International Transport Forum

Automation and the Value of Time in Passenger Transport
Discussion Paper

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Roundtable

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The International Transport Forum

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Table of contents

Introduction

New technology is emerging that promises to free car drivers from driving, allowing them to use their in-vehicle time for other purposes. Similarly, mobile devices allow public transport users to spend their time in transit more productively than before. Travel time, then, is becoming less costly for travellers, thus lessening the value of reducing it.

The impact of technology on the productivity of travel time depends on the characteristics of the transport mode. Laptops and mobile internet have increased the productivity of time spent in planes, trains and even buses[1]. Travel time can be spent on work (of the kind that can be done on a laptop or similar), playing games, watching movies, etc. Comfort is of great importance, of course: productivity is clearly low in a crowded bus or train. Car manufacturers promise a future in which car drivers are freed from driving, effectively turning car drivers into car passengers. But what are the policy implications from this broad change?

To a large extent, transport policy focuses on the trade-off of money for time. This is particularly true for the provision of infrastructure, where money is spent in order to save travel time for travellers. Hence, the value of travel time is vital for assessing transport policy. The core of the economic evaluation of an infrastructure project is to translate the consequences of travel times into an aggregate monetary value that can be compared with the cost of the project.

The same is true for congestion pricing, which one might say is about making travellers pay for spending other people's time. It is also true for the pricing of transport facilities (e.g. ferries, bridges), where travellers' willingness to pay depends on how much travel time they might save.

Individual travel choices are guided by the value of travel time. This does not require that travellers be conscious of any such number. However, the choices travellers make between routes and transport modes generally involve active trade-offs of travel time and comfort against monetary costs. Such choices, then, implicitly incorporate their underlying value of travel time. More broadly, the decision to travel or not is affected by the cost of travel time.

Through the value of travel time, transport policy connects to fundamental urban policy issues. The attractiveness of locations depends significantly on their accessibility to other locations through the transport system. Property values and urban densities fluctuate according to changes in travel times and costs brought about by transport policy.

Value of travel time is derived from first principles in a microeconomic framework that assumes a consumer cares about leisure and consumption. Assuming that time spent traveling is not completely available for work or leisure, reducing travel time has value when the time gained can be used for such activities. This framework allows us to predict the effect of making travel time more productive, that increasing the productivity of travel time will decrease the value of travel time.

The theory established in this paper will distinguish between the productivity of time allocated for work and that allocated for leisure during travel. This will help determine whether people choose to work or partake in leisure activities while traveling. The paper will discuss the individual willingness to pay to save travel time. It is concerned with the private value of time rather than the social. This allows for an agnostic view (for the present purpose) of how individual values should be aggregated to social values.[2]

The next section derives the value of private travel time and examines the implications of enabling in-vehicle time to be used productively. A discussion on business travel will follow. With this in place, the paper will undertake a basic static analysis of congestion pricing and will discuss the implications of increased in-vehicle productivity. This will then be extended to dynamic models that take the timing of trips into account, examining rush hour traffic and travel time variability. A brief discussion on the impact on urban form, using the monocentric city framework will follow. The paper will then make some observations that are relevant for providing high-level rough estimates of the willingness-to-pay for self-driving technology. It will revisit an old issue in the valuation of travel time: the value of small travel time savings, particularly whether or not all time savings should be treated equally, regardless of their size (despite increased in-vehicle productivity). The paper ends with a summary of the policy-relevant implications that can be drawn from the analysis.

The value of travel time for private travel

The basic microeconomic theory[3] underlying the value of travel time is based on the utility maximisation problem of a consumer who allocates his[4] time to various activities. The consumer cares about consumption, how much time he spends at work, on leisure and on travel. Work time is rewarded at a fixed wage rate (net after tax) that determines the monetary budget. The time required for travel is exogenously determined, while the allocation of time between work and leisure is chosen by the consumer within the available time budget.

This paper will establish the basic microeconomic model for this problem and derive the value of travel time within this context. This basis can later be extended to include possibilities for working and producing leisure while in transit. For concreteness, the paper will focus on car drivers, noting that the same theory applies to other modes of transport.

