and that at over-capacity junctions[26].
- Volume to capacity ratio (V/C).

7.2.18. The first two can be applied at the link or route level. The third only really works at the link or junction, rather than route, level.

7.2.19. It would be possible to develop more definitions but the above are probably the simplest, and would be familiar to all modellers. It could be argued that, ideally, the best definition would be the one that gives the best fit to the data. However, there are theoretical and practical constraints (discussed below) that also need to be considered.

Requirements for Minimum-Cost Path Finding Algorithms

7.2.20. A key component of any highway assignment model is an algorithm that, for a given set of link costs[27], finds the minimum cost path through the network for each origin-destination (OD) pair. This is typically based on algorithms such as D'Esopo-Pape (used in SATURN and Visum), Bellman-Ford (used for a new feature in SATURN to make use of GPUs[28]), or Dijkstra.

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[25] To use existing data (which presented 'congestion' as discrete categories) would require some assumptions about how to translate those categories into a continuous function (e.g. 'light traffic' means 5-10% of total journey time is equal to delay). This would best be done using a data set with quite a few categories (e.g. from the M6 toll study), but would still be quite approximate.

[26] This idea can be extended even further to distinguish between stationary queuing and other queuing, though most macro-scopic assignment models do not distinguish between the two.

[27] Here we use 'link costs' in their most general sense, to include delays at turning movements at junctions. Most assignment software will deal with junction delays by 'exploding' the junction node and representing each turning movement as a separate link (although this process may not be visible to the software user).

[28] GPU is the Graphics Processing Unit in a computer. Its processing power can be used to speed-up non-graphics computations.

7.2.21. These algorithms usually start at the origin (in some cases destination) zone centroid then build a minimum cost path to every node in the network including all destination zone centroids[29]. This process is then repeated for each origin zone. Run times are therefore approximately proportional to the number of origin zones.

7.2.22. Within this process, the link costs are (temporarily) fixed, to be updated later in response to changes in modelled link flows.

7.2.23. Given the way these algorithms work, if we were to implement a cost function of the form of equation (3) it would require *VTT(cong)* to be determined before finding the minimum cost paths. This could be possible if *VTT(cong)* were defined for each link, with the same value for all OD pairs using that link (for a given user class). They would not work if *VTT(cong)* is defined by route, with different ODs using the same link having different values.

7.2.24. This means that *VTT(cong)* would, ideally, be defined at the link level rather than the route level.

7.2.25. Any potential need to overhaul a key component of existing software represents a major barrier to implementation and, therefore, availability to end users. There would therefore be significant advantages in developing a definition of generalised cost that would require minimal changes to existing software. We have defined the following desirable characteristics of a cost function, taking into account implementation in the SATURN software (though, to the best of our knowledge, all highway assignment models use very similar algorithms for minimum cost path finding):

- The total route cost is the sum of the individual link costs comprising the route.
- The coefficients of the generalised cost function are fixed for a given user class, i.e. they do not vary according to the characteristics of the route; in particular they do not vary between alternative routes for the same OD pair.

7.2.26. In addition to the above, we of course also need to ensure that the cost function reflects a preference for free-flow conditions over congested conditions, other things being equal.

A Revised Generalised Cost Function

7.2.27. Based on all of the above we propose the following cost function. As discussed above, this was used in our GIS analysis.

$$GC=VTT_{FreeFlow}\times T_{FreeFlow}+VTT_{Delay}\times T_{Delay}+PPK\times D+C \quad (4)$$

7.2.28. Here the total travel time is partitioned between free-flow and delay time, each with its own value of time (with the expectation that $VTT_{Delay}>VTT_{FreeFlow}$).

7.2.29. $VTT_{FreeFlow}$ and VTT_{Delay} are both fixed (for a given user class) and do not vary according to the characteristics of the route or link.

7.2.30. As noted above, delay is the difference between actual modelled travel time and free flow time. It could be partitioned further between junction and link-based delay. Junction delay could be further partitioned between transient and over-capacity delay although there is no evidence that these are valued differently (and it may

[29] A 'zone centroid' just being a special kind of node where traffic can enter and leave the network.

prove difficult to distinguish between them with either SP or RP data). Nevertheless, allowing for this greater segmentation of delay would lead to the following, more general, cost function:

$$GC=VTT_{FreeFlow}\times T_{FreeFlow}+VTT_{LinkDelay}\times T_{LinkDelay}+VTT_{JunctionDelayUnderCapacity}\times T_{JunctionDelayUnderCapacity}$$

$$+VTT_{JunctionDelayOverCapacity}\times T_{JunctionDelayOverCapacity}+PPK\times D+C \quad (5)$$

7.2.31. The above functions were motivated by the desire to use a measure of congestion that is readily available in standard highway assignment models and that has the desirable characteristics identified above, namely:

- Congestion (in this case delay) is a continuous function.
- The cost coefficients are fixed (for a given user class),
- It is valid at the link level, not just the route level.
- Route costs are the sum of individual link costs in the route.

7.2.32. Coincidentally, we subsequently discovered that a very similar cost function to equation (4) had been used in some SATURN-based research work in the early 1990s (which we discuss further in Section 7.8).

7.2.33. We present this cost function as one possible option that will 'work' in modelling and appraisal. However, in any future work to calibrate an appropriate cost function, the widest possible range of alternative cost functions should be considered with the aim of identifying the one best supported by evidence.

The Impact on Average VTT

7.2.34. The average value of time implied by equation (4) is the total time-related cost in money units, divided by the total travel time, i.e.:

$$VTT_{Average}=\frac{VTT_{FreeFlow}\times T_{FreeFlow}+VTT_{Delay}\times T_{Delay}}{T_{FreeFlow}+T_{Delay}} \quad (6)$$

7.2.35. In other words, the average VTT is a weighted average of the VTT for free-flow conditions and the VTT for delay. This means that the average VTT is bounded by these two values:

$$VTT_{FreeFlow}\leq VTT_{Average}\leq VTT_{Delay} \quad (7)$$

and it varies between the two in a way that is linear with respect to the proportion of delay time (relative to total travel time).

7.2.36. It should be noted that there does not appear to be any hard evidence (from our review) that the congestion-dependent value of time should vary in this way (but equally there is no evidence for an alternative function for VTT as a continuous function of delay).

7.2.37. There is some similarity here to the latest WebTAG function for VTT as a continuous, increasing, function of distance, which also places lower and upper bounds on VTT[30]. So, the above equation for the average VTT is not unreasonable, but would need to be backed up by more substantial evidence. In the meantime however, it

[30] Box 1 of https://www.gov.uk/government/publications/webtag-tag-unit-a1-3-user-and-provider-impacts-march-2017

provides a reasonable cost function to be used in GIS analysis and, perhaps, for a test implementation in highway assignment software.

7.3 INTERACTION WITH DISTANCE-DEPENDENT VTT

7.3.1. As discussed above, for employers' business trips TAG Unit A1.3 now recommends the use of distance-dependent VTT in economic appraisal. The preference is to use VTT as a continuous function of distance, rather than the previously mooted distance bands.

7.3.2. It might be reasonable to hypothesise that there is a correlation between congestion and distance, with shorter, more urban trips spending proportionally more time in congested conditions than longer, more inter- urban trips. Nevertheless, Table 6 shows that VTT depends on congestion *and* distance: the table shows the elasticities for time, distance and cost. These all increase with trip distance and, taken together, show that VTT increases with trip length for all purposes, even after accounting for congestion.

7.3.3. The question then arises how to define a generalised cost function that depends on congestion and distance. As noted above, highway assignment models do not currently include distance-dependent VTT, and DfT's response to the consultation on the value of travel time savings in October 2015 makes it clear that it is not mandatory to do so.

7.3.4. We are not aware of any plans from software developers to include distance-dependent VTT (as a continuous function) in highway assignment models. For the time being then, the question therefore only applies to the possible inclusion of distance and congestion-dependency in demand models and economic appraisal.

7.3.5. The use of distance (and indeed cost) dependent VTT is well established in the UK and elsewhere, with a number of functions in use[31]. However, it is too early to say how these should interact with congestion-dependent VTT, given that we don't yet know how best to represent the latter. One possibility would be that one or both of the time coefficients in equation (4) ($VTT_{FreeFlow}$ and VTT_{Delay}) could be a function of distance. For example, VTT_{Delay} could increase as distance increases. This would need to be explored in more detail as part of any further evidence gathering and analysis of a congestion-dependent VTT function.

7.4 IMPLICATIONS FOR FINDING SUPPLY-SIDE (ASSIGNMENT) EQUILIBRIUM

7.4.1. Assuming we have a link-based generalised cost function that includes congestion-dependent VTT and allows minimum cost paths to be calculated, the next issue to be addressed is the potential impact on finding the equilibrium solution. Here we focus on Wardrop user equilibrium, which is used for almost all highway assignment models in the UK. This is stated as[32]: "*Traffic arranges itself on congested networks such that the cost of travel on all routes used between each O-D pair is equal to the minimum cost of travel and all unused routes have equal or greater cost.*"

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[31] For example, the cost damping section of TAG Unit M2 presents two: one where VTT is a power function of distance, and another using the 'log cost plus linear cost' formulation.

[32] There are number of different, but equivalent, ways of stating this. The text here is taken from the SATURN User Manual.

7.4.2. A range of algorithms has been developed by researchers that aim to find this equilibrium in the most efficient way possible. Many commercial packages (including SATURN and Visum) offer a choice of algorithms. It is beyond the scope of this report to discuss these in detail. However, they tend to follow the following structure:

1. Allocate all demand for and OD-pair to the current minimum cost path for that OD.
2. Update link and turn costs using the current demand.
3. Check for convergence. If stopping criteria are met then end.
4. Re-allocate demand for each OD over the available paths[33].
5. Return to step 2 and iterate until convergence.

7.4.3. The key theoretical questions that arise are:

- Does an equilibrium exist?
- Is it unique?
- Will the convergence algorithm find it?
- Are the above affected by congestion-dependent VTT?

Existence

7.4.4. The question of the existence of an equilibrium was dealt with by (amongst others) Smith (1979) who stated that a *sufficient* condition for existence was that link costs are a continuous function of flow[34]. This further confirms our stated view that any congestion-dependent VTT should be based on a continuous, not categorical, definition of congestion. Provided this condition is met, we need have no concerns about the impact of congestion-dependent VTT on the existence of an equilibrium.

Uniqueness

7.4.5. Uniqueness of the equilibrium is more problematic[35]. Smith (1979) provided a sufficient condition for uniqueness that Dafermos (1980) demonstrated was equivalent to the Jacobian of link costs with respect to flow being positive-definite. Less formally, Watling (1996) characterises this as:

- the travel cost on each link is an increasing function of the flow on that link, when other link flows are held constant; and
- the dominant explanatory factor in a link's cost is the flow on that particular link, rather than any other link flow.

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[33] This is the step where there is most difference between algorithms. Some may do this in a way that seeks to minimise an objective function, others are more heuristic.

[34] Remembering that we are using 'link' here to encompass flows and costs for turns as well. This condition implicitly allows for interactions between links, e.g. where the cost on link *i* depends on the flow on link *j*, for example as would happen at a priority junction.

[35] Here uniqueness refers to link flows. In general, a Wardrop user equilibrium will not be unique in path/route flows. In the case of multiple user class (MUC) assignment uniqueness is in terms of total link flows, not UC-specific link flows.

7.4.6. Watling then points out "*In practice, such conditions are often violated: for example, at a priority junction, where delay on a minor arm is strongly dependent on the flows on the major road*."

7.4.7. It is important to emphasise that Smith's condition is *sufficient* but not *necessary*. In other words, meeting the condition guarantees uniqueness. If the condition is not met then a unique equilibrium may still exist, but it is difficult, if not impossible, to prove that it is unique.

7.4.8. In general then, there are question marks about the uniqueness of the equilibrium for any highway assignment model that includes junction interactions (i.e. the cost on one link depends on the flow on another). This is an issue that has been around for nearly 40 years and has not been completely resolved.

7.4.9. However, there seems to be no clear theoretical reason why congestion-dependent VTT would increase the risk of a non-unique equilibrium.

Ability of algorithm to find equilibrium

7.4.10. As noted above there is a range of different algorithms in use which all seek to find a Wardrop equilibrium solution. Some are backed up by theory which demonstrates the conditions under which they are guaranteed to converge. Others will be more heuristic, but still converge in practice.

7.4.11. A detailed investigation into all such algorithms is beyond the scope of this project. However, we have discussed the issue with Dirck Van Vliet (the original developer of SATURN) and PTV (the developers of Visum).

7.4.12. One issue raised by Dirck Van Vliet is that one of the algorithms used in SATURN (Frank-Wolfe) is implemented in such a way that, for multiple user class assignment (which is now standard for all applications), the objective function requires that only one component of the generalised cost function depends on flow.

7.4.13. Equation (4) in paragraph 7.2.27 meets this requirement as only T_{Delay} depends on flow (though equation (5) does not). It is possible that further research would lead to a function being recommended that has more than one component that depends on flow. However, Dirck Van Vliet's view is that this would not be a show-stopper as there are other algorithms available in SATURN that do not have this requirement and could be used instead; therefore there is unlikely to be an impact on convergence (assuming these other algorithms perform as well).

7.4.14. Other than this, no concerns have been expressed, from a theoretical point of view, about the inclusion of congestion-dependent VTT having an adverse impact on the ability of current algorithms to find equilibrium.

7.4.15. On the other hand, practical experience shows that, in some models, it can be challenging to achieve acceptable levels of convergence within practical run times. This is particularly the case in congested networks with explicit junction modelling, where small changes in flow can lead to large changes in delay, leading to unstable route choice.

7.4.16. The inclusion of congestion-dependent VTT could exacerbate this by increasing the sensitivity of route choice to congestion, making it challenging to achieve stable results. Conversely, by being more likely to route traffic away from congested junctions it could actually reduce overall congestion levels and thus aid convergence.

7.4.17. Which of these effects dominates may well vary between networks, and according to the level of congestion. It will only be possible to establish whether there is a significant impact on convergence through extensive testing across a range of networks and different demand levels.

Summary

7.4.18. Overall, provided that we use a continuous definition of congestion, we do not expect the inclusion of congestion-dependent VTT to cause any further theoretical issues relating to the existence and uniqueness of a Wardrop equilibrium solution and the ability of current solution algorithms to find that equilibrium. One particular algorithm in SATURN may not work if more than one component of generalised cost depends on flow, but alternative algorithms are available.

7.4.19. There is a risk of an adverse impact on the ability to achieve acceptable convergence in acceptable run times, but that can only be determined through testing.

7.5 MICROSIMULATION AND DYNAMIC ASSIGNMENT

7.5.1. In this section we consider whether congestion-dependent VTT raises any issues for microsimulation and mesoscopic[36] assignment models over and above those already discussed above. It is not intended to be a comprehensive survey of all currently available software, but raises some general issues.

7.5.2. The first point to note is that most microsimulation software allows the user to pre-define the route choice used by traffic. This may be in the form of fixed volumes of traffic for each defined route (perhaps derived from a macroscopic assignment), or fixed turning proportions at each node. This is sometimes referred to as 'static routeing'. In these cases the software does not calculate route choices and the question of including congestion-dependent VTT in route choice within the microsimulation model does not arise.

7.5.3. However, most software packages offer the option of calculating route choice within the microsimulation model. In some packages (Vissim, for example) this is referred to as 'dynamic assignment'. This may be across a set of pre-defined routes, or the software can calculate optimum routes using similar algorithms to those used in macroscopic models.

7.5.4. The option to calculate a Wardrop equilibrium solution is available in at least some software (e.g. Vissim). The algorithms used to find this equilibrium tend to be the more heuristic ones. We presume this is because the complex nature of microsimulation models means that, for example, formulae for link costs as a function of flow cannot be formally defined and therefore it is not possible to use algorithms that require the minimisation of an objective function (such as the Frank-Wolfe algorithm commonly used in SATURN).

7.5.5. We are not aware of any formal research into the existence and uniqueness of equilibrium solutions in microsimulation models.

7.5.6. From a theoretical perspective there do not appear to be any additional issues raised by using congestion-dependent VTT in microsimulation, compared to macroscopic models.

7.5.7. From a practical perspective we expect software would need to be modified. Take Vissim for example. This is PTV's microsimulation (and mesoscopic) partner to the Visum macroscopic assignment software. However,

[36] Mesoscopic models are between microsimulation models and macroscopic (e.g. SATURN) models in their level of detail. They are more detailed than the latter, particularly in the modelling of time-dependent flows and delays but, unlike the former, they do not go down to the detail of individual vehicles. They are currently little used in the UK, but many software developers offer it as an option in their modelling suites.

Vissim is much less flexible than Visum in terms of the definition of the generalised cost function and would not be able to include congestion-dependent VTT without changes to the software.

7.6 SEGMENTATION

7.6.1. One issue to be resolved is whether the inclusion of congestion-dependent VTT has any impact on the appropriate level of segmentation of travellers and trips in transport models.

7.6.2. Table 6 above shows the levels of segmentation in UK VTT, with Section 5 covering a range of other UK and European studies. These studies usually show different congestion multipliers for at least a subset of the following segments:

- Journey purpose: commuting, employers business, other/leisure
- Modes: P&R, car
- Time of day: morning and afternoon

7.6.3. These are broadly consistent with the typical WebTAG-recommended levels of segmentation currently used in the UK. There is therefore no firm evidence that the use of congestion-dependent VTTs requires any change to the level of segmentation in models. However, it is possible that more detailed analysis of the data would reveal significant differences between segments that are more detailed than those that have been reported to date.

7.7 IMPLICATIONS FOR PUBLIC TRANSPORT ASSIGNMENT

7.7.1. Since the subject of this project relates to VTT for *highway* congestion we are specifically interested here in public transport (PT) assignment for modes that use the highway and whose journey times will be affected by highway congestion. This primarily means bus, but may include some light rail/tram systems that share road space with other vehicles. For convenience we will simply refer to ‘bus’.

7.7.2. By PT assignment, we mean the assignment of passengers, not of public transport vehicles.

7.7.3. ‘Congestion’ here refers to the congested traffic conditions in which the vehicle is travelling, which has the effect of increasing in-vehicle times. It is a separate issue from ‘crowding’, which refers to congestion of passengers within the vehicle.

7.7.4. The first point to note is that there is very limited evidence as to whether bus passengers place a greater value on travel time in congested road conditions compared to free-flow. Only one of the studies reviewed presented bus travel times for different levels of congestion to respondents, the 2015 Arup/ITS Leeds/Accent study. In that study, bus in-vehicle times were presented for three different congestion levels. The VTT multipliers that were estimated are presented in Table 14.

Table 14: Bus VTT multipliers from 2015 Arup/ITS Leeds/Accent Study

Time component	Commute		Other non-work	
	Estimate	t-ratio wrt 1	Estimate	t-ratio wrt 1
Free flow time	1.09	0.36	1.13	0.44
Slowed down time	1.54	1.50	1.27	0.88
Dwell time	0.75	-0.39	1.46	0.93

7.7.5. In general, the multipliers are plausible, indicating that VTT increases as the level of congestion increases. However, none of the valuations are significantly different from one, and the low dwell time valuation for commute is counter-intuitive. None of the other studies reviewed collected information on variation in bus journey time preferences with congestion.

