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The attribution of transport user benefits by source using discrete choice models

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ABSTRACT

A major transport project would typically affect the cost of travel of several different alternatives, and give rise to a combination of gains and losses to users of each alternative. The attribution of benefits to each of the travel alternatives needs to recognise that travellers may change their behaviour as a result of the project. These changes in demand arise not only from changes in the cost of each specific alternative but also from cost changes in other competing alternatives. The appropriate treatment of inter-modal effects is central to the determination of the user benefit produced by each alternative.

The paper sets out a number of desirable criteria that source-related measures of user benefit should satisfy which include local consistency with the rule of a half. It explores the effect of alternative path specifications on the resulting measures and demonstrate that they can give different results when larger cost changes can occur, such as in modelling a new alternative. Appropriate measures that are able to treat this problem are developed and the results compared to those obtained by numerical methods.

1. Benefit attribution in the context of transport appraisal: theory and practice

The problem addressed in this paper is the attribution of user benefits to their source modes using the information available from standard runs of transport models that would be used in project appraisal. The transport models of interest are assumed to represent travel demand by means of discrete choice mechanisms. Most commonly the models employed would be of the tree-nested logit type and these models are given detailed attention in the paper.

Discrete choice models of the GEV class, such as nested logit models, are associated with an in-built measure of total user benefits, but theoretical expositions rarely consider how to identify the source of these benefits. Part of the reason for this may be because while total benefits are based on a path-independent integral the attribution of benefits by source requires the issue of path dependency to be addressed.

The context of the discussion is longer-term forecasting; when the project under consideration may either directly or indirectly change the characteristics of more than one travel option, and where travel demand is forecast by transport models. It is set in the cost-benefit framework generally used in the UK but may be relevant for other administrative contexts also.

For ease of exposition, the different travel options will typically be referred to as “modes”. However the analysis given here is applicable whether the fundamental choices are sub-modes, destinations or time periods, or other discrete choices represented by the travel demand model. The methods described here are seen to be of particular interest in the appraisal of new travel modes (modes that were not available in the base situation), where the rule of a half is not applicable.

A major transport project would typically affect the cost of travel of several different modes, and give rise to a combination of gains and losses to users of each mode. The attribution of benefits to each of the travel modes needs to recognise that travellers may change their mode as a result of the project. These changes in modal composition arise not only from changes in the cost of that mode but also from cost changes in other competing modes. The appropriate treatment of inter-modal effects is central to the determination of the user benefit produced by each mode.

The need to attribute benefits to specific modes arises because each mode provides a source that contributes to total user benefit and stakeholders would be better informed if these sources could be identified quantitatively. For example, in analysing a portfolio of

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investments the total return and its volatility may obscure a mixture of low return, low risk and high return by high risk investments. A detailed attribution analysis may help to identify alternative investment strategies that offer both higher return and lower risks. In UK transport appraisal (DfT TAG 3.5.3) there is a similar need to attribute benefits by their source, albeit at a fairly high level of aggregation. Such an attribution is typically obtained by the rule of a half. However this rule has limited applicability when cost changes are large and cannot accommodate new travel options. These limitations motivate the current investigation.

We will start with a simple basic formulation of the attribution problem and will see that this can give rise to issues that do not appear to have been extensively discussed in the discrete choice modelling literature. A resolution to the problem will be proposed that extends the tool-kit of methods that are currently available. These methods are of especial interest in the appraisal of new modes, when it is desired to attribute benefits to such modes in a robust and cost-effective manner.

The resolution embodies a principle stated in Sugden and Williams (1978):

> "…*a change in the consumers' surplus associated with a particular good measures a change in consumers' welfare only if the change in surplus is caused by a change in the price of that good. Changes in consumers' surplus caused in other ways (for example, by changes in the price of other goods) have no similar interpretation.*"

The need to attribute user benefits according to their source is also reflected in the UK Department for Transport's requirements for appraisal: "… *the disaggregation of user benefits by mode* …" (DfT TAG 3.5.3, para 2.1.1).