Suppose, then, that the consumer maximises utility

$$U(C,t_L,t_W,t_D),$$

where C, t_L, t_W and t_D represent consumption, leisure time, time spent at work and time spent driving.

The consumer faces a number of constraints. The first is that the total time spent at work, in leisure activities or driving is limited by the total time available, $T=t_W+t_L+t_D$. Second, the time spent driving cannot be less than the time it takes to cover some exogenously given distance, $t_D \geq t_0$. Third, time spent working is paid at the (net after tax) rate w.

This basic model leads to the familiar conclusion that the value of travel time is

$$w+\frac{U_{t_W}}{U_C}-\frac{U_{t_D}}{U_C},$$

where U and its subscripts denote the marginal utilities for consumption, work or driving time. This expression is discussed in more detail below.

Decreasing the time required for travel is valuable for the consumer as it relaxes the time budget constraint. The consumer reallocates the time saved in some proportion to work or leisure. More leisure time is always desirable, *ceteris paribus*. Time spent at work affects utility directly (depends on how nice is it to be at work) or indirectly, by allowing more consumption of goods.

The value of travel time is the willingness to pay to reduce travel time. It has three components in this analysis. The basis is the wage rate, net after tax. The second component is the marginal willingness to pay to increase work time. This component concerns only the effect on utility of spending time at work, i.e. how pleasant (or not) it is to work. It does not comprise the effect that more work enables more consumption. The third component is the marginal willingness to pay to decrease travel time, again holding everything else constant.

The last two components combine into the difference in marginal willingness to pay for time working relative to time spent travelling. If the marginal utilities of work time and travel time are equal, then the value of travel time is just the wage rate, as the last two terms cancel each other out. If working is nicer than travelling, then the consumer is willing to pay more than the wage rate to reduce travel time. Conversely, if travelling is nicer than working, then the consumer is willing to pay less than the wage rate to reduce travel time.

In addition, the rational consumer balances work and leisure and, therefore, additional leisure time has the same value as additional work time. This is a very useful observation. It means the wage rate, which is observable, can be used to measure the value of additional leisure time.

This theory in place, it is possible to compare the value of travel time in two different modes of transport that are not equally comfortable. The marginal willingness to pay to reduce travel time is lower in the more comfortable mode. Accordingly, the value of travel time is lower in the more comfortable mode.

A meta-study of estimates of the value of travel time from 389 European studies (Wardman, Chintakayala and de Jong, 2016) finds values of travel time for non-business trips in the range 32-64% of the gross wage rate. For studies conducted since 2001, they find a rate of 44% for commuting, 54% for other non-business travel purposes, and 43% for those studies that did not segment by travel purpose. Taking into account that the top bracket marginal income tax rates is roughly around 50% in Western Europe and that high income individuals are over-represented in the total distance driven on roads, it may be suggested that the value of travel time tends to be close to but lower than the net wage rate.[5] This, in turn, suggests that the marginal utility of work time is less than the marginal utility of in-vehicle time, i.e. for most people, driving tends to be nicer than working.

This basic theory assumes that it is not possible to work during travel. However, if sufficiently advanced self-driving cars become generally available, they will enable car drivers to carry out other activities, whether they are work or leisure related, while driving. Of course, this has long been possible on trains and buses and increasingly so with expanding mobile internet availability.

In-vehicle work productivity

Were the model extended to include the possibility of working while driving, one would assume the following utility

$$U(C,t_L,t_W,t_D+t_{DW}).$$

Doing so assumes that working while driving and just driving are perfect substitutes. The benefit of working while in transit is assumed to arise since working time while driving (t_{DW}) is productive. One supposes that consumption is a function net wage rate and time spent on productive work, i.e. $w\cdot(t_W+\alpha_W t_{DW})$, where $\alpha_W 0<\alpha_W\leq 1$, is the productivity while driving relative to productivity at work. The closer α_W is to one, the closer the productivity working in the car is to productivity at work.