7.7.6. The uncertainty arises, in part, because we have little understanding as to *why* car drivers place a greater value on congested travel time. Once reliability-related effects have been accounted for then it might be hypothesised that at least part of the extra cost/disutility to car drivers comes from the inconvenience of repeatedly switching between braking and accelerating, and frequent gear changes. This does not apply to bus (or indeed car) passengers and could explain why no significant effect for bus passengers has been found.

7.7.7. Based on existing evidence there is therefore a very weak case for congestion-dependent VTT for bus passengers. However, in case the evidence base is strengthened in the future we should still consider what impact would this have on PT assignment models.

7.7.8. PT assignment models require bus travel times (in-vehicle times, or IVT) to be defined. These may be in terms of link times, or times between stops. Depending on the capabilities of the software, the scheme being modelled, and the level of complexity required, these times may be simply those from published bus timetables (perhaps with a simple factoring to allow for future increases in congestion), or they may be taken from a linked highway assignment model. The latter option will usually give a more realistic estimate of bus IVT, as long as the highway assignment model provides a good fit to observed travel times.

7.7.9. In addition to IVT, PT assignment models also require information on bus routes (in terms of stopping patterns) and frequencies (either in terms of explicit timetables or, more simply, average headways (e.g. 4 buses per hour). This allows the model to find optimum paths through the network for each OD pair.

7.7.10. The generalised cost function used to find these paths is a weighted combination of some or all of the following:

- Access time
- Waiting time
- In-vehicle time (IVT)
- Transfer time (waiting)
- Transfer time (walking)
- Number of transfers (interchange penalty)
- Egress time
- Fare
- Crowding

7.7.11. The last of these, crowding, is rarely modelled for buses in the UK. Where it is modelled, it tends to be accounted for as a weight on in-vehicle time, where the weight may range from 1.0 for an empty vehicle to around 2.0 for a fully loaded vehicle at capacity (including standing), although the latter figure can vary considerably.

7.7.12. There is an analogy between weighting IVT to account for crowding and, potentially, weighting IVT to account for congestion. When defining IVTs in the assignment model it would be possible to weight these to allow for the impact of congestion. For example, suppose:

- Total IVT is 10 minutes, of which
  - Free-flow time is 6 minutes
  - Delay is 4 minutes
- Delay time is valued at 1.5 times free-flow time

7.7.13. Then the value of 10 minutes of congested IVT is equivalent to 12 minutes of free-flow IVT *(= 6 + 1.5 x 4)* and this is the value that could be coded in the model.

7.7.14. This approach would work best in the case where the PT model obtains bus times from a highway assignment that can split times between free-flow and delay.

7.7.15. VTT typically only explicitly appears in the cost function in the coefficient of fare, which is usually (1/VTT) to convert the fare from money units to time units (so that the generalised cost is in units of generalised time). If we were to adjust the VTT used in the cost function to account for congestion then this would mean a different VTT for each bus route and/or OD pair. This would not be possible, for the reasons outlined in Section 7.2.

7.7.16. Weighting the IVT to account for congestion therefore appears to be the most practical way forward. However, further consideration will be needed as to how this might affect the VTT used to calculate the fare coefficient. Our initial thoughts are that if the numeraire for IVT is “free flow minutes equivalent” then VTT should be that for free-flow time. The precise units for generalised cost would then be “generalised time, free flow minutes equivalent”. This can be resolved once further evidence for congestion-dependent VTT for bus travellers is available.

7.7.17. When investigating further evidence for congestion-dependent VTT for bus travellers it will be important to understand how this might affect coefficients on other cost components, particularly the weights for other time components (access, egress, waiting, transfer) as these will need to be relative to the chosen time numeraire (free-flow time in the above example).

7.7.18. The above describes a general workaround for representing congestion-dependent VTT in bus assignment models. The specifics will need to be consistent with the preferred method for representing congestion-dependent VTT in highway generalised cost functions.

7.7.19. However, it could be argued that there will very rarely be opportunities for bus passengers to avoid congestion by choosing alternative routes and that it would therefore be an unnecessary complication to include congestion-dependent VTT in bus passenger assignment models. That would not prevent it from being included in demand models, where the impact may be more significant, for example when modelling the choice between bus and rail.

7.8 THE CURRENT CAPABILITIES OF KEY SOFTWARE PACKAGES

7.8.1. In this section we discuss the capabilities of the two most commonly used (in the UK) highway assignment packages: SATURN and Visum. Demand modelling software is discussed in Section 8.2.

7.8.2. The focus is on the ability of the software to:

1. Include congestion-dependent VTT in the generalised cost function; and
2. Skim appropriate quantities for the purposes of passing to a demand model and for use in appraisal.

7.8.3. We assume that congestion-dependent VTT is represented using a continuous function.

SATURN

7.8.4. The basic generalised cost function available in SATURN is essentially the same as equation (2) in paragraph 7.2.2, i.e.:

$$GC = VTT \times T + PPK \times D + C$$

7.8.5. This can be extended to include additional user-defined link attributes through the use of so-called KNOBS parameters. The value of these attributes is fixed for each link so can’t be updated dynamically to, for example, include some measure of congestion.

7.8.6. The standard release version of SATURN would therefore require modification by the software developers to incorporate congestion-dependent VTT in the generalised cost function.

7.8.7. Research work using SATURN to assess road user charging in the early 1990s (Milne and Van Vliet, 1993) did use an alternative generalised cost function that is, coincidentally, equivalent to equation (4) in paragraph 7.2.27. This was invoked using the MILNE parameter. Our understanding is that this parameter is not available for use in current, or recent, versions of SATURN.

7.8.8. Making this option available once again will therefore require some modifications to the existing version of SATURN. It is likely, though not certain, that making these modifications would require less work than starting from the beginning again. It therefore offers a relatively attractive option for proof of concept testing in SATURN.

7.8.9. SATURN is very flexible regarding skimming. All link and turn attributes are available to be skimmed. These attributes can be manipulated before skimming at the link/turn level, or after skimming at the matrix level.

7.8.10. Attributes can be skimmed as flow-weighted averages over used paths or along current minimum cost paths. The cost used for the latter can be the same as that used in the assignment, or some other definition (e.g. time only or distance only).

7.8.11. In summary, it would appear that SATURN is unlikely to require any software modifications in order to provide skims to account for congestion-dependent VTT in demand modelling or appraisal.

Visum

7.8.12. Visum offers greater flexibility than SATURN in the definition of the generalised cost function (referred to as 'impedance' in Visum). Essentially all link and turn attributes, input and output, are available for use. Simple functions of these attributes can also be included.

7.8.13. As an example, take equation (4):

$$GC=VTT_{FreeFlow}\times T_{FreeFlow}+VTT_{Delay}\times T_{Delay}+PPK\times D+C$$

7.8.14. In Visum, free flow time is referred to as *t0* and the total travel time is *tCur*. Equation (4) can therefore be implemented in Visum by rearranging as:

$$\begin{aligned}GC&=VTT_{FreeFlow}\times t0+VTT_{Delay}\times(tCur-t0)+PPK\times D+C\\&=(VTT_{FreeFlow}-VTT_{Delay})\times t0+VTT_{Delay}\times(tCur)+PPK\times D+C\end{aligned}$$

7.8.15. Note that the coefficient on *t0* may be negative (since we would expect $VTT_{Delay} > VTT_{FreeFlow}$) but we have been assured by PTV that this is not a problem as the overall cost will be non-negative for each link/turn.

7.8.16. Similarly to SATURN, Visum is flexible in the attributes that can be skimmed.

7.8.17. To demonstrate that it is possible to implement congestion-dependent VTT in a practical model environment a limited number of initial tests have been carried out using a Visum model network and are reported in C.

Summary

7.8.18. Visum is very flexible in the generalised cost/impedance functions that can be defined, provided that the total cost is non-negative for each link/turn. This offers the ability to implement congestion-dependent VTT without any software modifications as demonstrated in the initial model tests that are reported in C.

7.8.19. SATURN offers less flexibility in this regard and would require modifications to allow congestion-dependent VTT in the generalised cost function. One option would be to re-instate a previous research-based option (the MILNE parameter).

7.8.20. Both packages are flexible in terms of cost skimming for use in demand modelling and appraisal and software modifications are unlikely to be required in either case.

8 IMPLICATIONS FOR DEMAND MODELLING

8.1 OVERVIEW

8.1.1. As discussed in earlier sections, there is strong evidence for car drivers having a higher VTT in congested conditions compared to free-flow. Further work is required to establish the best way to include this in behavioural models, but our working assumption is that the end result will be more realistic models, capable of producing better forecasts of travel behaviour.

8.1.2. In this section we discuss the implications of congestion-dependent VTT on demand modelling. We focus on two areas: the practical implications for commonly-used demand modelling software, and whether there are likely to be any issues for demand-supply (assignment) convergence.

8.1.3. We assume that the only significant change to the demand models themselves is that the generalised cost/utility function includes congestion-dependent VTT in a way that is broadly compatible with that used in the highway assignment model[37].

8.1.4. We assume that the rest of the demand model structure is fundamentally unchanged, and that only the parameter values would, potentially, need to be updated to account for congestion-dependent VTT. It would be helpful if this could be confirmed by estimating a demand model with and without congestion-dependent VTT, if a suitable dataset exists or could be collected.

8.2 SOFTWARE

DIADEM

8.2.1. DIADEM[38] was developed by Mott MacDonald for DfT in the early 2000s and is currently maintained by Atkins. It was designed to provide a relatively straightforward way of implementing variable demand models, to coincide with the release of the first version of WebTAG guidance on variable demand modelling (VDM). Up until that point, most scheme-based models in the UK only included highway assignment and there was a shortage of VDM skills in the modelling profession.

8.2.2. The DIADEM demand model is based around the incremental hierarchical logit model, with options to model distribution/destination choice, mode choice, time period choice and trip frequency responses.

[37] It is generally recommended that the same cost function is used in the assignment and demand models. If this is not done, the behavioural response in the two models may be inconsistent and convergence may be difficult to achieve. In some cases, cost terms can be dropped from the assignment if they do not affect route choice for a given OD pair (i.e. the cost is the same for all routes for the OD), e.g. parking costs. In practice, the demand model may include a level of segmentation that is not practical in the assignment, or have non-linear components in the cost functions that can't be included in the assignment, so full compatibility is not always possible.

[38] https://www.gov.uk/government/publications/diadem-software

8.2.3. DIADEM was originally developed as a way of bolting on VDM to existing assignment models. It is still widely used, particularly for Highways England projects. The Regional Traffic Models use DIADEM, as do a large number of scheme-specific models currently being used for the appraisal of RIS1 schemes.

8.2.4. In designing DIADEM to be straightforward for non-expert demand modellers a number of compromises had to be made. One of these was a lack of flexibility in the model, in terms of, for example, the generalised cost function and the functional form of the demand model.

8.2.5. One consequence of this lack of flexibility is that it would not be straightforward to include congestion-dependent VTT without software changes. Once the appropriate cost function for congestion-dependent VTT has been established, they key DIADEM software changes required would be:

- Update the user interface (and the control file)[39] to allow the definition of the required additional cost coefficients (e.g. separate coefficients for free-flow and delay time).
- Update the DIADEM code that skims and then reads in SATURN costs to ensure that all the required cost components are skimmed and read (e.g. free-flow time and delay)
- Update the DIADEM code that calculates the total generalised cost.

8.2.6. That is not to say it would be impossible to include congestion-dependent VTT in DIADEM without software changes. A small number of modellers have modified DIADEM to provide additional functionality. This is done by intercepting calls made by DIADEM to run SATURN programs[40], where these calls are intended to carry out one of the following operations:

- Skimming costs from a completed assignment.
- Carrying out an assignment.
- Converting demand and cost matrices between comma-separated variable (CSV) and the bespoke binary UFM format used by SATURN.

8.2.7. The workaround involves replacing the standard SATURN program used to carry out the operation in question, with one that carries out the required additional operations and *then* calls the standard SATURN program. A common example is applying 'fitting on factors' to the demand matrix output by DIADEM, before it is assigned by SATURN.

8.2.8. A similar process could, in principle, be used to modify the costs skimmed from SATURN before they are read by DIADEM. For example, additional operations could be inserted to skim free-flow and delay times separately, then apply a weight to the delay times before adding the free-flow time to obtain a total "weighted" travel time.

8.2.9. While technically possible, we would strongly advise against such workarounds. The lack of transparency, and the lack of proper error trapping and warning messages if anything goes wrong make this an extremely risky

[39] The DIADEM control file is an xml file that contains all the data entered via the user interface. It can be edited either in the user interface, or in a suitable text file editor.
[40] SATURN is actually a suite of a number of different programs, each with its own specific role. For example there is one program for assigning (SATALL) and another for skimming costs from an assignment (SATLOOK).

way of working (thought the risks can partly be mitigated by extensive checking of model results and interim outputs).

Other demand models

8.2.10. In the UK, where DIADEM isn't being used, the EMME and CUBE software platforms are those that are most widely used to develop demand models. Visum offers similar functionality to these but is rarely used for the demand modelling in the UK.

8.2.11. Demand models in these packages tend to make extensive using of scripting languages. In recent years, scripting languages that are bespoke to a particular software package have been replaced by more widely-used languages, specifically Python.

8.2.12. These packages may offer specific modules for common demand model operations (for example a multinomial logit model), which eliminates or reduces the need for scripting.

8.2.13. Even where such modules are used, they can be enhanced and extended through the use of scripting. This means that such demand models are extremely flexible in their approach.

8.2.14. There should therefore be no particular obstacles to developing demand models in these packages that use a generalised cost function with congestion-dependent VTT. The only requirement is that it should be possible to skim the individual components of generalised cost from the highway assignment model.

8.3 CONVERGENCE

8.3.1. TAG Unit M2 emphasises the importance of achieving a satisfactory level of convergence between demand and supply (assignment) models. Failure to do so risks introducing an unacceptable level of error into subsequent analyses, including the calculation of economic benefits, and noise and air quality impacts.

8.3.2. The theoretical aspects of demand-supply convergence are essentially the same as for highway assignment:

- Does an equilibrium exist?
- Is it unique?
- Will the convergence algorithm find it, and how quickly?

8.3.3. It would be fair to say that, historically, these questions have received more attention in the context of highway assignment models, than for demand-supply equilibrium.

8.3.4. Cantarella (1997) was one of the first to address the question of existence and uniqueness of equilibrium in (variable) demand-supply models. He set out some general conditions for the existence and uniqueness of equilibrium, similar to what Smith (1979) did for highway assignment models.

8.3.5. Cantarella invokes Brouwer's Fixed Point Theorem to demonstrate the existence of an equilibrium point for a very wide range of demand models.[41]

[41] The key requirement is that the demand for a particular alternative is non-negative and has an upper bound. This seems to be true for nearly all demand models. The possible exceptions include elasticity-based demand models.

8.3.6. As is the case with assignment-only models, the uniqueness of the equilibrium is more problematic. For uniqueness of demand-supply equilibrium, the conditions on the cost functions used in the assignment are essentially the same as those required to ensure a unique highway assignment solution. As noted in Section 7.4 these conditions are not guaranteed for assignment models with junction interactions, so it follows that uniqueness of the demand-supply equilibrium is not guaranteed for such models.

8.3.7. Rich and Nielsen (2015) provide an overview of the algorithms most commonly used to achieve demand-supply equilibrium, including a number of *sufficient* conditions for these to converge. It is worth noting that one of these conditions is that the equilibrium should be unique. Otherwise, the conditions for these algorithms to converge do not depend on the properties of the demand and supply models.

8.3.8. As per the previous discussion on highway assignment, it is worth re-iterating that these are only sufficient conditions and the algorithms may still converge even if these sufficient conditions are not met. For example, the 'fixed step length' algorithm that is available in DIADEM does *not* meet these conditions but often converges more quickly and to a better level of convergence than the method of successive averages, which does meet the conditions.

8.3.9. Overall then, the use of congestion-dependent VTT will not affect the existence of a demand-supply equilibrium. Nor is there is any particular reason to suppose it will increase the risk of a non-unique equilibrium. Therefore, nor should it affect the theoretical properties of convergence algorithms and their ability to find an equilibrium.

8.3.10. However, putting the theoretical properties of convergence algorithms to one side, practical experience suggests that a number of factors can affect the ability of these algorithms to achieve an acceptable level of convergence within a reasonable run time.

8.3.11. One of these factors is the degree of convergence within the highway assignment[42], and therefore the amount of noise in the costs that are skimmed for use in the demand model. As noted in Section 7.4, it is uncertain how congestion-dependent VTT would affect this.

8.3.12. A second factor is the supply-side elasticity, i.e. how sensitive travel costs (times) are to changes in demand. At one extreme, a completely inelastic supply model (i.e. fixed costs) can converge in one iteration (depending on the starting point). At the other extreme, anecdotal evidence is that demand-supply convergence can be harder to achieve if supply is very elastic (i.e. in very congested models), though that may just be because it makes it harder to achieve acceptable highway convergence within acceptable run times.

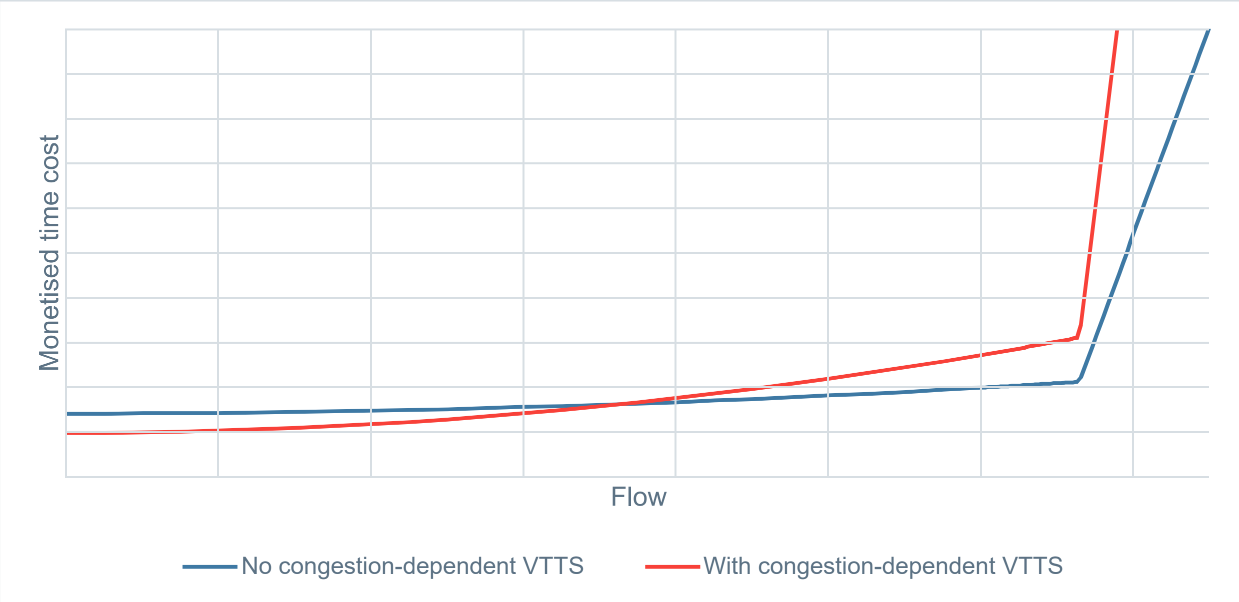
8.3.13. Demand elasticities can also affect convergence. Similarly to supply elasticities, if demand is completely inelastic there is no need to iterate between demand and assignment, and increasing demand elasticities can make it harder to achieve convergence.

