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The cost of travel time variability: Three measures with properties☆

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ABSTRACT

This paper explores the relationships between three types of measures of the cost of travel time variability: measures based on scheduling preferences and implicit departure time choice, Bernoulli type measures based on a univariate function of travel time, and mean-dispersion measures. We characterise measures that are both scheduling measures and mean-dispersion measures and measures that are both Bernoulli and mean-dispersion. There are no measures that are both scheduling and Bernoulli. We consider the impact of requiring that measures are additive or homogeneous, proving also a new strong result on the utility rates in an additive scheduling measure. These insights are useful for selecting cost measures to use in applications.

1. Introduction

This paper considers three types of measures of the cost to travellers of travel time variability that have been used in travel demand modelling and transportation economics. We consider measures based on scheduling preferences, Bernoulli type measures based on a univariate cost function, and mean-dispersion measures. The objective of the paper is to decide to which extent such measures are the same. That is, when can a measure of one type be represented as a measure of another type? This is important, as it informs the modelling choice of which cost measure to use in a given context, depending on which properties that one desires for a cost measure. We introduce the different measures in detail below.

Travel time variability, the fact that travel times are random and unpredictable from the point of view of travellers, is an important problem in general. Traffic congestion not only induces delays, but also makes travel times highly variable and unpredictable. The economic cost to societies of travel time variability is comparable to the cost of average delays and is therefore clearly significant from the perspective of national economies (see e.g. Winston, 2013 for an overview). It is therefore of interest to first be able to describe how travellers behave when faced with travel time variability and second to be able to take the effect on travel time variability into account when we evaluate alternative transport policy measures, infrastructure investments or other interventions in the transport system. It is also important to be able to communicate the extent of travel time variability to the public. For these purposes we require measures of the cost to travellers of travel time variability. Cost measures may have advantages in terms of communication to the public, they may have advantages

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in terms of mathematical simplicity, or they may have advantages in terms of their foundation in underlying theory. Most importantly, of course, they may differ in their ability to describe observed behaviour. We define some useful properties that cost measures may have and show how these properties constrain which types of cost measures are possible. This is informative about how different advantages may be combined in one cost measure.

The first type of measure that we consider is based on scheduling preferences. We consider forms in which travellers achieve utility at some rate prior to departure and at some other rate upon arrival at the destination of a trip. Then the utility cost of a trip depends on the departure time and on the arrival time and thereby indirectly on the random duration of the trip. The departure time is assumed to be chosen such that it maximises the expected utility. The main advantage of scheduling measures is that they have a foundation in an underlying theory of scheduling behaviour. This ensures basically that scheduling measures make behavioural sense, being consistent with a description of rational scheduling behaviour. Furthermore, the underlying scheduling model may be used to predict departure times.

The second type of measures is inspired by the economics literature on risk preferences going back to Bernoulli (1954, translated from the 1738 original), which considers utility as a function of a monetary amount. It is possible instead to consider the time-related utility cost of a trip to be just a function of travel time with the timing of the trip playing no role. When travel time is random, travellers are assumed to care about the expected utility cost. An advantage of this type of measure is that it makes it possible to employ the corresponding economic theory regarding risk preferences. We ask among other things whether a Bernoulli type cost measure is consistent with the existence of underlying scheduling preferences and find that the answer to this question is negative in general.

The third type of measures consists of measures that are linear in the mean travel time and some measure of the dispersion of travel time. These measures are then defined directly in terms of statistics of the travel time distribution, not relying on an underlying classical utility defined over travel outcomes. This type of measure has the advantage that it can build on some concept of travel time variability that is deemed to be intuitive and capable of being widely communicated. Mean-dispersion models include the mean-standard deviation model, the mean-variance model as well as models that take the expected time cost to depend on the mean and the difference between two quantiles of the travel time distribution. We find that a mean-dispersion measure is equal to a Bernoulli measure only if the measure is proportional to the mean travel time while the travel time variability plays no role.

We consider specifically two properties that cost measures may have. If travel time is the sum of two independent components, then an *additive* cost measure of the travel time is just the sum of the cost measure applied to the two components. Additivity is useful in network models for aggregating costs from the link level to the path level, when one is prepared to assume that travel times are (sufficiently) independent across links. We find that all additive scheduling measures are also mean-dispersion measures, while there exists additive mean-dispersion measures that are not scheduling measures.

A cost measure is *homogeneous* if multiplying travel time by a positive factor scales the cost by the same factor. This is a useful property, since it implies that a change in the time unit only affects the scale of the cost measure. It is furthermore useful in relation to mean-dispersion measures: we may define the reliability ratio to be the ratio between the marginal cost of dispersion to the marginal cost of mean travel. Homogeneity then implies that the reliability ratio is independent of the scale of the travel time distribution. Most mean-dispersion measures used in practice have this property. We find, however, that there are no homogeneous cost measures that are both mean-dispersion measures and scheduling measures. Thus, requiring homogeneity of a mean-dispersion measure rules out that it can have a foundation in a scheduling model. We also find that any homogeneous Bernoulli measure must be proportional to the mean travel time and hence it is not sensitive to random travel time variability.

The scientific literature on travel time variability is becoming large. We provide some bibliographical notes at the end of each the three sections introducing the different cost measures. More generally, a recent introduction is Fosgerau (2015). Recent literature reviews are provided in Carrion and Levinson (2012) and Li et al. (2010). Small (2012) reviews the broader literature on the valuation of travel time. Concerning freight transport, a recent review is provided by Feo-Valero et al. (2011). The reader may refer to these papers for a more comprehensive overview of the literature.

The layout of the paper is the following. Section 2 introduces the three types of measures, along with references to the literature. Section 3 presents our results concerning equivalence of cost measures, Section 4 considers additivity and homogeneity, while Section 5 concludes.

2. Three types of travel time cost measures

Travel time $T \geq 0$ is a bounded, almost surely non-negative random variable, and the class of all these random variables is denoted Φ. This includes, e.g., all non-negative discrete distributions. The assumption that travel time is bounded ensures that all relevant integrals will exist, which is convenient for the mathematical exposition. This does not prevent the cost measures that we will consider being applied to unbounded distributions, such as the normal, lognormal, gamma and stable distributions that have been applied in the literature.

In general, a travel time cost measure is a functional $C\colon\Phi \to \mathbb{R}$, In this section we will define the three types that we discuss in this paper. For the sake of brevity, we shall talk just about cost measures.