A straightforward analysis of this extended model shows that consumers switch completely to working while driving, i.e. $t_D=0$ and $t_{DW}=t_0$. This is intuitive, as working pays a wage while just driving does not. By assumption, consumers are otherwise indifferent between working or not while driving. The value of travel time becomes

$$(1-\alpha_W)w+\frac{U_{t_W}-U_{t_D}}{U_C},$$

which is exactly the same as in the case without the possibility of working while driving, except the wage rate is multiplied by the difference between productivity at work and in the car. The previous result is reproduced if productivity α_W is zero, while the wage rate drops out of the value of travel time if working while driving is as productive as working at work.

In-vehicle leisure productivity

There is also the possibility that time in transit may be used to participate in leisure activities. One may, for example, watch a film while driving. Sleeping can also be called a leisure activity and counts as a productive use of travel time. To account for this, the model must be extended as

$$U(C,L,t_W,t_D+t_{DW}+t_{DL}),$$

where now t_{DL} is time spent partaking in a leisure activity while driving and the various time uses while driving are still perfect substitutes. This extended model supposes that the in-vehicle productivity of leisure time is a factor α_L of the productivity of leisure time elsewhere.

As before, working while driving and just driving are perfect substitutes. Whether the consumer will work or partake in a leisure activity depends on what time use yields the highest marginal utility. The consumer will produce leisure if

$$\alpha_W U_C w<\alpha_L U_L,$$

which happens if the wage is low or if leisure can be produced more effectively than work. The same inequality may be written as

$$\alpha_W<\alpha_L+\alpha_W\frac{U_{t_W}}{U_L}.$$

Then, if time at work has no direct impact on utility, the choice between work and leisure is solely determined by the relative size of the productivities. The choice is tilted towards leisure if time at work has a direct positive effect on utility and vice versa if it has a negative effect. This is intuitive: if time spent at work is not pleasant, then it makes sense to conduct that work elsewhere if the opportunity exists.

The leisure-producing consumer has a value of travel time that is

$$(1-\alpha_L)w+\frac{(1-\alpha_L)U_{t_W}-U_{t_D}}{U_C}.$$

As leisure production while driving becomes increasingly productive, the wage term gradually drops out of the expression for the value of travel time. At the same time, the influence of the marginal utility of working at work also gradually drops out. If travel time was fully productive, then the value of travel time would only reflect the pure comfort effect of driving.

In-vehicle productivity

The main take-away from this analysis can be isolated by ignoring the component of the value of travel time derived from the difference in marginal utility between time spent at work and time spent in the car. The value of travel time is then limited to the net wage rate, multiplied by a factor that expresses the productivity difference between time use out of the car and time use in the car. The value of travel time in the simplest case is just

$$(1-\alpha)w\ ,$$

where α is the productivity of time in the car relative to the productivity of time out of the car.

Without imposing further assumptions, one cannot determine from this theory whether people will tend to work or partake in leisure activities during travel, nor the influence of income on that decision. This is an empirical issue.

Business travel

It is easier to assess the value of travel time for business travel, understood as any travel during work, than it is to assess the value of travel time for people travelling outside working hours. The traditional cost savings approach assumes that travel time is completely unproductive and that time not spent travelling is used productively. Workers are assumed to derive the same utility whether they work or travel during work hours. In that case, the value of business travel time is simply the gross wage rate, i.e. the cost to the employer per unit of employee time. The gross wage rate should be in market prices to be comparable to the consumer willingness-to-pay. That is, it should include value-added tax as well as other indirect taxes, such that it corresponds to the savings to consumers from productivity gains due to reduced transport costs. This embodies an assumption of perfect competition, which might be an adequate approximation for the present purpose.

With the cost savings approach, the introduction of driverless cars would have no impact on the value of business travel time. This is clearly unreasonable and the problem is that the cost savings approach assumes that travel time is completely unproductive.