8.3.14. Inclusion of congestion-dependent VTT will tend to increase supply-side elasticities in congested conditions, as seen in Figure 7 below. This shows a simple flow-delay curve with and without congestion-dependent VTT. Specifically, it shows the SATURN flow-delay curve used in Highways England's Regional Traffic Models for a

[42] This is more than just achieving the WebTAG requirements for convergence. A % gap statistic well below the WebTAG target is often required, and even then isolated nodes with unstable delays can cause problems for demand-supply convergence.

rural single carriageway road, with monetised time costs. With congestion-dependent VTT the curve is steeper over its full range, with the difference particularly noticeable above capacity.

Figure 7: Monetised time costs as a function of flow[43]



8.3.15. So, while congestion-dependent VTT may have little effect on the theoretical existence and uniqueness of demand-supply algorithm, and the ability of algorithms to find equilibrium, it is possible that there will be some impact on the ability to achieve an acceptable degree of convergence in an acceptable run time.

8.4 SUMMARY

8.4.1. In terms of software, DIADEM would require some modification to accommodate congestion-dependent VTT. Other demand modelling software, which are usually based around a scripting language, should be able to deal with it more readily, albeit requiring some extra scripting.

8.4.2. Congestion-dependent VTT does not appear to lead to any particular issues regarding the theoretical existence and uniqueness of demand-supply equilibrium, and the theoretical ability of convergence algorithms to find that equilibrium. There may be some practical impact on the ability of these algorithms to achieve acceptable convergence within acceptable run times. This will need practical testing to resolve.

[43] This particular graph uses the 'average' VTT and free-flow VTT from Table 11, with VTT for delays valued at three times that for free-flow time. However, the general conclusion does not depend on the precise values used; as long as delay time is valued more highly than 'average' then the red line will be steeper than the blue one.

9 IMPLICATIONS FOR APPRAISAL

9.1 OVERVIEW

9.1.1. As discussed in earlier sections, there is strong evidence for car drivers having a higher VTT in congested conditions compared to free-flow. Further work is required to establish the best way to include this in the modelling and appraisal process, but our working assumption is that the end result will be more realistic models, more accurate valuations of travel time savings from transport schemes, more robust appraisal results, and therefore better decision making.

9.1.2. In this section we consider the implication of congestion-dependent VTT on the appraisal of transport schemes. We start with the economic appraisal of user benefits, considering first the implication for data processing and calculation, and then the possible impact on results. For the latter we consider what might happen if transport models are not updated to include congestion-dependent VTT, and what might happen if they are.

9.1.3. We then discuss other appraisal impacts that use outputs from traffic models.

9.2 ECONOMIC APPRAISAL (USER BENEFITS)

Calculation

9.2.1. For most transport schemes in the UK, particularly road schemes, DfT's TUBA software is used for the calculation of user benefits[44]. This uses matrices of trips, travel times, distances, and charges (tolls, parking charges, fares etc.), extracted from the model for each modelled year and scenario (Do-Minimum (DM) and Do-Something (DS)) to calculate user benefits. For highway trips these benefits are divided into:

- Travel time benefits
- Vehicle operating cost benefits
- User charge benefits

9.2.2. Only the calculation of the first of these, travel time benefits, would be affected by congestion-dependent VTT. The results from the other may be affected by changes in the model results, but the calculation process would remain the same.

9.2.3. Additional TUBA input data would be required to account for congestion-dependent VTT. The details would depend on the definition of congestion, and the exact functional form of congestion-dependent VTT. Assuming something similar to equation (4) is used, then additional data would be required to split travel time between free-flow and delay so that the appropriate VTT can be applied to each OD pair.

9.2.4. From the user's point of view the simplest way to do this would be to input an additional matrix (or matrices) for free-flow time, which would have to be skimmed from the model. TUBA could then use this to calculate

[44] https://www.gov.uk/government/publications/tuba-downloads-and-user-manuals

delay, and therefore the appropriate VTT. Depending on the scheme, free-flow time may or may not vary between base year, future year DM and future year DS[45].

9.2.5. Along with additional input matrices, the TUBA economics file would also need modifying with the additional parameters required to calculate congestion-dependent VTT[46].

9.2.6. There is a close analogy here with the relatively recent introduction of distance-dependent VTT in TUBA. In addition to the 'standard' set of TUBA input matrices, a reference distance matrix is required to allow the appropriate VTT to be calculated for each OD pair[47].

9.2.7. In summary, some changes to the TUBA software would be required and users would need to provide more input data in the form of free-flow time matrices (subject to confirmation of the functional form for congestion-dependent VTT). The TUBA economics file would also need updating with the additional parameters required to calculate VTT.

Impact on benefits – Congestion-dependent VTT not included in model

9.2.8. Suppose congestion-dependent VTT are used to calculate user benefits using existing model outputs, i.e. the models themselves do not use congestion-dependent VTT. What impact would this have on user benefits?

9.2.9. Firstly, only user travel time benefits should change. Whether these would go up or down compared to using current VTT depends on what proportion of the travel time benefits come from changes in congested travel time (delay), and what proportion from changes in free-flow time.

9.2.10. It is reasonable to assume that the majority of schemes in the Highways England Road Investment Programme target congestion hotspots, i.e. where congestion (either now or in the future) is worse than average. If this is the case, then VTT is likely to be higher than average at these locations and therefore the use of congestion-dependent VTT would be expected to increase travel time benefits.

9.2.11. There are some schemes where at least some of the travel time benefits come from a change in free-flow times. For example, if dualling a single carriageway changes the speed limit from 60mph to 70mph then some travel time benefits will arise from the reduction in free-flow time. These benefits will apply throughout the day, not just in the (relatively) uncongested inter-peaks, off-peaks and weekends. For example, in the AM peak a 120 second reduction in travel time might comprise a 30 second reduction in free-flow time and a 90 second reduction in delay[48].

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[45] For example, a scheme that affects the speed limit, e.g. dualling a single carriageway road, would change the free-flow speed.

[46] The TUBA economics file contains a variety of parameters used in the calculation of user benefits, most of which are taken from the WebTAG data book. These include VTT by purpose and mode and real growth rates in VTT.

[47] It would be possible to include congestion-dependent and distance-dependent VTT if a suitable functional form can be defined.

[48] This could lead to some unintended consequences. Suppose the DS speed in the AM peak with the dual carriageway is 50mph, and this would be the same whether the speed limit is 60mph or 70mph. If the speed

9.2.12. A more extreme example would be the Lower Thames Crossing, where the construction of a new crossing of the Thames much further east than existing crossings would significantly reduce free-flow times for some movements.

9.2.13. Of course, schemes like dualling single carriageways and new estuarial crossings reduce delays as well as free-flow times. The net impact of congestion-dependent VTT depends on the balance between the two and it is not possible to say, a priori, what the result would be.

9.2.14. Not all road schemes are focused on reducing congestion. Some are predominantly aimed at improving safety. One such measure would be to reduce the speed limit on a road. This is usually associated with a travel time disbenefit because of the increase in free-flow times. With congestion-dependent VTT there would still be a disbenefit, but it is likely to be smaller.

Impact on benefits – Congestion-dependent VTT included in model

9.2.15. The above discussion is based on the assumption that existing model results are used, but what if the models are also updated to take account of congestion-dependent VTT?

9.2.16. The results in Section 6.3 show that as congestion (delay) is given more weight relative to free-flow time then there is increasing preference for routes which have more free-flow time and less delay. This means it is possible that in forecasting models with congestion-dependent VTT there will be less congestion and delay compared to existing models. This could reduce travel time benefits of any given scheme (as measured in person hours, before monetisation).

9.2.17. The effect is likely to be increased with variable demand modelling, with increasing congestion more likely to cause travellers to switch to alternative destinations and modes.

9.2.18. The same results also show that distance travelled tends to increase as more weight is given to delay. This could result in a change in the magnitude of vehicle operating cost benefits (which can be positive or negative, depending on the nature of the scheme).

Summary

9.2.19. In summary, if congestion-dependent VTT were to be included in economic appraisal, but not behavioural modelling, we would expect the benefits of most schemes (i.e. those targeted at reducing congestion) to increase compared to using existing VTT. Some schemes include a change in free-flow times, which would be valued less than with existing VTT; the net impact for such schemes is unclear.

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limit is 60mph then the free-flow time would be unchanged and the whole 120 second reduction in time would be counted as a delay reduction and therefore valued more highly than if the speed limit were 70mph (with a 30 second free-flow time reduction and 90 second delay reduction). However, in each case the driver experience would be identical. Does it make sense for the benefit to depend on the speed limit, i.e. should the cost of driving at 50mph on a dual carriageway depend on whether the speed limit is 60mph or 70mph? The potential for this kind of anomaly needs further consideration when deciding on an appropriate function for congestion-dependent VTT.

9.2.20. Including congestion-dependent VTT in behavioural modelling (but not appraisal) could, other things being equal, reduce travel time benefits. There could also be some impact on vehicle operating cost benefits, in either direction.

9.2.21. Including congestion-dependent VTT in behavioural modelling and economic appraisal could change travel time benefits in either direction compared to current practice.

9.3 OTHER APPRAISAL USING MODEL OUTPUTS

9.3.1. As well as user benefits, a range of other WebTAG impacts make use of outputs from transport models, for example:

- Accidents
- Noise
- Air quality
- Greenhouse gases

9.3.2. These all use flows and, in some cases, speeds from the traffic model. While some of the numbers will change if congestion-dependent VTT is used in behavioural modelling, the processes will not be affected by congestion-dependent VTT.

10 IMPLICATIONS FOR MODELLING CONSULTANTS AND THEIR CLIENTS

10.1.1. In this section we consider the possible implications of including congestion-dependent VTT on modelling consultants and their clients. We do this under the broad headings of:

- Model development
- Model application
- Use and interpretation of model results

10.1.2. The implications may vary according to the precise functional form used to represent congestion-dependent VTT. For now, we assume something similar to equation (4) will be used. We also assume that any software-dependent issues raised earlier have been resolved and modellers have the necessary tools for the job.

Model development

10.1.3. The table below summarises possible model development impacts which are then discussed in more detail afterwards.

Table 15: Possible impacts of congestion-dependent VTT on model development

Area	Impact
Model extent (Area of detailed modelling, Rest of FMA, External)	Possible use of longer routes to avoid congestion could increase area of influence of transport schemes and therefore may need to extend the area of detailed modelling and/or the fully modelled area.
Level of network detail	Possible requirement for more link categories and more precise definitions of junction capacities. Possible greater model extents would increase network detail in some areas.
Model zoning	Possible extension of AoDM and FMA could increase number of zones in some areas.
Prior matrix development	None
Generalised cost function definition	Minimal
Journey time validation	May need to validate free-flow and delay times separately. This may lead to: - Additional processing of observed data - Wider range of link categories/speed-flow curves - A need for more accurate link and junction capacities
Link flow calibration and validation	In principle, may prove easier, but not certain.
Required skills	Possible increase in requirement for those skilled in journey time validation, and resolving convergence issues, but not a major step change.

10.1.4. The main impacts on model development stem from the desirability of being able to demonstrate an accurate split between free-flow time and delay in the base model (assuming that the preferred generalised cost function splits total travel time in this way), and the possibility that models will need to cover a wider area to pick up the use of longer routes to avoid congestion.

10.1.5. Regarding the distinction between free-flow and delay times, it is possible that this split is already accurate in a large number of existing models, and would just need to be backed up by evidence in the form of more detailed analysis of modelled journey times. Alternatively, some models may require significant improvement in this area. We do not have the evidence either way, though we note that journey time validation would currently be hard to achieve if the free-flow/delay split were not reasonably accurate.

10.1.6. At the moment, highway assignment models are validated against observed journey times along defined routes. With congestion-dependent VTT it may become desirable to validate against free-flow and delay time separately. This is perhaps not quite as onerous as it might appear.

10.1.7. For observed data, the general availability of sources such as Trafficmaster makes it easy to estimate free-flow times (as we have done in Section 6). Once free-flow times are known it is straightforward to then calculate delay in any given time period.

10.1.8. Free-flow times are an input to the model. 'Validating' the model to free-flow times should therefore just be a formality[49].

10.1.9. Validating the models to delays should then be no more onerous than the current journey time validation requirements.

10.1.10. To facilitate the above it may prove to be desirable to include more link categories in the model, with a wider range of speed-flow curves. This is by no means certain.

10.1.11. Similarly, it will be important to use accurate values for link and junction capacities to model delays accurately, but that is already the case.

10.1.12. The evidence presented in Section 6 suggests that as more weight is attached to congested travel times then longer routes are used to avoid congestion. This suggests that the extents of the area of detailed modelling[50] and/or the rest of the fully modelled area[51] may need to be increased to ensure that these longer routes are accurately modelled.

10.1.13. Network detail may therefore need to be increased in some areas of the model, with an associated increase in the number of zones.

10.1.14. Definition of the generalised cost function may be slightly more complicated in assignment and demand models. Provided appropriate cost coefficients continue to be made available in the WebTAG data book then the extra burden on modellers would be minimal.

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[49] 'Validating' is in quotes here as it is arguably not a true validation using independent data.

[50] Defined in WebTAG as 'the area over which significant impacts of interventions are certain. Modelling detail in this area would be characterised by: representation of all trip movements; small zones; very detailed networks; and junction modelling (including flow metering and blocking back).'

[51] Defined in WebTAG as 'This is the area over which the impacts of interventions are considered to be quite likely but relatively weak in magnitude. It would be characterised by: representation of all trip movements; somewhat larger zones and less network detail than for the Area of Detailed Modelling; and speed/flow modelling (primarily link-based but possibly also including a representation of strategically important junctions).'

10.1.15. An interesting potential benefit of congestion-dependent VTT is in the calibration and validation of link flows. In principle, congestion-dependent VTT should lead to more realistic modelling of route choice in the model which could make models easier to validate. In practice however, the widespread use of matrix estimation from counts usually means that any errors in the route choice in the model are automatically compensated for during model calibration, and there may be no discernible benefit for calibration, though the robustness of the model may improve.

10.1.16. The final question to address here is whether the transport modelling profession has the appropriate skills to successfully implement congestion-dependent VTT. Assuming appropriate software is available, and WebTAG provides appropriate parameter values then we do not anticipate a major change in the skills required. More attention may need to be paid to journey time validation, and there may be more convergence-related problems to resolve. These are skills that are already required in model development and application, so this does not represent a step-change in the level of modelling skills and resources required. This is in contrast to the publication of the first version of WebTAG, where the 'new' recommendation for variable demand modelling led to a significant learning curve for large parts of the profession.

Model application

10.1.17. The biggest implication for model application is likely to be the impact on run times and convergence. As noted in Sections 7.4 and 8.3, there is a risk that congestion-dependent VTT will make satisfactory convergence harder to achieve for both the assignment model and the demand-supply loop. On the other hand, it is possible that convergence would improve. Practical testing would be required to acquire greater understanding of this issue.

10.1.18. There may be a small additional computational overhead in the modelling software to calculate generalised costs with a more complicated cost function, but this should be negligible and have no noticeable effect on run times.

Use and interpretation of model results

10.1.19. While the numbers may change, the use of model outputs and their interpretation will be fundamentally unchanged by the inclusion of congestion-dependent VTT. As noted in Section 9, economic appraisal will require additional data processing of model outputs, but this should be manageable.

11 RISK REGISTER

11.1.1. The following table summarises the risks and opportunities from including congestion-dependent VTT in behavioural modelling and/or economic appraisal

Table 16: Risk register

Area	Description	Likelihood	Severity	Mitigation
Modelling & economics	Uncertainty about appropriate functional form for representing congestion-dependent VTT. Incorrect functions could lead to unrealistic behavioural responses in models and incorrect results for economic appraisal.	Medium	High	Undertake further research to obtain robust functions.
Modelling & economics	Uncertainty about appropriate parameter values for representing congestion-dependent VTT. Incorrect values could lead to unrealistic behavioural responses in models and incorrect results for economic appraisal.	Medium	High	Undertake further research to obtain robust parameter values. Use sensitivity testing to understand impact of a range of parameter values on decision making.
Modelling & economics	Software developers unwilling to modify software to accommodate congestion-dependent VTT.	Medium	High	DfT to make budget available for TUBA and DIADEM updates. Discuss with other software developers before releasing draft WebTAG guidance.
Modelling	Increased burden on modellers in terms of level of detail in model and model extent.	Medium	Low	Undertake pilot testing to establish if this is significant before releasing draft WebTAG guidance.
Modelling	Harder to validate models.	Low	Medium	Undertake pilot testing with existing models to establish if this is significant before releasing draft WebTAG guidance.
Modelling	Harder to achieve acceptable convergence in acceptable run times.	Medium	Medium	Undertake pilot testing with existing models to establish if this is significant before releasing draft WebTAG guidance.
Economics	Reduces value for money of some transport schemes.	Low	Medium	None: provided results are robust, this will lead to improved decision making.

12 SUMMARY AND RECOMMENDATIONS

12.1 SUMMARY

UK VTT Study Stated Preference

12.1.1. In the Arup/ITS Leeds/Accent SP study, three experiments were presented to car respondents:

- SP1: a time/money trade-off.
- SP2: a time/money/reliability trade-off.
- SP3: a time/money/congestion trade-off.

12.1.2. It is the data from the SP3 experiment that has been used to estimate congestion multipliers.

12.1.3. Each SP3 choice option presented travel times for three traffic conditions to respondents:

- Free flowing – you can travel at your own speed with no problems overtaking.
- Light traffic – you can travel close to the speed limit most of the time, but you have to slow down every so often.
- Heavy traffic – your speed is noticeably restricted and frequent gear changes are required.

12.1.4. The visual image associated with the heavy traffic option seems to imply gridlock conditions and in general the meaning of the light and heavy traffic levels was vague and therefore open to different interpretations.

12.1.5. Cognitive depth interviews were undertaken at the pilot stage to investigate respondents' experiences in completing the questionnaire. There was no evidence from these interviews that respondents had difficulties in understanding the SP3 congestion experiment. During the main survey, diagnostic questions were recorded for the SP3 experiments. These found that in general respondents found the options to be understandable, realistic, related to real life choices and easy to choose between, though a significant fraction thought differently. However, the analysis reported was for all modes rather than for car respondents alone.

UK VTT Study Model Specification

12.1.6. Advanced model specifications were developed by the study team, using multiplicative rather than additive error structures, incorporating random heterogeneity in VTT, and taking account of reference dependence using size, sign and asymmetric effects.

12.1.7. A key feature of the models was that they were estimated by pooling the data across the three SP experiments. This approach reduces ambiguity and allows for increased robustness for those attributes shared across the different experiments, and also means that the congestion multipliers were directly estimated together with associated measures of statistical significance. Multipliers on total VTT were included in the model specification that account for the impact of congestion on the respondent's reference trip on their VTT.

12.1.8. Informed by the literature review we conclude that an appropriate and advanced model specification was used for the VTT analysis.

UK VTT Study Model Results

12.1.9. The key model results in the context of this study are the congestion multipliers from the SP3 experiment. These are reproduced in Table 17 which shows, for each purpose, the multiplier on the left and the associated t-ratio on the right.