In contrast to these considerations, the measure of user benefit available from the theory of discrete choice is typically a measure that is aggregated over all of the choices available. However, in this paper we establish a strong connection between such a choice-aggregated measure and the choice-specific measures that are required for appraisal applications. Such connections open up the prospects for both improved accuracy and extension of the scope for transport appraisal practice.

For the purposes of this discussion, modal travel demand is expressed in terms of a traveller's mode choice probability and it is assumed that the traveller makes a fixed total number of trips.[2] Subsequent aggregation of individual travellers into coarser choice groups would depend on the needs for project appraisal. Aggregation into the main travel modes would be a typical requirement. In the application given later this includes public transport sub-mode choices (rail and bus), but also includes the opening of a new public transport mode.

Following Sugden and Williams, for each mode of travel j, a demand curve is constructed with travel demand p_j along the horizontal axis and generalised cost C_j along the vertical axis. The user benefit per traveller is the area to the left of the demand curve. If the demand curve was the *partial* demand curve for the mode of interest *and there were no changes in the costs of other modes*, this area would represent both the total benefit and the benefit attributable to the mode of interest.

However, transport modelling applications typically treat situations where changes in costs for several different modes occur simultaneously. Treating each of these changes one at a time is not generally a practical proposition for large transport models and, even for smaller models, the results would be difficult to interpret.

Sugden and Williams instead replace the partial demand curve by one that incorporates price changes in the other modes, stating on p. 139:

> "*The relationship between price and quantity that can be traced directly is the observed demand curve, which joins the combinations of prices and quantities that are actually observed in the market. … It will emerge that knowledge of the position of the observed demand curve is sufficient to allow an analyst to calculate the net social costs or benefits of a price change*".

We now turn to matters of practical implementation. In order to calculate the resulting user benefits Sugden and Williams suggest the use of the rule of a half and give a user benefit measure:

$$UB_j = \frac{1}{2}\left(p_j^{\mathrm{DM}} + p_j^{\mathrm{DS}}\right)\left(C_j^{\mathrm{DM}} - C_j^{\mathrm{DS}}\right) \quad (1.1)$$

The superscript DM denotes the 'do minimum' (base) and DS denotes the 'do something' (test) scenario. Equation (1.1) is widely deployed in transport appraisal practice and in the majority of situations it gives results that are sufficiently accurate for comparing the benefits of schemes to their expected costs, as well as for comparing the benefits obtained from alternative schemes.

However, the analysis provided by Sugden and Williams is very much more general than this widely adopted approximation. Consider a space in which there are as many dimensions as there are competing modes, with coordinate axes defined as the generalised costs of each mode. Construct a path in this space of modal costs and trace this path by means of an index t than runs from the base scenario at $t = 0$ to the test scenario at $t = 1$. Modal demands are then implicit functions of the path index. The more general measure of user benefit suggested by Sugden and Williams's analysis is an integral of the form:

$$UB_j = -\int_{t=0}^{t=1} p_j(t)\mathrm{d}C_j(t) \quad (1.2)$$

It can be verified that if a) choice probabilities are linear functions of the costs of all modes and b) all modal costs are linear functions of the path index, then equation (1.2) reduces to equation (1.1) and the rule of a half would provide an exact solution for the required choice-specific measure of user benefit.

Partly, but by no means exclusively, because of its accommodation of joint price changes, the rule of a half has become established as the workhorse for the appraisal of user benefits, at least in those cases where changes in travel costs have a material effect on travel demand. Alternative approaches need to be compared with benefits calculated using this rule. The better known limitation of the RoH is assumption a), which requires modal demand to be sufficiently well approximated by linear functions of travel cost. Less well known is the requirement that linearity must also apply to the responses to the cost of other modes. To treat substantial departures from linearity, which typically arise when cost changes are large, numerical integration has been developed as a supplementary tool (DfT, 2004, 2012). Implementing numerical integration requires additional model runs. This can be computationally onerous, particularly if it is used to appraise new modes of travel, and Nellthorp and Hyman (2001) provide an indication of the level of additional computation that would be required. The robustness of the resulting benefit calculations merits further discussion. Numerical integration requires the integration path to be specified, and some numerical paths may yield measures that are less robust than others. The dependency of choice-specific benefit measures

[2] Generalisation to a variable total number of trips would not be difficult but would complicate the discussion.