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The marginal social cost of travel time variability

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ABSTRACT

This paper investigates the cost of travel time variability for car users at the peak hour. In particular, we derive the marginal social cost of travel time variability, which takes the feedback of travel time unreliability on the congestion profile into account. This is in contrast with the value of travel time variability, which treats congestion as an exogenous phenomenon. Congestion is modeled using the standard bottleneck model of road congestion, which we amend by adding a random delay. For individuals with (α, β, γ) preferences and uniformly distributed delays, the marginal social cost of travel time variability is strictly lower than the value of travel time variability. Moreover, we show that the former tends toward the latter when σ, the standard deviation of the random delay, tends toward $+\infty$. For normally distributed delays, numerical application leads to similar conclusions. Analysis of data from the Paris area suggests that given the plausible range of σ, the marginal social cost of travel time variability is markedly lower than the value of travel time variability. When appraising the economic benefits of reliability improvements, one should prefer the marginal social cost of travel time variability for the peak period, and the value of travel time variability for the off-peak period.

1. Introduction

Travel time reliability is an important consideration when people make travel decisions (Li et al., 2010; Carrion and Levinson, 2013). Bates et al. (2001) distinguish two main ways in which unreliable travel times impact people. First, it may disturb their activity schedule by causing early or late arrivals at destination. When excessive, the delay can even lead to the cancellation of an activity: for instance, an unpredicted traffic jam can cause one to arrive too late at the theater and miss the play. Second, people could dislike travel time variability *per se*. The unpredictability of the travel time would generate some form of anxiety, or cause some additional planning costs (Noland et al., 1998).

The valuation of travel time variability has accordingly become an increasing concern in transport economics, to the extent that the value of travel time variability (also referred to as the value of reliability) is now along with the value of time one of the most important values obtained from travel demand studies (Carrion and Levinson, 2012). The work of Fosgerau and Karlström (2010) has been central in this regard. In line with Polak (1987) and Noland and Small (1995), the authors study the choice of departure time for a traveler facing variable travel times. Their major contribution lies in deriving the value of travel time variability (VTTV) in a case relatively general, thereby providing a sound theoretical foundation to this notion. Still, one element limits the extent of their results. In line with the others before them, Fosgerau and Karlström (2010) study the behavior of one traveler only and model congestion as an exogenous phenomenon. Hence, the VTTV does not capture the impact that changes in travel time variability have on congestion. Likely limited for the off-peak period, this

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feedback effect could be sizable at rush hour when congestion becomes a primary feature of traffic. As all individuals (and not only one) adapt their departure time in response to changes in travel time variability, the congestion time profile is likely to change. To address this shortcoming of the VTTV, we propose an alternative indicator, the marginal social cost of travel time variability (MSCTTV), which differs from the VTTV in that it does capture the equilibrium mechanism just mentioned.

This paper studies the cost of travel time variability for car users when congestion is modeled as an endogenous phenomenon. We are especially interested in the spread between the value of travel time variability and the marginal social cost of travel time variability: for a given individual, it reflects the difference between the short term and long term (*i.e.* before and after other individuals adjust their departure time) costs of a change in the variability of travel times. We model congestion using the standard bottleneck model of peak-load congestion, which we amend by introducing a random delay. Derivation of the Nash equilibrium in departure times yields first the equilibrium expected scheduling disutility as a function of the standard deviation of the delay, then the MSCTTV by differentiation. We focus the analysis on the case of uniformly distributed delays as it leads to closed-form solutions. This allows a direct analytical comparison of the VTTV and the MSCTTV. The more realistic case of a normal law is also considered using numerical simulation, analytical derivation of the equilibrium solution being unfeasible in this case.

The primary impact of travel time variability on the Nash equilibrium is peak spreading. Departures are spread more evenly over the rush hour than under certain travel times, resulting in less congestion. As a result of this mitigating mechanism, the MSCTTV is strictly lower than the VTTV. When the scale of the random delay is small enough compared to the total length of the rush hour, the MSCTTV is even null in the case of a uniform law, and close to null in the case of a normal law. Individual adjustments regarding the departure time offset, partly or even entirely, the direct cost of an increase in travel time variability. As far as cost-benefit analysis is concerned, this means that direct uses of the VTTV, in particular in 4-step models, overestimate the benefits of policies aiming to reduce travel time variability on a road network, and likely strongly so. One should consider the effect of such policies on the departure time profile (and thus on the O–D matrix when using a 4-step model) to avoid this bias, one solution being to use the MSCTTV. Additionally, our relatively strong result that the MSCTTV is null in some cases tends to corroborate the finding of Börjesson et al. (2012), which is that (α, β, γ) preferences only capture part of the cost that travel time variability puts on travelers. Future research might want to delve into this issue.

The layout of the paper is as follows. Section 2 reviews the prior literature. The model is presented in Section 3. Section 4 elaborates on the case where the random delay follows a uniform law, while Section 5 addresses more succinctly the case of a normal law, using numerical simulation. Section 6 discusses the results, and Section 7 concludes.

2. Prior literature

This paper is directly related to two main strands of the literature on the cost of travel time variability. The first one focuses on the individual and his preferences through the notion of value of reliability. The second one considers interactions between individuals and studies the impact of travel time variability on the traffic equilibrium and the cost of travel. We shortly review both.

2.1. Value of travel time variability

The value of travel time variability captures how much an individual values (in monetary terms) the cost associated with a marginal increase in travel time variability. As such, it is mainly a property of preferences. The literature on this topic is structured according to three main modeling frameworks (Li et al., 2010; Carrion and Levinson, 2012): the mean–variance model, the mean lateness model, and the scheduling model. The mean–variance and mean lateness models follow a descriptive approach. While they assume that individuals dislike travel time variability, they do not purport to explain why. These two modeling frameworks provide valuable econometric specifications to estimate the VTTV, but lack theoretical foundations.[1]

Scheduling models aim to fill this gap and provide a micro-economic foundation to the value of reliability. They represent the choice of departure time for an individual who faces time constraints (e.g. work start time). Typically, they assume that a traveler has a scheduling disutility function $U(t,T)$, which depends on the departure time t and travel time T, and study the optimal departure time and the associated minimum disutility. Building on Gaver (1968) and Vickrey (1969), Small (1982) has specified and estimated the following functional form for the scheduling disutility, which is widely used in works on the value of travel time variability:

$$U(t,T) = \alpha T + \beta(t^* - t - T)^+ + \gamma(t + T - t^*)^+ + \delta \mathbf{1}(t + T - t^*) \tag{1}$$

where $(x)^+ = x$ if x is positive, 0 otherwise, and $\mathbf{1}(x)$ is the Heaviside step function (equal to 1 if $x \geqslant 0$, 0 otherwise). $t^* - t - T$ is the schedule delay. It is measured relatively to a preferred arrival time t^*, which usually represents the work starting time. The cost of 1 min of travel time is α; the cost of being 1 min early at your destination is β and the cost of being 1 min late is γ. Lastly, δ is the fixed penalty for being late. These parameters set the terms of the trade-off between travel time and schedule

[1] As pointed out later, Fosgerau and Karlström (2010) provided a theoretical grounding to the mean–variance formulation *a posteriori*, using the scheduling model. The mean–variance model remains a descriptive model *per se* nonetheless.