Table 17: SP3 congestion multipliers

	Commute multiplier	Commute t-ratio	Employees' business multiplier	Employees' business t-ratio	Other non-work multiplier	Other non-work t-ratio
Free flow time	1	n/a	1	n/a	1	n/a
Light traffic time	1.40	1.71	1.61	3.25	1.76	2.85
Heavy traffic time	2.66	4.04	2.99	6.79	3.98	6.08

12.1.10. These values are high in comparison with values quoted in the literature, which in the UK are around 1.5 on average and rarely exceed 2. The valuations for heavy traffic, particularly for other non-work, are implausibly high and therefore we conclude that they are not robust, and we do not recommend that these values be used as the basis for practical transport model applications.

12.1.11. There are a number of possible explanations for the high valuations. First, the visual presentation of heavy traffic conditions looks like gridlock and may have biased how individuals responded. Second, having been asked to focus on congestion levels in the SP3 experiment respondents may have over-reacted to them. Third, there may have been confounding between reliability and congestion. Fourth, there is some evidence that respondents making long-distance trips are more sensitive to congestion and that their valuations may have biased the congestion multipliers upwards. Finally, assuming that the congested VTT distributions were the same as the overall VTT distributions may have biased the congestion multipliers upwards.

12.1.12. It is noted that the first three of these explanations relate to how individuals have reacted to the information presented to them, rather than the analysis used to estimate the congestion multipliers. Therefore, while further analysis of the data may be valuable we think it likely that estimated values of the congestion multipliers will remain high given the inherent issues with the data that has been collected.

UK VTT Study SP Quality Assurance and Audit

12.1.13. A number of QA checks were employed throughout the model development process by ITS staff. These checks included detailed QA checks of the final car commute model code which was used to estimate CVTT for commute. Without access to the model code we cannot be certain that there is not an error with the coding for the SP3 experiment that contributes to the high CVTT estimates, but the level of QA checking applied throughout the model development process means that this is unlikely.

12.1.14. An independent audit was undertaken by SYSTRA, Imperial College London and the Technical University of Denmark. The auditors raised five main concerns, none of these relate to the SP3 experiment or analysis and furthermore the auditors do not comment on the high CVTT estimates that emerge from the modelling.

Congestion Multipliers from the Literature Review

12.1.15. In the UK, the Abrantes and Wardman (2011) meta-analysis provides mean congestion multiplier values based on 29 separate valuations. The valuations are simply for congested time, and the average values show a good correspondence between SP evidence (1.55) and RP evidence (1.51) (though the RP value is based on just 4 studies so highly uncertain).

12.1.16. Two SP studies in the UK have calculated congestion multipliers using a more finely differentiated grading of traffic conditions, with six levels in total. The 2004 study estimated congestion multipliers that ranged from 1.20 in busy traffic to 1.96 in gridlock. The 2006 study used the same six levels, and estimated multipliers ranging from 1.14 in busy traffic and 1.78 in gridlock. Both sets of estimates are consistent with an overall congestion multiplier of around 1.5.

12.1.17. There is limited evidence from other recent European VTT studies. The Danish study was unable to identify an estimate for congested time that was higher than free flow time, and therefore constrained the two parameters to be equal. The study in Sweden did not present congested time separately and therefore did not estimate any congestion multipliers. However, VTT in Stockholm was found to be 1.3 times higher than average, after accounting for income differences, and it was suggested that this may be a result of high levels of congestion in Stockholm compared to the rest of Sweden. The study in the Netherlands did not present congested time separately and therefore did not estimate any congestion multipliers. Finally, the study in Switzerland found no significant evidence that congested time was valued more highly than free flow time.

12.1.18. Two further studies undertaken in Europe do provide useful insight. An SP study undertaken in Stockholm identified congestion multipliers that ranged from 1.42 in the morning to 1.53 in the evening. Finally, a study undertaken in Denmark using RP GPS data estimated multipliers of 1.46–1.50 in the peak and 1.25–1.26 in the off-peak.

12.1.19. The meta-analysis of UK studies did not provide purpose specific estimates of the congestion multipliers, and there is insufficient UK evidence to provide purpose specific congestion multiplier values. Combining the evidence from the UK and Europe, the general pattern is for the multipliers to be lowest for commuting travel, and highest for other non-work travel. This pattern is consistent with the Arup/ITS Leeds/Accent findings and it is intuitive for commuters to have the lowest valuations as would expect congestion become more acceptable to those making high-frequency trips.

12.1.20. Overall the literature review suggests a UK value for the congestion multiplier of 1.5, and this valuation is consistent with the wider European evidence. Higher UK multipliers are obtained for travel in gridlock conditions but the valuations remain below a value of two. These values are substantially lower than those obtained in the Arup/ITS Leeds/Accent analysis and suggest the values obtained in that study for heavy traffic conditions to be implausibly high and therefore not robust as mentioned above.

Relative Impacts of Reliability and Congestion

12.1.21. The literature review has identified little hard evidence of confounding between congestion and reliability effects because reliability was not presented alongside congestion in the majority of the studies reviewed in detail. However, reliability information was included in some of the studies identified in a meta-analysis undertaken by Wardman and Ibáñez (2012). Their study reported results from a meta-model that included congestion multiplier valuations estimated from models that presented reliability information alongside congestion. The reliability term was not significant and so there was no impact that including reliability, or conversely omitting reliability from the presentation, impacted on the estimated congestion multipliers.

12.1.22. In the same study an SP experiment was undertaken where the alternatives were described by differences in travel time at different congestion levels alone. To mitigate possible confounding between congestion and reliability, care was taken in the presentation to present the choice between two options where it was not immediately obvious which was more reliable.

12.1.23. The authors of the 2007 Danish value of time study suggest that the accepted congestion multiplier in Denmark of 1.5 is greater than one because it captures the disutility associated with lower levels of reliability associated with travel in congested conditions. No information on the relative impact of reliability and congestion was available from the Danish, Swedish, Swiss and Dutch VTT studies.

12.1.24. The single RP study reviewed estimated models where the impacts of reliability and congestion were both directly represented. In these models the congestion multipliers ranged from 1.25 to 1.5, and so significantly higher valuations associated with congestion were identified over and above reliability effects.

Tests of the Impact of Congestion Multipliers on Simple Networks

12.1.25. We have used a combination of Trafficmaster journey time data and a GIS-based routeing algorithm to investigate the impact of congestion-dependent VTT on optimum (i.e. minimum cost routes). This analysis looked at a single urban OD pair and a single inter-urban OD pair.

12.1.26. It would be unwise to generalise too widely from this analysis, but the results suggest that:

- Congestion-dependent VTT can, in some cases, affect the optimum route.
- The optimum routes identified seem sensible in that they do not result in excessive increases in distance in order to avoid congestion.

Implications of Congestion-dependent VTT for Assignment Software

12.1.27. One of the biggest impacts of congestion-dependent VTT is on the algorithms that find minimum cost paths for each origin-destination pair. The algorithms in most commercial software impose a number of requirements on the characteristics of a generalised cost function which includes congestion-dependent VTT. These include the use of a continuous function of congestion, rather than categorical definitions. They also require that the total route cost is the sum of the cost on individual links in that route.

12.1.28. We have suggested an alternative cost function that meets these requirements, which decomposes total travel time into free flow time and delay and assigns a separate value of time to each. Further alternatives could be proposed and the final recommended function should be determined by the evidence.

12.1.29. Congestion-dependent VTT does not appear to offer any theoretical difficulties for assignment models, over and above those that already exist. There is a risk that models could take longer to achieve acceptable levels of convergence, but that is by no means certain.

12.1.30. Our assessment is that some functions for congestion-dependent VTT could be implemented in Visum without any modifications to the software, and this has been demonstrated and reported in C. However, modifications are likely to be required for SATURN and microsimulation software.

12.1.31. There is no immediately apparent reason why congestion-dependent VTT should affect the recommended level of segmentation in transport models. This should be kept under review as further evidence is gathered and analysed.

12.1.32. It should be possible to update bus travel times in PT assignment models to reflect the impact of congestion-dependent VTT. However, given that there will very rarely be bus route choice between congested and uncongested routes this may not be worthwhile.

Implications of Congestion-dependent VTT for Demand Modelling Software

12.1.33. Congestion-dependent VTT does not appear to offer any theoretical difficulties for demand models, over and above those that already exist. There is a risk that models could take longer to achieve acceptable levels of convergence (in iteration with assignment models), but that is by no means certain.

12.1.34. DIADEM software would need to be modified to allow congestion-dependent VTT. Other demand model software, which tends to use scripting languages to implement demand models, is more flexible. While the scripts would need to be updated, the software itself should not need to be modified.

Implications of Congestion-dependent VTT for Appraisal

12.1.35. TUBA software would need to be modified to accommodate congestion-dependent VTT.

12.1.36. If congestion-dependent VTT is included in economic appraisal, but not behavioural modelling, it is likely to increase the user travel time benefits, particularly for those schemes aimed at reducing congestion. This is less likely to be true for schemes where a significant proportion of the benefits come from a change in free-flow speed (such as dualling a single carriageway, or a new estuarial crossing).

12.1.37. Including congestion-dependent VTT in behavioural modelling may reduce user travel time benefits, as it will tend to discourage travellers from choosing more congested options (routes, modes and destinations), and therefore reduce congestion in the do-minimum.

12.1.38. The methods used to calculate other appraisal impacts from model results (for example, noise, air quality and accidents) would be unaffected, though the results themselves may change as the model outputs change.

Implications of Congestion-dependent VTT for Modelling Consultants and their Clients

12.1.39. Congestion-dependent VTT is likely to impose some additional burden on modelling consultants, particularly during the development of the base year model. However, it would not require the acquisition of any additional skills, compared to what is already available.

12.1.40. There is a risk that models could take longer to achieve acceptable levels of convergence, but that is by no means certain.

12.2 RECOMMENDATIONS

12.2.1. Overall, there is a strong body of evidence that travel time is valued more highly in congested conditions. However, that evidence is currently insufficient to allow us to formulate VTT as a function of congestion in a way that would allow it to be included in modelling and appraisal. Further work is therefore required to get to the position where congestion-dependent VTT could become a WebTAG requirement. The following sections set out some of the details.

Further Analysis of the UK VTT Study SP Congestion Data

12.2.2. Given the significant investment in data collection in the 2015 UK VTT study we have considered what further analysis could be undertaken with this data, and whether following that analysis the data might yield congested VTT estimates that could be used in highway assignment models.

12.2.3. There are a number of pieces of additional analysis of the SP congestion data that we believe would be insightful in better understanding the robustness of the current multipliers and may lead to the identification of lower and more plausible congestion multipliers.

12.2.4. First, investigating whether congested VTT has a different, and potentially more right skewed, distribution than overall VTT. If the congested VTT distribution is different then capturing this using a modified model specification may allow lower and more plausible CVTT estimates to be obtained.

12.2.5. Second, investigating the variation in the congestion multipliers with trip length to determine whether the high proportion of long distance trip makers in the sample population influenced the high valuations[52]. A potential outcome of this analysis, if there is a significant positive relationship between the multipliers and distance, is that congested multipliers are calculated at a representative mean trip length (the multipliers estimated by ITS represent an average over all trips and given the nature of the sample will be biased towards longer distance

[52] The existing model specification takes account of the impact of trip length on overall VTT, however it does not allow the congestion multipliers to vary with distance.

trips). One simple approach to this would be to split the telephone and intercept surveys, given that the telephone surveys asked for a 'recent typical' journey we would expect these to have significantly lower mean trip lengths than the intercept surveys.

12.2.6. Third, checking that all dominant choices have been removed from the data, and if not, removing them and investigating the impact on the congestion multipliers.

12.2.7. Finally, analysing the responses to the diagnostic questions for car users alone to better understand car respondents' ability to comprehend and relate to the information that was presented to them. If this analysis suggests a significant fraction of car respondents did not understand the information presented, it would be worth excluding these respondents to investigate the impact that they had on the congestion multipliers.

12.2.8. That said, we believe that a number of the issues that contribute to the high congestion multiplier estimates are inherent in the data that has been collected rather than as a result of the approach used to analyse the data. Specifically, confusion around the meaning of the congestion levels, overreactions to levels of congestion and confounding between reliability and congestion[53]. These issues with how respondents have responded to the congestion experiment cannot be altered at this stage, and therefore it is quite likely that even after further analysis the congestion multipliers will be unacceptably high.

12.2.9. Further to this, and perhaps most important for practical implementation given the issue raised in Section 7 above, because total free flow time information was not presented to respondents it would not be possible to reanalyse the data using a continuous specification for variation in VTT with congestion level. Therefore, to determine congestion valuations for use in practical models alternative options need to be considered. These are discussed further below.

12.2.10. Overall, given our concern that even after further analysis the congestion multipliers are likely to be too high, and that whatever their values, the congestion multipliers cannot be used in practical models, we do not recommend proceeding with this option.

Recommendations for Subsequent SP Studies

12.2.11. A number of recommendations emerge that would be useful for any subsequent SP VTT studies that incorporate a congestion experiment.

12.2.12. First, there needs to be a careful consideration of the congestion levels presented to ensure that respondents properly understand the congestion associated with each level, potentially using a short video to illustrate the differences between different congestion levels more effectively than static images.

12.2.13. Second, the potential for confounding between congestion and reliability needs careful consideration, options to account for this are as follows:

- to explicitly state to respondents in the congestion experiment that each choice option should be considered equally reliable – this would need to be presented carefully noting that some respondents may view congestion and reliability to be inseparable;
- present options where the two alternatives appear equally likely to be equally reliable; and

[53] Note that while we believe some degree of confounding between congestion and reliability is likely to have occurred there is no hard evidence to confirm this, let alone quantification of the impact on the congestion multipliers.

- present reliability information alongside congestion if that can be done without over-burdening respondents with information.

12.2.14. Third, and most importantly for practical implementation, the congestion information presented to respondents should be presented together with total travel time in free flow conditions (equivalent to the two time skims output from highway assignment packages) so that continuous measures of congestion can be specified that are compatible with the outputs from highway assignment packages.

Use of Big Data

12.2.15. The use of big data to support estimation of congestion valuations offers the potential for using existing route choice data rather than needing to collect additional costly stated preference data. A further advantage of the approach is that by using RP data the actual route choices made by travellers in presence of congestion can be used in model estimation and this helps to avoid some of the issues that have potentially impacted the Arup/ITS Leeds/Accent SP study such as respondents understanding of the congestion information presented to them and confounding between congestion and reliability. The limitations are that respondents may not know the actual level of congestion when making their route choices, their knowledge of alternative routes may be imperfect, and most seriously journey purpose information is often not available[54].

12.2.16. The analytical approach we outline here is not untested, it follows the same logic that was employed by Prato *et al* (2014) to successfully estimate congestion multipliers from GPS data collected in Copenhagen.

12.2.17. The key requirement in the big data approach is a large route choice dataset. An obvious candidate is the Trafficmaster data that provides GPS data from a total of 135,000 vehicles, though it is understood that a relatively high fraction of these are vans.[55] The Trafficmaster data is centrally purchased by the DfT and so should be available for research purposes. The Trafficmaster data would provide both route choice information, and route/link attributes such as distance, free flow time and congested time to support the estimation of route choice models. A limitation of the Trafficmaster data is that it is not available by journey purpose and this means that it would not be possible to estimate separate congestion valuations by journey purpose. Furthermore, the Trafficmaster data is likely to have biased purpose shares, with employer's business over-sampled, and the income distribution may also be biased compared to the general population. Any trip length bias could be controlled for in model estimation.

12.2.18. Another candidate data source of routeing information is the Highways England Trip Information System (TIS) which has been built using O2 Telefonica mobile phone data. The TIS data uses a routeing engine to generate the three quickest routes between the trip origin and destination based on road speed limits (i.e. assuming uncongested conditions), and then selects the route which best matches the observed locations of the mobile phone en-route. Thus the route identified is not directly observed, and is based on three route options that are generated in the absence of congestion effects. Therefore we conclude that the TIS data is not suitable for this analysis. However, other mobile phone data sources may be suitable if they provide route choice information for cars, in particular if the information can be segmented by journey purpose.

12.2.19. Once the route choice data has been assembled it needs to be linked to a highway network, and distance and travel time information assembled for all possible routes. Trafficmaster data is a potential source for this

[54] Unless data is collected over successive days, and work and education locations are inferred. This entails significant amounts of additional analysis.
[55] http://www.basemap.co.uk/trafficmaster-data/, accessed 20/10/17.

information and has the advantage of being based on observed data. A process is then required to identify, for each observed route, a choice set of other route alternatives. Those route alternatives could be derived from the Trafficmaster data itself or a converged assignment from a validated highway network model could be used to supply free flow and congested travel times for all of route alternatives. The final stage would be to estimate route choice models and from these estimate the congestion valuations. If the routeing information is available by purpose, then it would be possible to estimate congestion valuations by purpose.

12.2.20. The key issue for the RP data option is that of journey purpose. If it is possible to obtain purpose-specific routeing information, e.g. from processed mobile phone data, or the Department is willing to accept a single set of congestion multipliers estimated across purposes then the RP data option is our preferred approach. Otherwise we recommend the collection of additional SP data to allow the estimation of purpose specific congestion multipliers.

Collecting Additional SP Data

12.2.21. Another approach to identifying up to date estimates of congestion valuations is to collect additional SP data. If the Department are happy to estimate valuations for time components alone, rather than cost and time, then the SP approach used by Wardman and Ibáñez (2012) successfully identified congestion multipliers for six levels of congestion, and further worked well in an earlier 2004 SDG study. In both of these studies the congestion multipliers identified are consistent with the wider literature.

12.2.22. Wardman and Ibáñez (2012) did not estimate separate models by purpose and so collecting purpose specific data would be necessary to allow purpose specific congestion multipliers to be determined. The approach should be modified to work with a continuous definition of congestion, to do this total free flow travel time should be presented to respondents as well as total travel time including congestion. One approach would be to present choices like:

- the journey takes 30 minutes in total including congestion (the same journey made at night when there is no congestion would take 20 minutes)
- the journey takes 35 minutes in total and there is no congestion (the same journey made at night when there is no congestion would also take 35 minutes)

No monetary cost information would be presented to respondents.

12.2.23. Accompanying visual presentations may help convey to respondents the levels of congestion presented, for example images or videos illustrating the different levels of congestion presented. Given the novelty of such an approach piloting of different presentation options would be required to demonstrate respondents understand what is being presented.

12.2.24. This option is recommended as the most straightforward and proven approach in a UK context to identifying congestion valuations from SP data.

Representing CVTT in the generalised cost function

12.2.25. If it is desirable to include CVTT in highway assignment models then it should be represented in a generalised cost function in a way that ensures:

- 'Congestion' is a continuous rather than categorical variable.
- The total route cost is the sum of the individual link cost over each link in the route.
- The coefficients of the generalised cost function are fixed for a given user class, i.e. they do not vary according to the characteristics of the route; in particular they do not vary between alternative routes for the same OD pair.

12.2.26. Meeting the above criteria should minimise the effort required to implement the function in highway assignment software packages, and avoid the need to develop fundamentally new methods for, e.g., minimum cost path building.

12.2.27. We have proposed a generalised cost function that meets these requirements. However, any further data collection and analysis should remain open-minded about the precise form of the function, with the fit to the data being one of the criteria used to define the function (the others being the criteria set out above).

12.2.28. It would be difficult to estimate a generalised cost function with a continuous definition of congestion from existing SP data. Previous studies have tended to use categorical definitions of congestion, with ambiguously defined breakpoints between categories.

Impact of CVTT on modelling and appraisal

12.2.29. A formal requirement in WebTAG to use congestion-dependent VTT in modelling and appraisal has the potential to impose an additional burden on model users and software developers, while having the opportunity to deliver more realistic model forecasts and scheme appraisal. It would also require significant further research to establish the appropriate functional form and parameter values.

12.2.30. We therefore recommend that further preliminary work is undertaken first, to try to establish the potential scale of the impact of congestion-dependent VTT on modelling and appraisal results. This should be in the form of two parallel threads:

- Use of an existing highway assignment model to implement congestion-dependent VTT using a range of multipliers. Analysis of results to confirm the scale of the impact and assess whether this is realistic. This would build on the GIS analysis presented in Section 6 and the initial model tests reported in C. For expediency we would recommend the use of Visum for this test, as no software modifications would be required. In the longer term, testing with SATURN would be desirable if arrangements could be made to modify the software.

- ‘Manual’ manipulation of TUBA outputs for a number of existing schemes to establish likely impact of congestion-dependent VTT. This would involve skimming free-flow and delay times separately from an existing model and running TUBA on each separately, using different input VTT estimates.

12.2.31. This would provide further evidence of the possible impact of congestion-dependent VTT and help to decide whether the potential benefits (more robust modelling and appraisal) outweigh the potential costs (short term investment in further research, followed by a possible longer-term burden on practitioners) of undertaking further work in this area.

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14 APPENDICES

A. Minimum Cost Routes – Leicester OD Pair

Figure A 1: Northbound AM peak

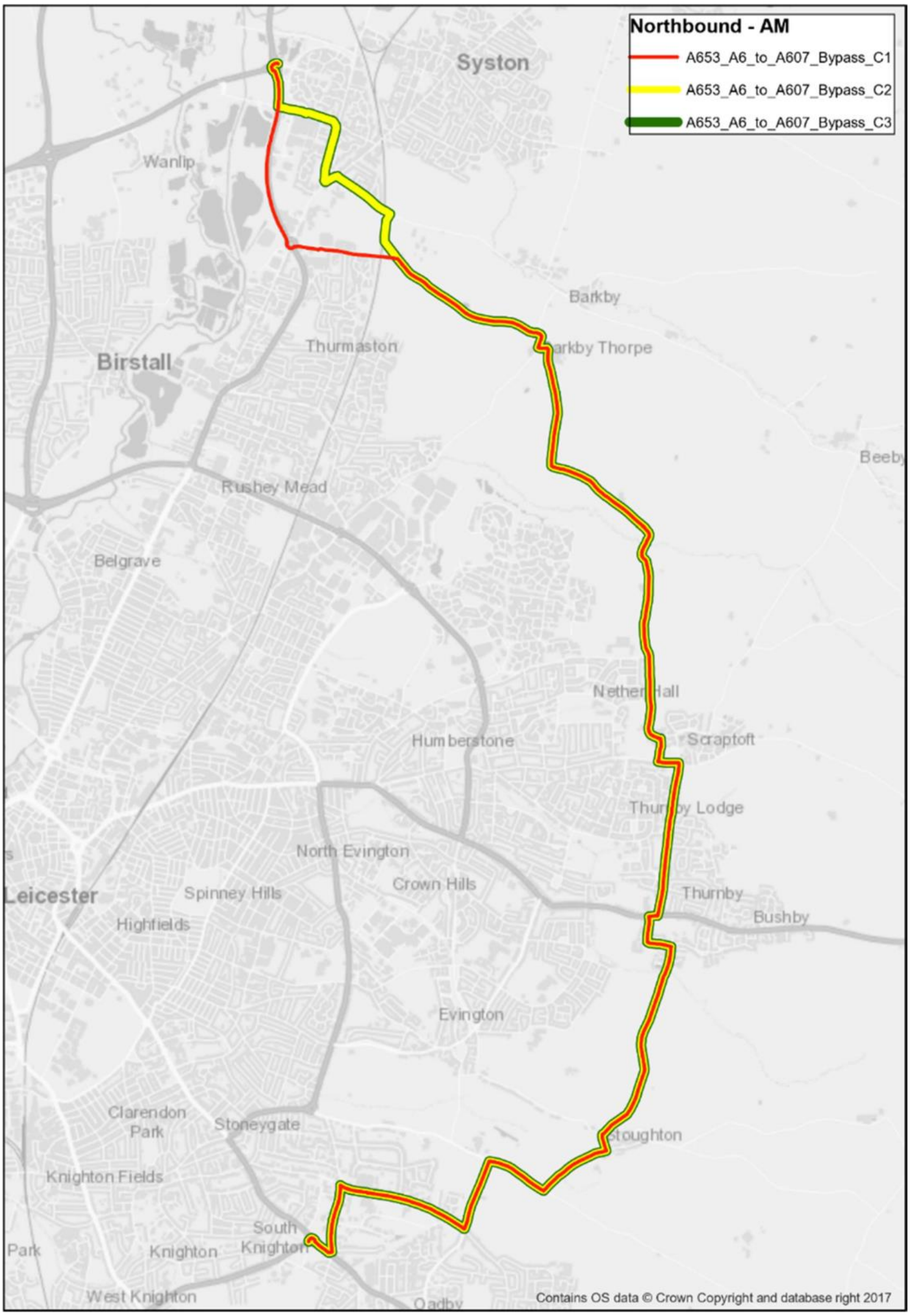


Figure A 2: Northbound Inter-Peak

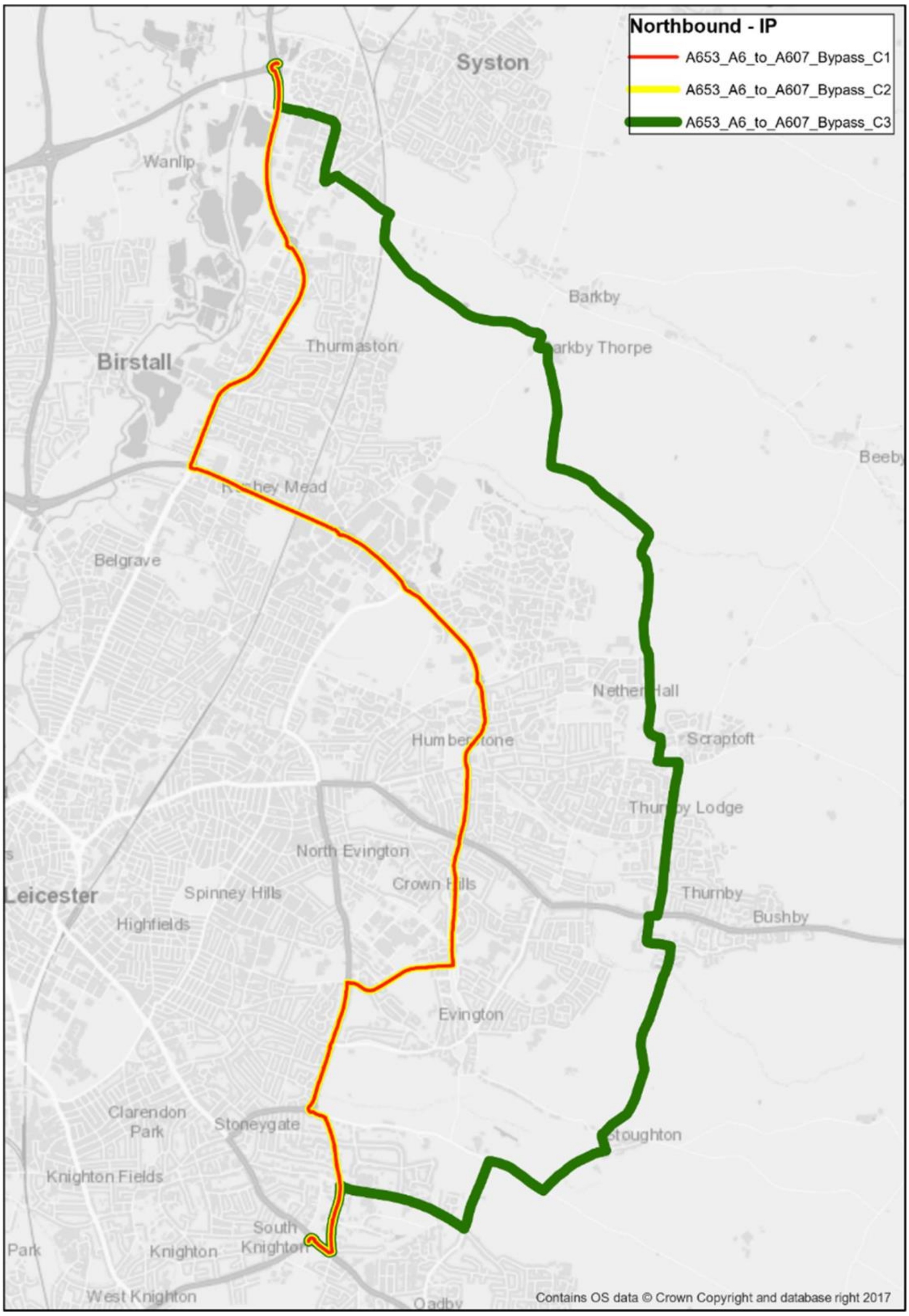


Figure A 3: Northbound PM peak

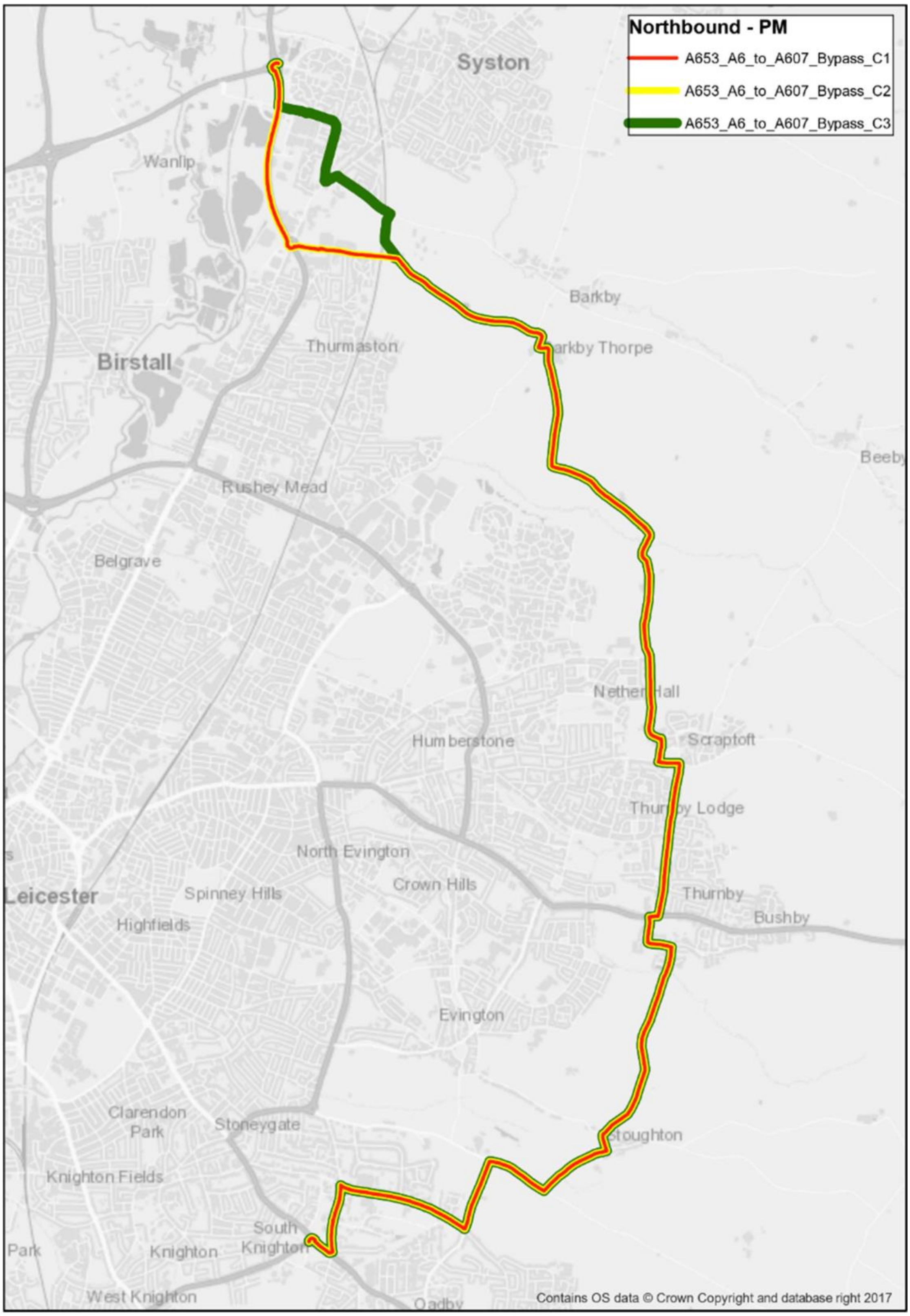


Figure A 4: Southbound AM peak

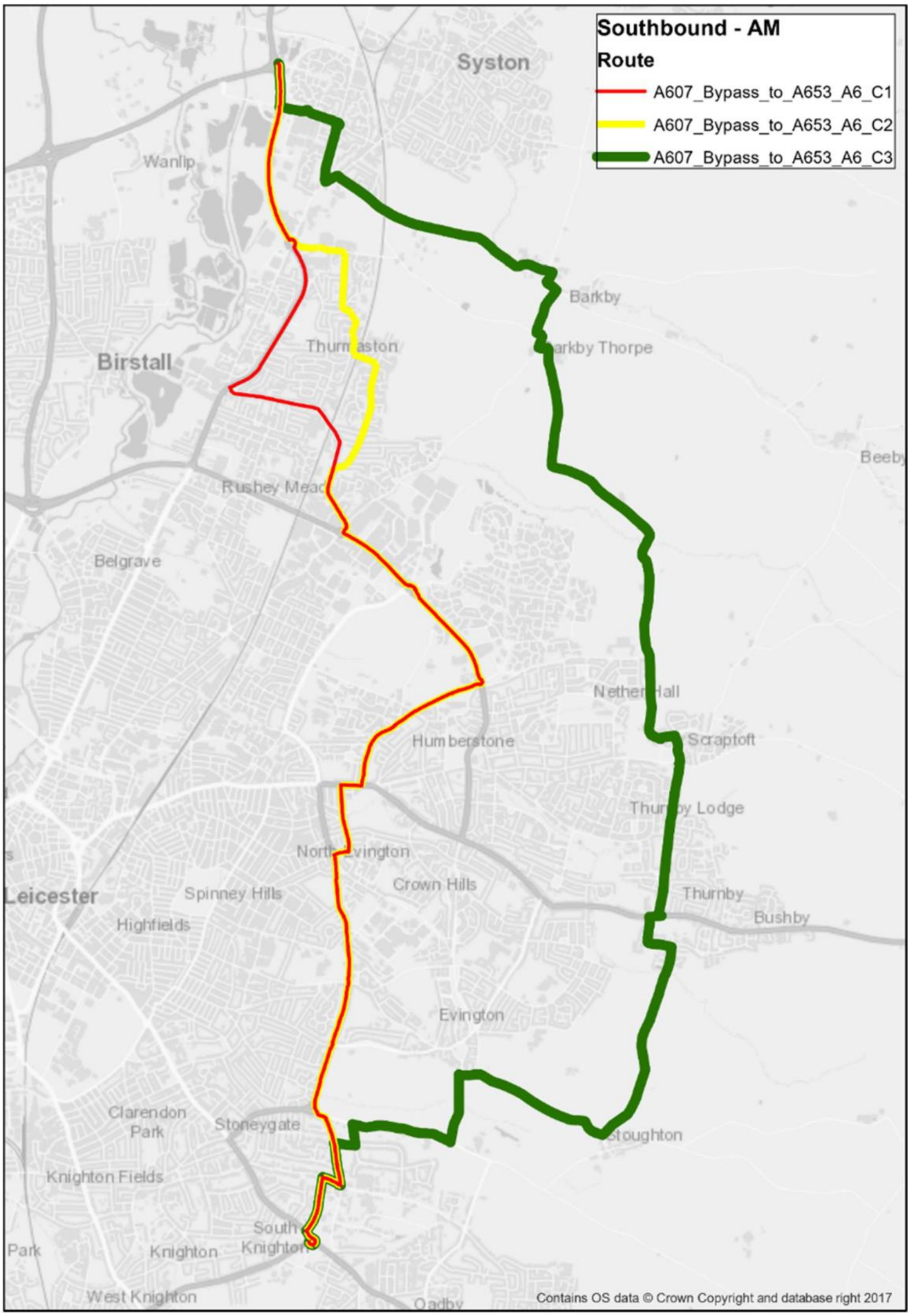


Figure A 5: Southbound Inter-Peak

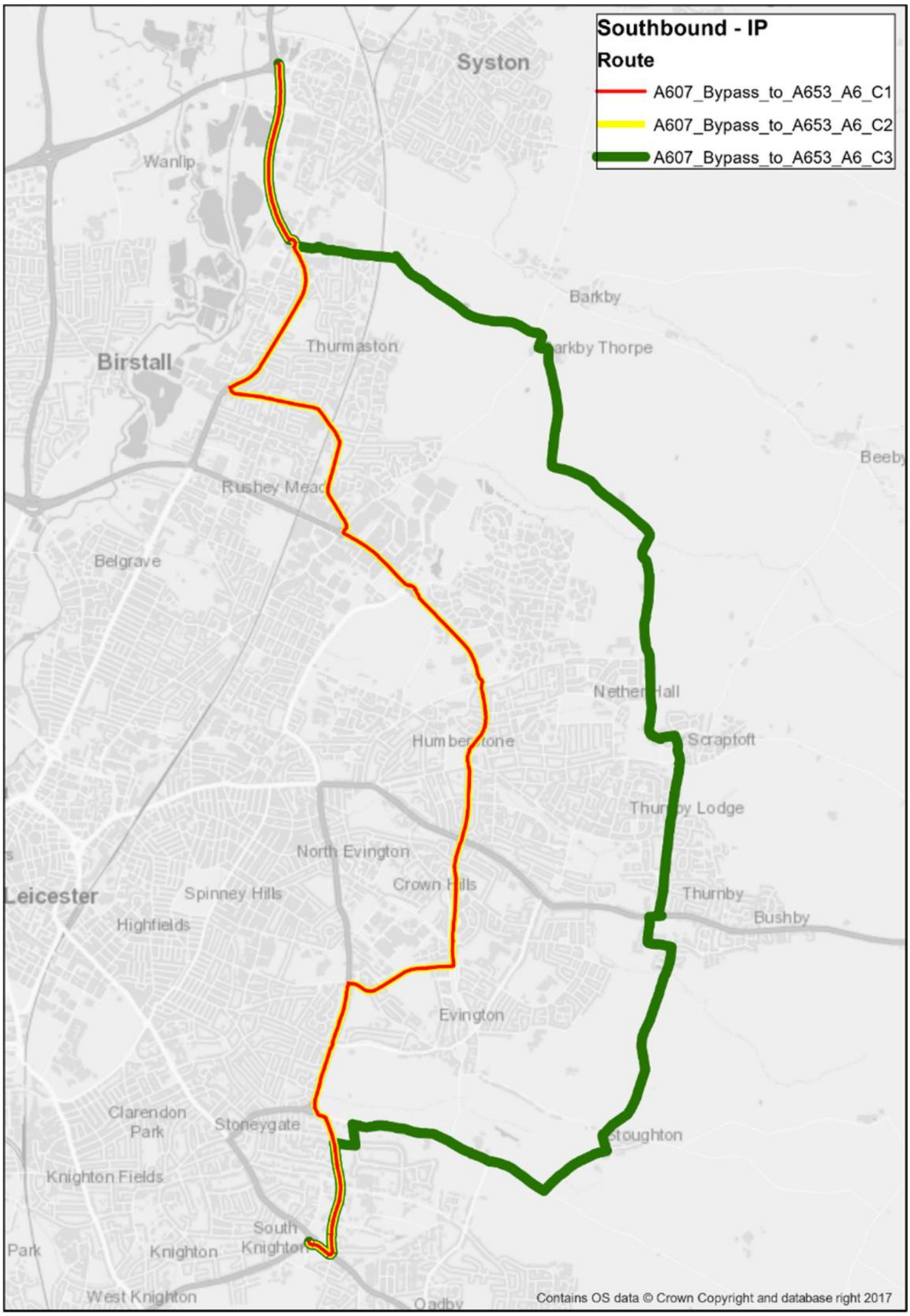
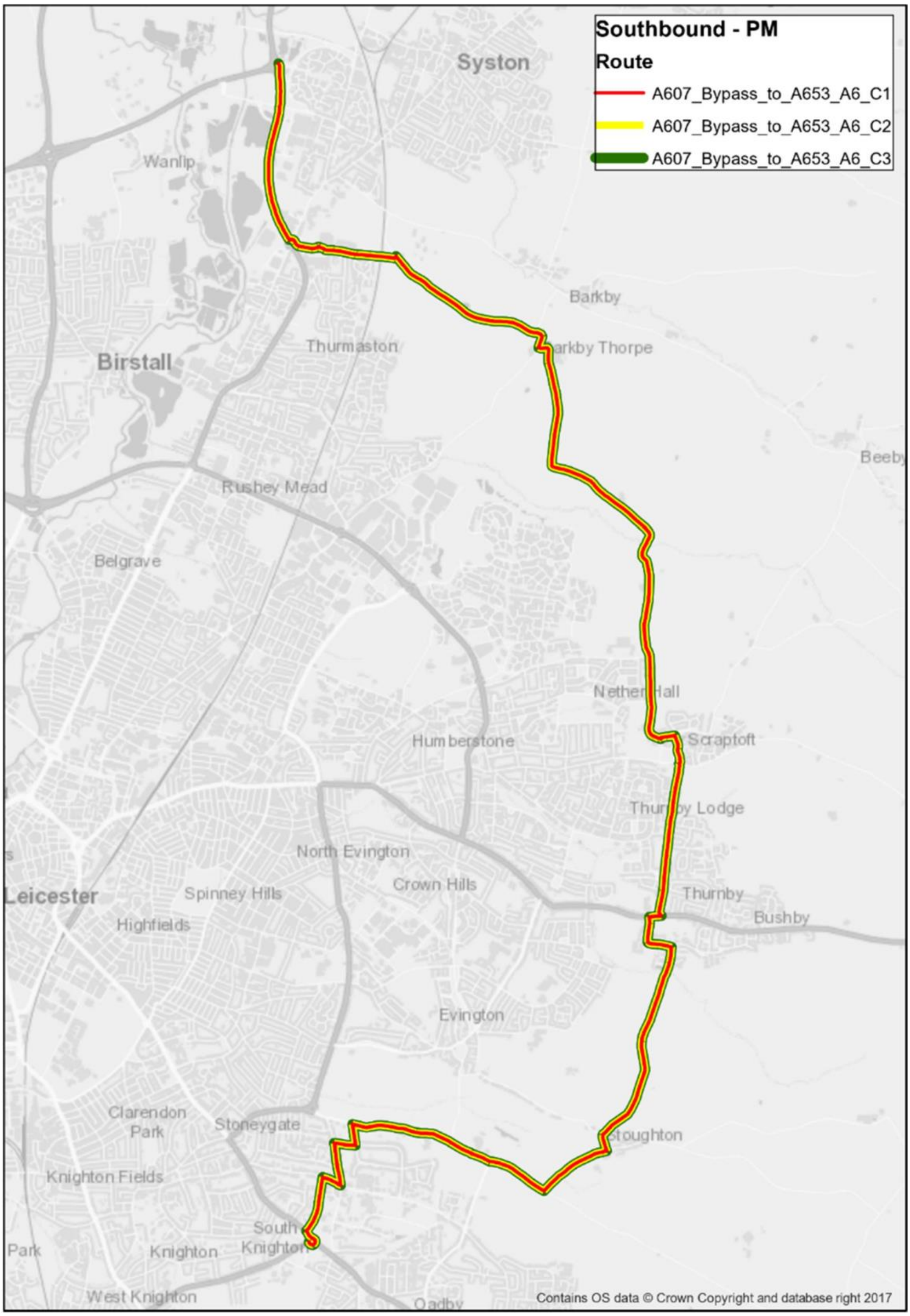


Figure A 6: Southbound PM peak



B. Minimum Cost Routes – Hampshire OD Pair

Figure B 1: Northbound AM peak

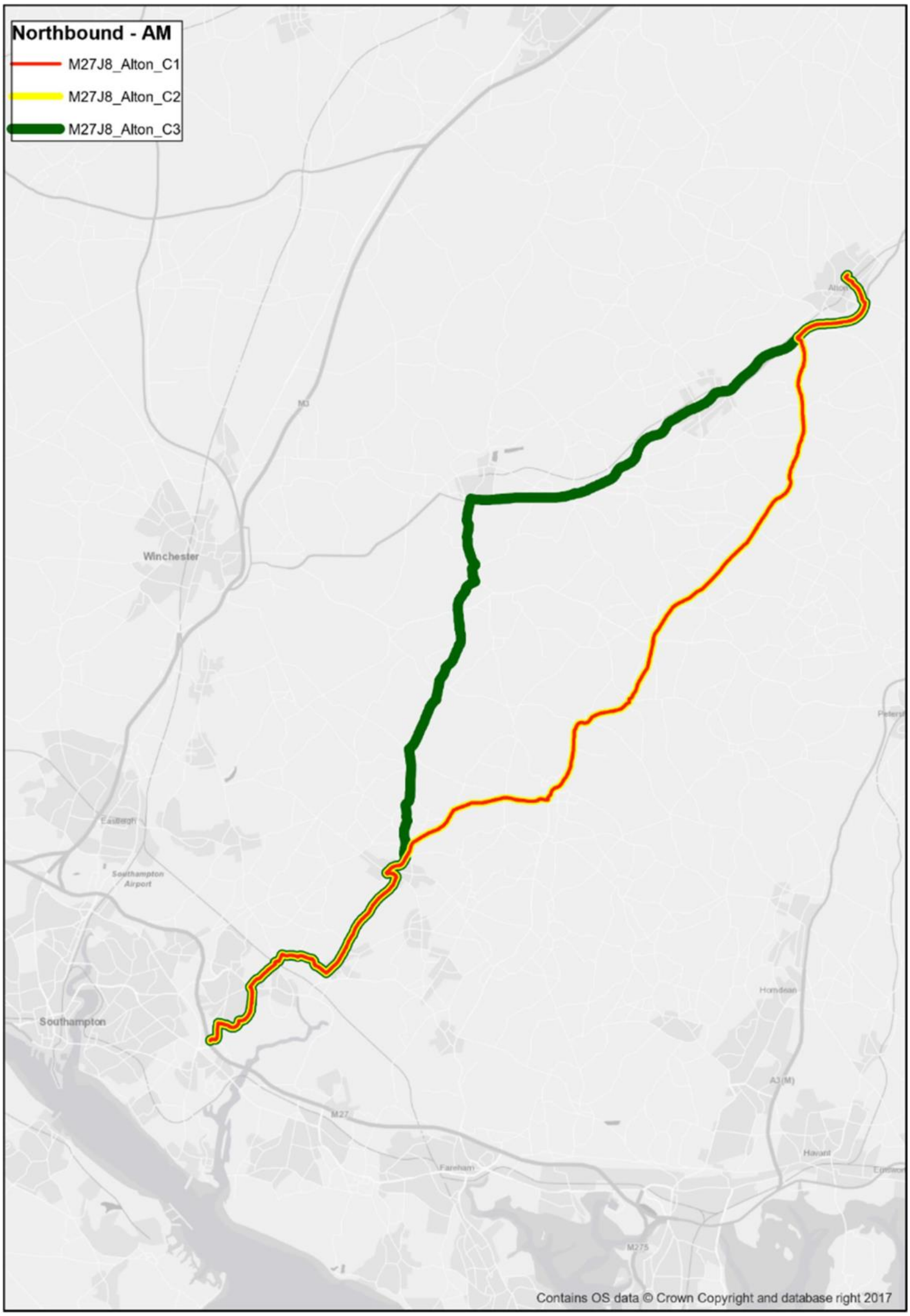


Figure B 2: Northbound Inter-Peak

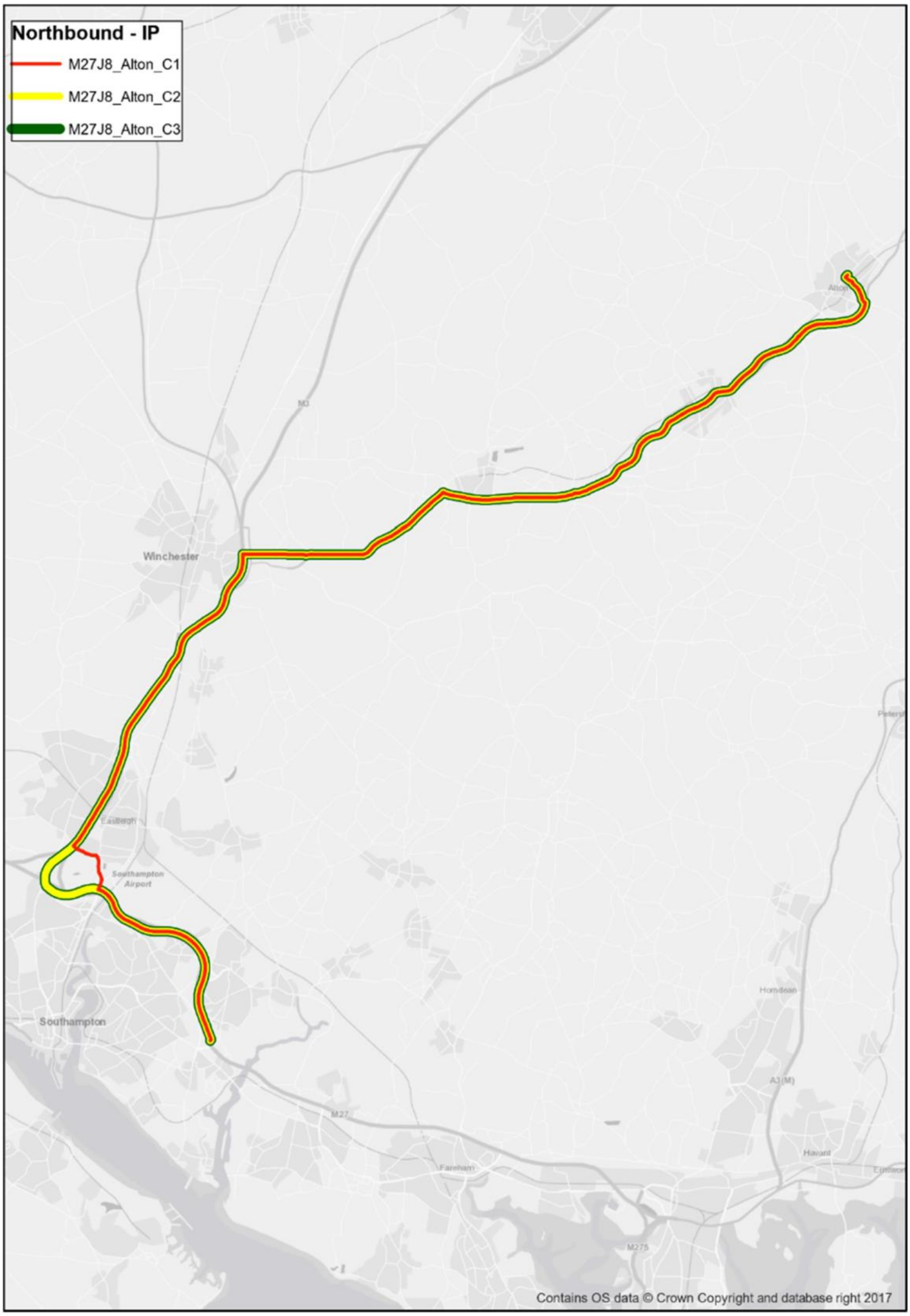


Figure B 3: Northbound PM peak

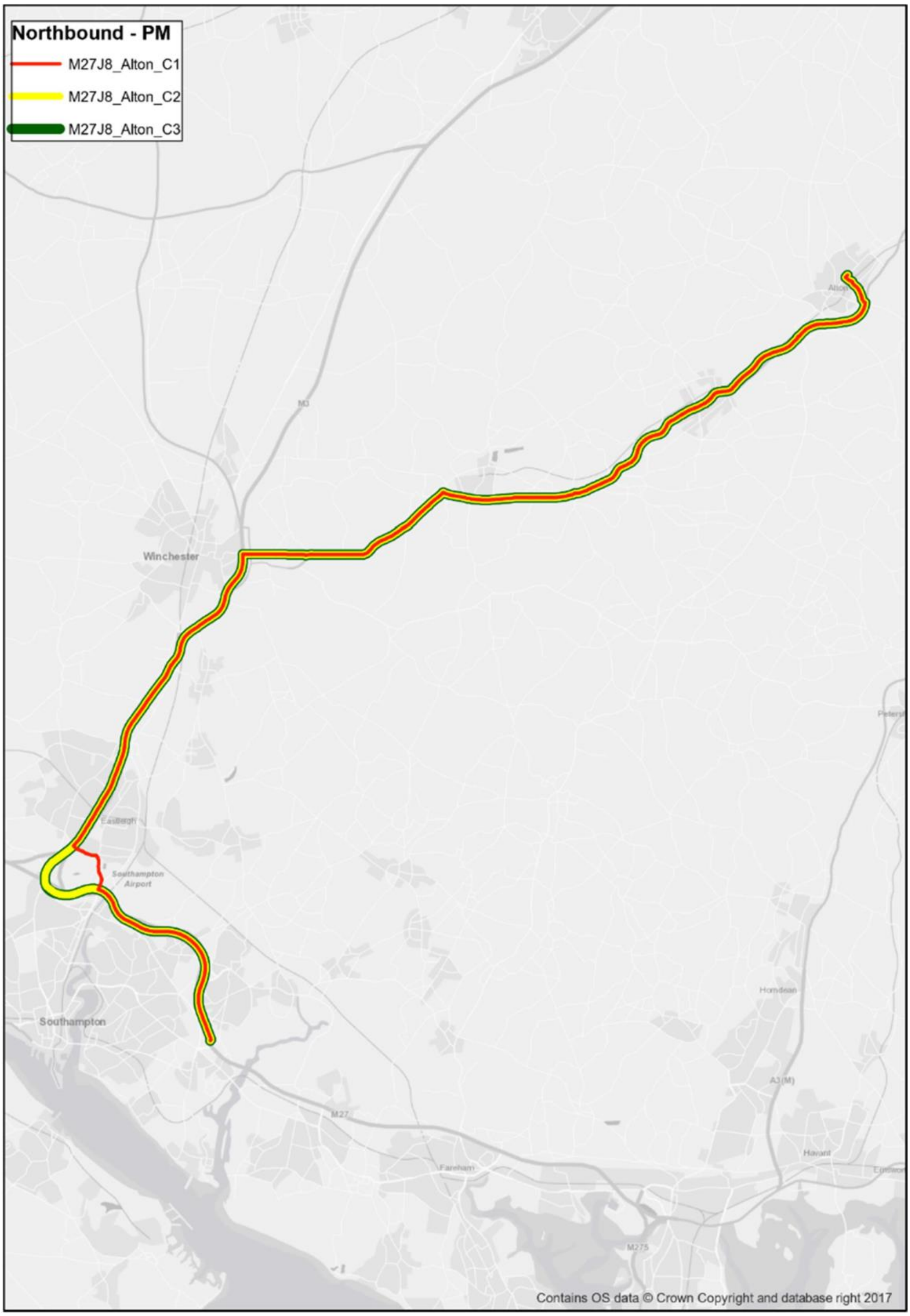


Figure B 4: Southbound AM peak

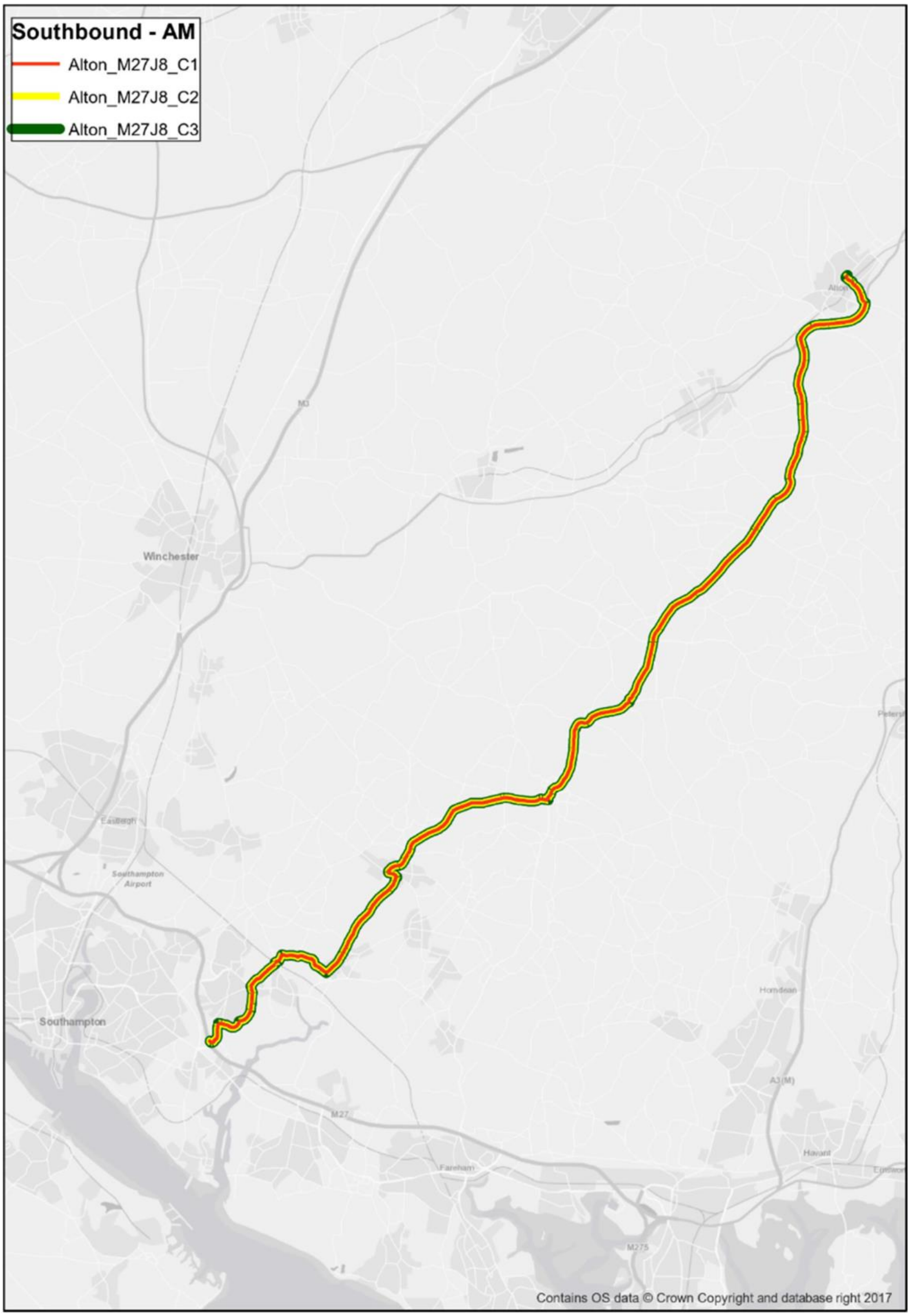


Figure B 5: Southbound Inter-Peak

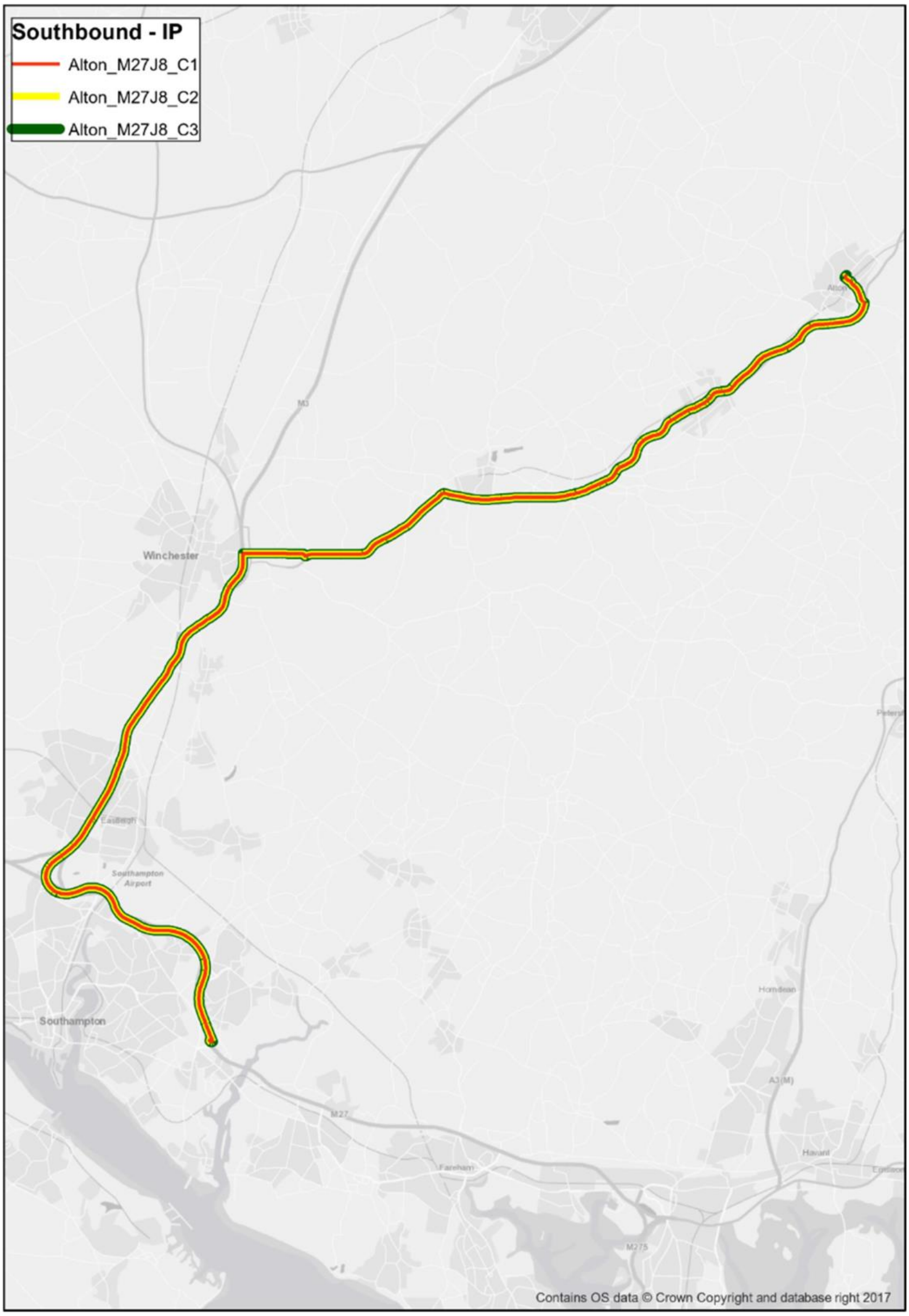
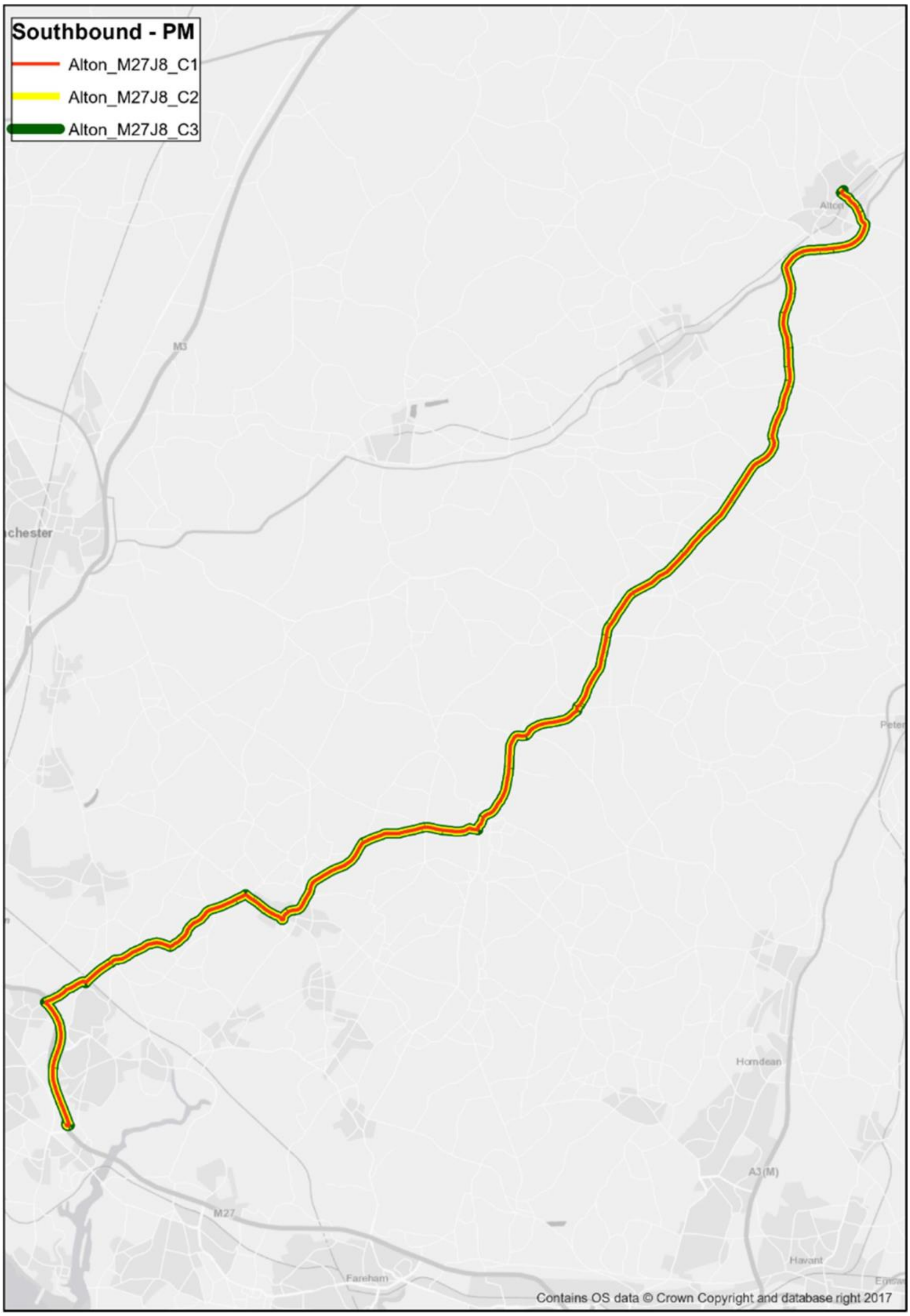


Figure B 6: Southbound PM peak



C. Visum Model Tests

C.1 Introduction

C.1.1 This appendix describes the initial testing of congestion multipliers in the Visum highway assignment software.

C.1.2 The main purpose of the testing is to demonstrate that Visum is indeed capable of modelling congestion multipliers and is, in effect, a proof-of-concept, as a prelude to more extensive testing that could subsequently be carried out.

C.1.3 The remainder of this appendix is structured as follows:

- Section C.2 describes the networks used in the test.
- Section C.3 describes the cost functions used.
- Section C.4 presents some headline results.
- Section C.5 sets out our conclusions from the tests.

C.2 Network

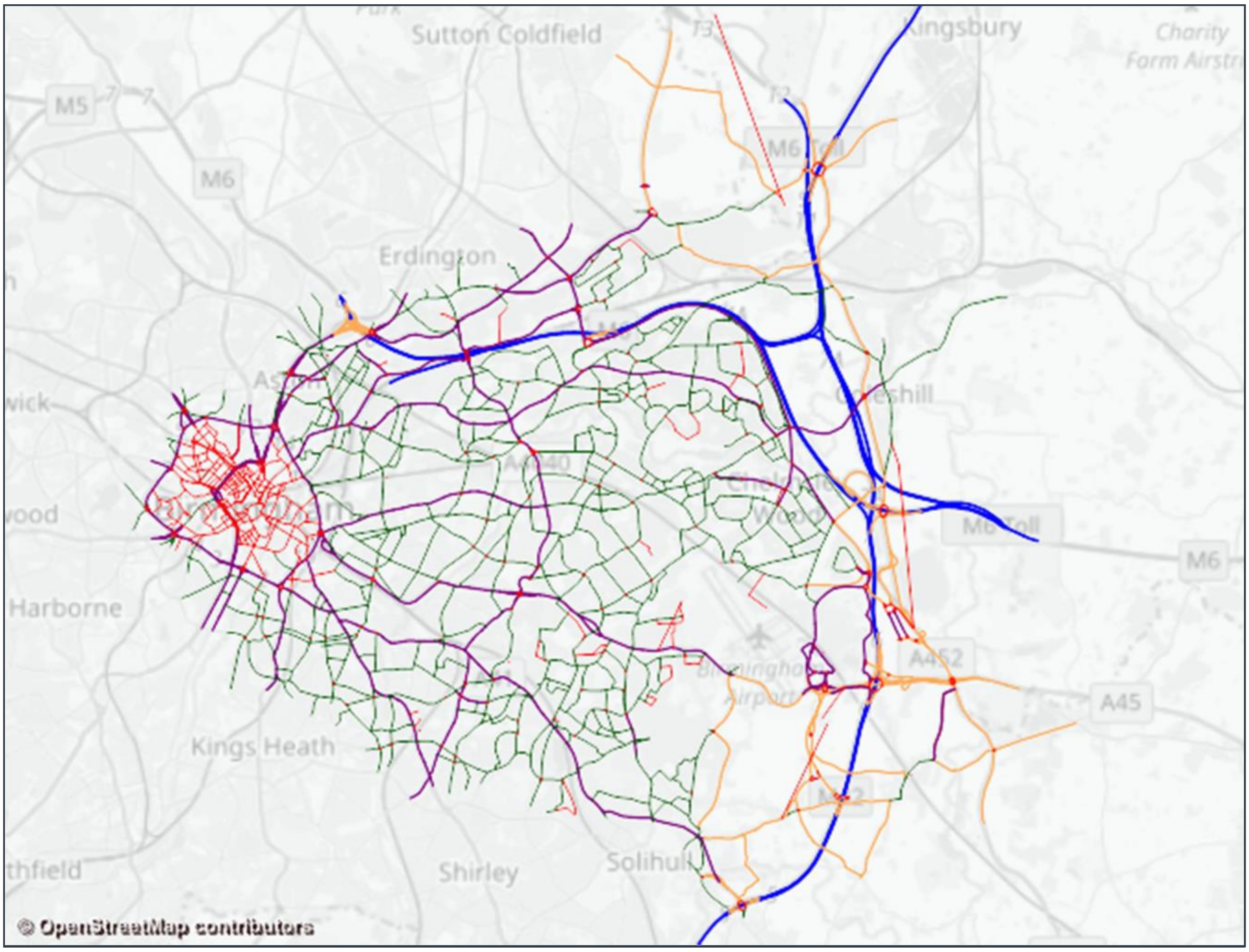
C.2.1 PRISM 5.056 is a multi-modal transport model of the West Midlands and includes a Visum highway assignment model. The PRISM Project Management Group (PMG, comprising the West Midlands Combined Authority (WMCA), the WMCA's seven constituent authorities, Transport for West Midlands, and Highways England) kindly gave permission to use PRISM 5.0 for the current study.

C.2.2 We appreciate the PMG's permission and acknowledge that this does not imply that the PMG endorses the findings and recommendations from this study.

C.2.3 To reduce model run times an existing cordoned version of the full network was used. This focuses on the area to the east of the centre of Birmingham, extending as far as the M42, as shown in the following map:

[56] http://prism-wm.com/

Figure C 1: **PRISM cordon used for testing**



C.2.4 The cordoned network still includes plenty of opportunities for drivers to change route in response to congestion, so is well suited to these tests.

C.2.5 The most distant forecast year, 2036, was used in the expectation that this would show the greatest impact from the use of congestion multipliers. Only the AM peak model has been used in the testing.

C.3 Cost Functions

C.3.1 Visum allows two different times to be included in the generalised cost function (referred to as ‘impedance’ in Visum), each with its own cost coefficient. These times are referred to in Visum as t0 and tCur, which correspond to the free-flow time and total time respectively, i.e.

$$t_0 = T_{FreeFlow}$$

$$tCur = T_{FreeFlow} + T_{Delay}$$

therefore

$$T_{Delay} = tCur - t0$$

C.3.2 The form of the generalised cost equation implemented in this testing is therefore as follows:

$$GC = VTT_{FreeFlow} \times t0 + VTT_{Delay} \times (tCur - t0) + PPK \times D + C$$
$$= (VTT_{FreeFlow} - VTT_{Delay}) \times t0 + VTT_{Delay} \times tCur + PPK \times D + C \quad (1)$$

Where:

VTT is the value of travel time (p/min)

T is the travel time (mins)

PPK is the vehicle operating cost (VOC) in pence per km

D is the distance in km

C is the non-operating monetary cost (e.g. parking, tolls) in pence

C.3.3 A multiplier value of 2 was used for delay VTT relative to free-flow VTT, i.e. $VTT_{Delay} = 2 \times VTT_{FreeFlow}$. This was chosen as being large enough to be able to see an impact on assignment results, while still being realistic.

C.3.4 Three tests were carried out, using different cost coefficients in equation (1):

Table C 1: **Car VTT and cost coefficients used in tests (2036 values in 2010 prices)**

Test	Journey purpose	$VTT_{FreeFlow}$ (p/min)	VTT_{Delay} (p/min)	*t0* coefficient (1/100 p per second)[57]	*tCur* coefficient (1/100 p per second)
A	Commute	27.85	27.85	0	46.42
	EB	41.54	41.54	0	69.23
	Other	19.22	19.22	0	32.03
B	Commute	27.85	55.71	-46.42	92.85
	EB	41.54	83.07	-69.23	138.45
	Other	19.22	38.44	-32.03	64.06
C	Commute	21.54	43.07	-35.90	71.79
	EB	32.12	64.23	-53.53	107.05
	Other	14.86	29.72	-24.77	49.53

C.3.5 In summary, the three tests are:

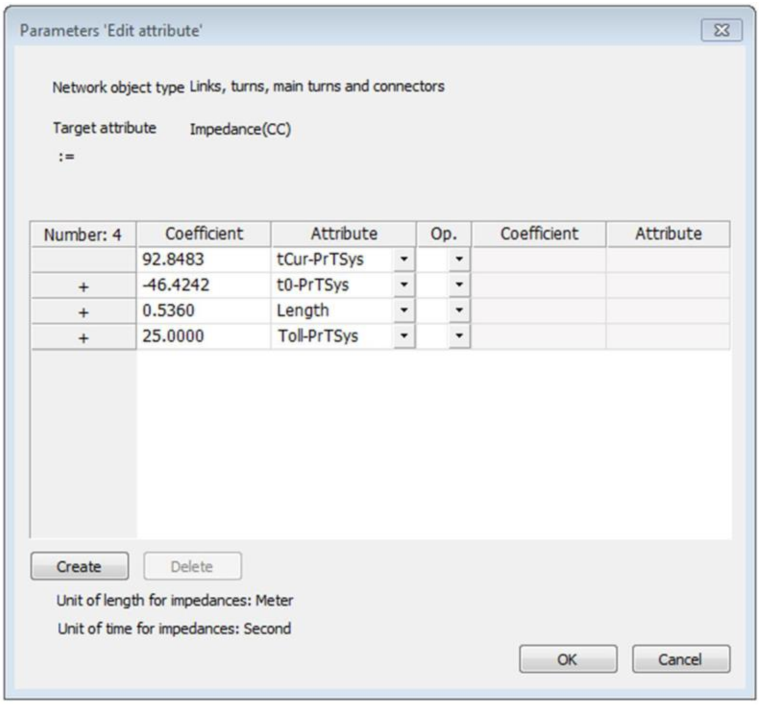
[57] Time coefficients in PRISM are in hundredths of pence per second (which can also be thought of as pence per hundred seconds). These units are used to increase the level of precision as a result of Visum only storing impedance values as integers.

- Test A: using standard PRISM cost coefficients, i.e. without any additional weighting on congestion.
- Test B: same $VTT_{FreeFlow}$ as Test A and $VTT_{Delay} = 2\times\ VTT_{FreeFlow}$.
- Test C: $VTT_{FreeFlow}$ calibrated so that the average VTT[58] is approximately the same as Test A; $VTT_{Delay} = 2 \times VTT_{FreeFlow}$.

C.3.6 The tests only involved changing the time coefficients for car trips. Distance and charge coefficients were unchanged, as were time coefficients for LGVs and HGVs.

C.3.7 The following screenshot from Visum shows the definition of the impedance function with separate coefficients for t0 and tCur (this example shows the commute coefficients for Test B).

Figure C 2: **Visum screenshot showing the definition of the impedance function**



C.4 Results

Convergence

C.4.1 Test A converged with a gap value of 0.07%, i.e. to WebTAG standards (which requires a gap of below 0.1%). Tests B and C reached gap values of 0.44% and 0.35% respectively, which is not to WebTAG standards. Ideally, this would be improved for any further testing.

[58] Calculated as the weighted average of $VTT_{FreeFlow}$ and VTT_{Delay} where the weights used are the total free-flow and total delay car vehicle hours from test A.

C.4.2 The fact that tests B and C do not converge as well as test A suggests that convergence may be harder to achieve with congestion-dependent VTT, though it would be unwise to generalise from just three tests on a single network.

Aggregate Results

C.4.3 Table C 22 shows the aggregate results from each test, by car journey purpose. This includes the total distance travelled and the total time, split between free-flow and delay.

Table C 2: Aggregate assignment statistics (cars)

Test	Journey purpose	Veh kms	Veh hrs (free flow)	Veh hrs (delay)	Veh hrs (total)
A	Commute	502,577	8,252	6,433	14,684
	EB	210,624	2,850	1,851	4,700
	Other	275,471	4,674	3,516	8,190
B	Commute	506,799	8,375	6,077	14,452
	EB	211,128	2,870	1,751	4,621
	Other	276,296	4,707	3,339	8,046
C	Commute	505,816	8,367	6,095	14,462
	EB	210,897	2,866	1,756	4,623
	Other	275,850	4,703	3,356	8,059

C.4.4 Comparing tests A and B, there is a consistent pattern for all purposes. Test B (which has double the value for VTTDelay compared to Test A) has higher vehicle kilometres, higher free-flow vehicle hours and lower delay vehicle free-flow hours. This is consistent with traffic choosing longer routes in Test B to avoid the most congested locations. This is also consistent with the GIS-based analysis in the main report.

C.4.5 The fact that there is a consistent pattern over all purposes, and between tests A, B, and C, suggests that these differences are genuine and not noise caused by imperfect convergence in tests B and C.

C.4.6 Test C sits between Tests A and B: vehicle kilometres and free-flow vehicle hours are higher than A but less than B; delay vehicle hours are lower than A but higher than B. This makes sense: as a result of re-calibrating VTTFreeFlow, the average value of time in Test C is less than in Test B, so drivers are less inclined to travel longer distances to avoid congestion.

C.4.7 The most significant changes are in vehicle hours (delay) which decrease by between 4.5% and 5.5% in tests B and C compared to test A. Vehicle kilometres increase by between 0.1% and 0.8%, and vehicle hours (free flow) increase by between 0.6% and 1.5%.

C.4.8 To determine whether the aggregate results are masking more pronounced differences at a more detailed level we have also analysed the assigned routes for two different origin-destination pairs. The results are presented in the next section. This represents only a limited analysis of results. Different parts of the appraisal process use different outputs, which may be affected by congestion multipliers in different ways, to a greater or less extent than the aggregate results above. For example, economic appraisal depends on OD times and distances, accident analysis on link flows, and noise and air quality analysis on link flows and speeds.

OD Routeing

C.4.9 Figure C 3 and Figure C 4 below show the assigned flows for traffic from Coleshill to Bromford, comparing Test A with Test B, then Test A with Test C. There is a significant difference. In Test A most traffic travels via Water Orton. In Tests B and C traffic routes further south using the A452, which runs parallel to the M6.

Figure C 3: **Comparison of Test A and Test B routes for Coleshill to Bromford**

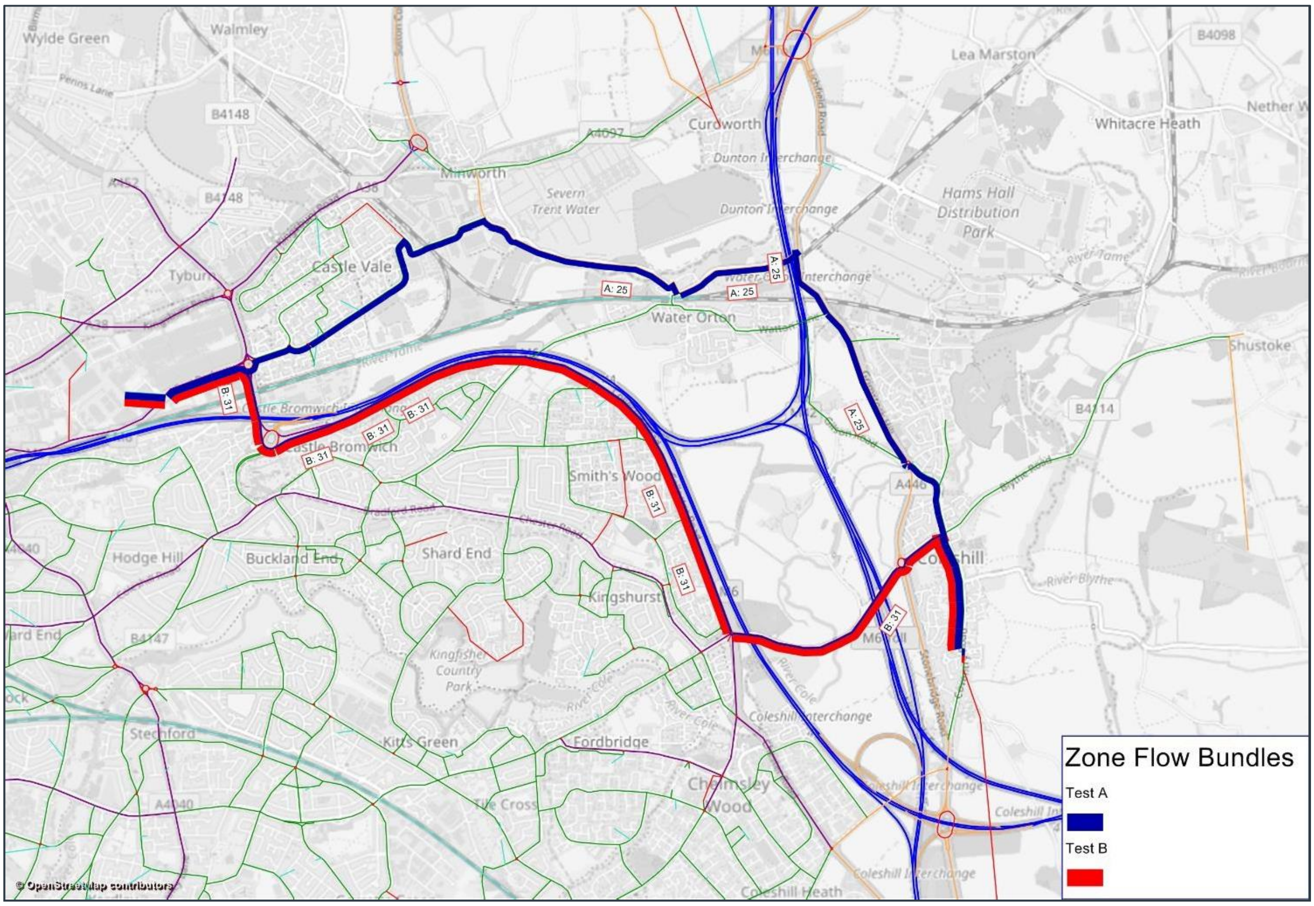
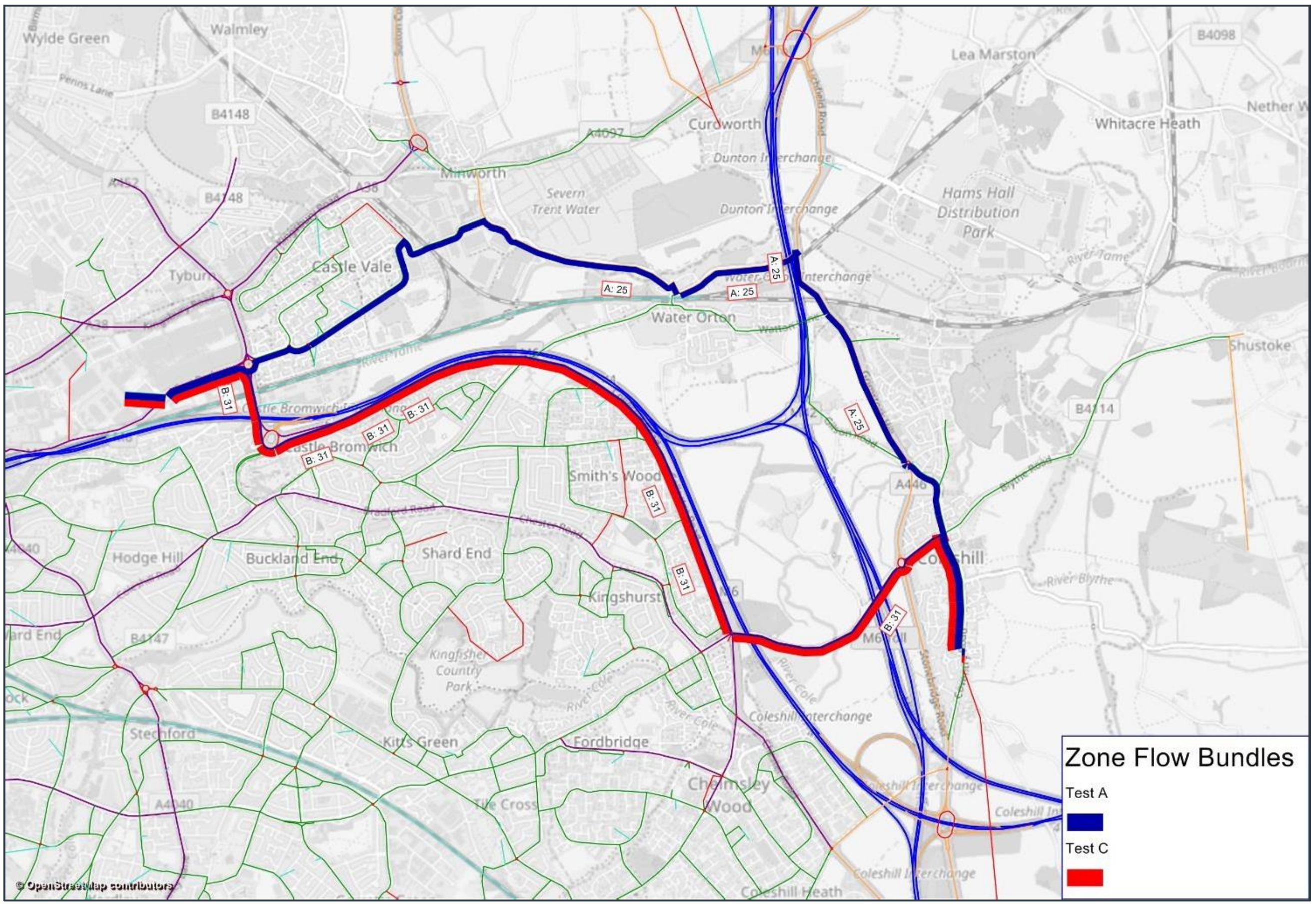


Figure C 4: **Comparison of Test A and Test C routes for Coleshill to Bromford**



C.4.10 Figure C 5 and Figure C 6 below show the assigned flow for traffic from M42 Junction 4 to Coleshill. There is less difference between the tests here, with the majority of traffic using the M42 in all cases.

Figure C 5: **Comparison of Test A and Test B routes for M42 J4 to Coleshill**

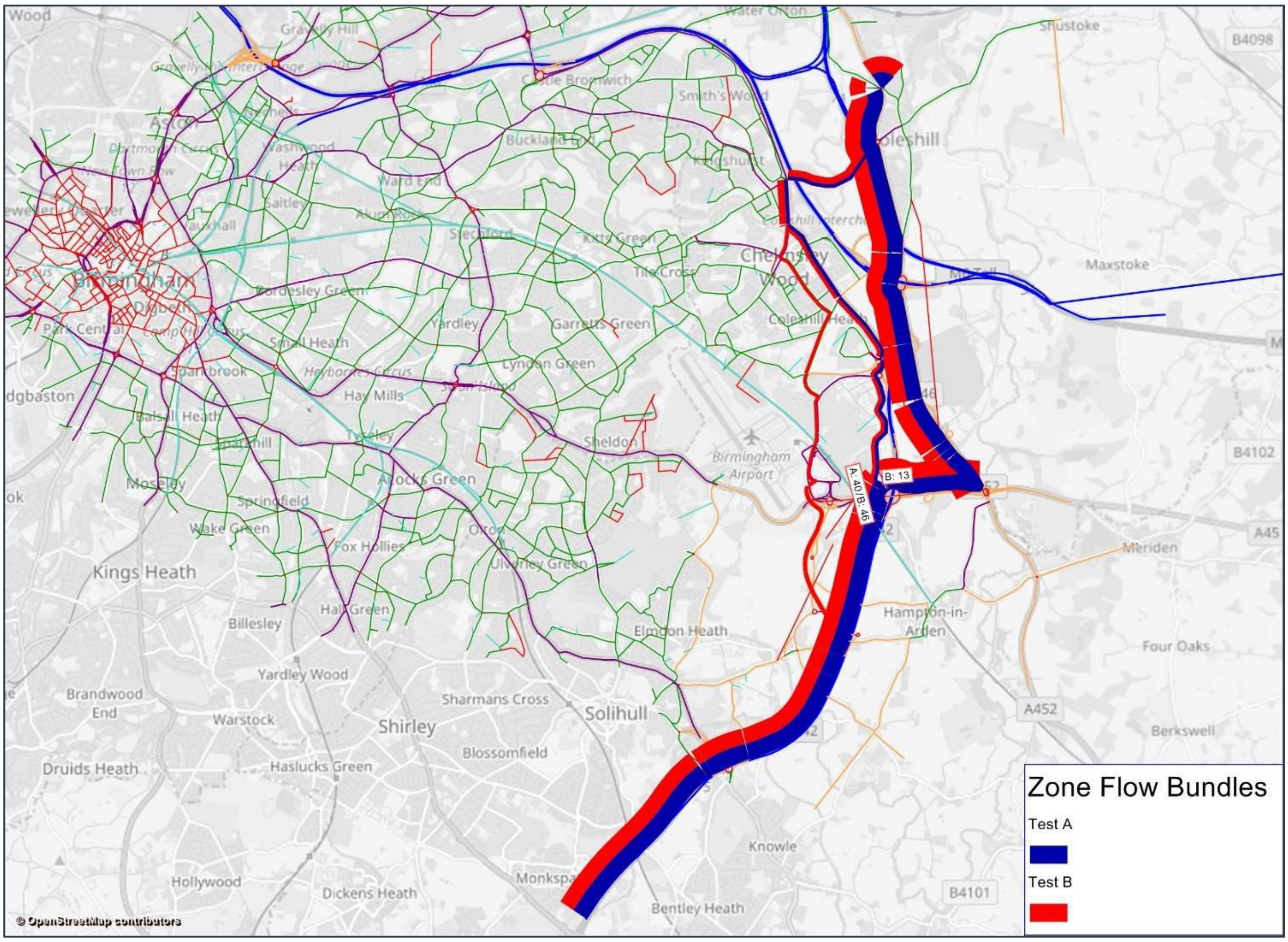
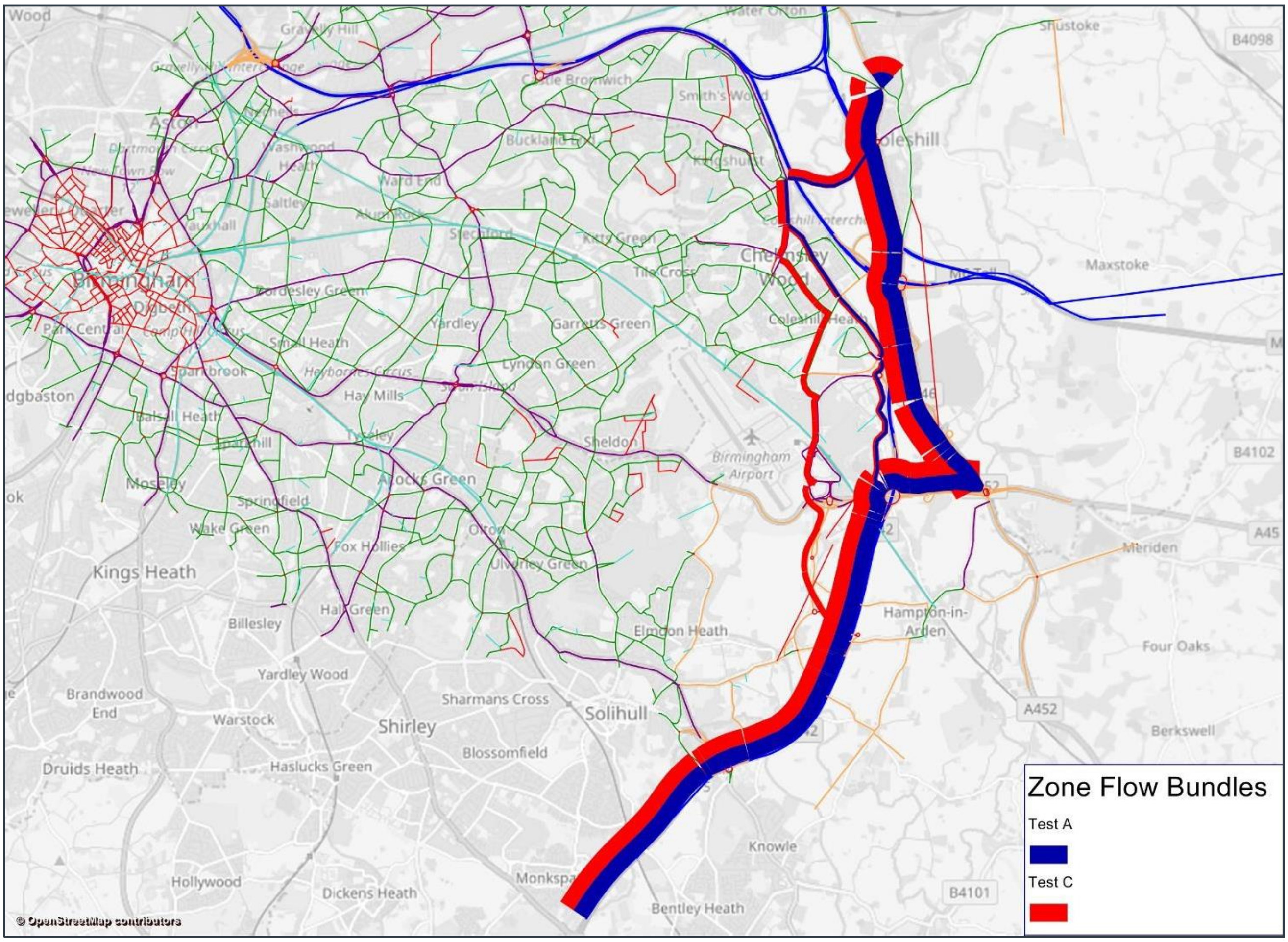


Figure C 6: Comparison of Test A and Test C routes for M42 J4 to Coleshill



C.5 Conclusion

C.5.1 The results of the three tests carried out differ in a way that is broadly consistent with the GIS analysis presented in Chapter 6.

C.5.2 The testing has achieved its main objective of confirming that Visum is able to model an increased VTT for delay, compared to free-flow time. This demonstrates that Visum is a suitable tool to use for further testing of congestion-dependent VTT.

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