The Hensher approach (1977) goes to the other extreme, taking an engineering-style approach to account for many relationships that could affect the value of business travel time. It decomposes the value into the following components: the gross wage rate, multiplied by the proportion of travel time that is unproductive (this takes into account that the business traveller may produce work or leisure during travel); the value of resting during travel (this takes into account that the business traveller may use travel time for restitution to become more productive after the trip); the worker’s willingness-to-pay for converting business travel time not spent in leisure activities into working time; and the worker's willingness-to-pay for converting business travel time spent in leisure activities into leisure time.

It seems the full Hensher formula is not applied in any appraisal guidelines in any country. The reason is that the formula is complicated and requires numbers to be assigned to a range of somewhat elusive concepts. It is safer to rely more on a number that can be credibly observed, namely the wage rate.

Most applications treat business travellers as zombies, whose personal willingness-to-pay for reducing travel time should be ignored. This avoids the serious problems that arise in assessing their willingness-to-pay for travel time savings for which they do not, in fact, pay.

Removing the corresponding items from the Hensher formula and simplifying it a bit leaves a formula that can be written $(1\text{-}\alpha)W$, where α is the share of travel time that is productive (for work, not leisure) and W is the gross wage rate. This is essentially the same as the expression $(1\text{-}\alpha)w$ derived in the earlier section, except that the analysis there concerns private travel and w is the net wage rate.

In conclusion, private and business travel may be treated in much the same way, with the exception that the value of private travel time is based on the net wage rate while the value of business travel time is based on the gross wage rate. It follows from this observation that the willingness-to-pay for technology that increases in-vehicle work productivity will be higher for business travel.

Basic analysis of congestion pricing

This section considers the effect of increased productivity of travel time on the basic analysis of congestion pricing. The economic argument behind congestion pricing is as follows.

Every potential traveller has some willingness-to-pay (expressed in monetary units) for a trip. The potential traveller travels if the cost of travel is less than her willingness-to-pay. If it is not, she does not. The number of travellers, then, is inversely related to a trip's cost: cheaper travel implies more travel.

The price of the trip depends first on the number of travellers, N, through the supply function S(N), which gives the travel time of a trip and takes into account that congestion causes the travel time to increase if the number of travellers increases. This quantity is multiplied by the value of travel time $(1\text{-}\alpha)w$ and added to a toll τ that may be zero. The cost of a trip, then, is

$$(1\text{-}\alpha)wS(N)+\tau\ ,$$

and the number of travellers adjusts such that it equals the number of potential travellers whose willingness-to-pay is greater than the cost of the trip. All of these attain a positive benefit of traveling, or a surplus, which is their willingness-to-pay less the trip cost.

Now consider a social planner aiming to maximise welfare. Welfare is defined as the sum of the willingness-to-pay over all travellers less their total travel time cost, i.e. as the total net benefit gained from traveling. In other words, the social planner aims to maximise the benefit derived from the ablity to travel. The social planner will set the toll τ at the level that maximises welfare.

Important to note is that the aim of tolling is not just to reduce traffic. Were that the case, it would be a lot easier to simply remove road capacity. On the contrary, the point of congestion tolling is to maximise the benefit derived from the transport system.

Toll payment does not affect aggregate welfare directly, as the loss for travellers is exactly offset by a corresponding gain for the rest of society. The toll has two indirect effects on welfare. First, it discourages some from traveling and these individuals then lose their willingness-to-pay for traveling. Second, the remaining travellers experience reduced congestion and this is the source of gain from congestion tolling. The social planner will increase the toll to the point where the gain from further increasing the toll is exactly offset by losses to those discouraged from traveling. This means that the optimal toll is

$$\tau=N(1-\alpha)wS'(N).$$

The optimal toll does not remove congestion. It ensures that the willingness-to-pay of the marginal traveller is exactly equal to the congestion cost that traveller imposes on the other travellers. The optimal does not in any way guarantee that travellers as a group gain from tolling. Generally, they will lose. It is only when the benefit associated with the toll revenue is added that there is a net welfare gain. The transfer away from travellers may easily be larger than the gain.

As in-vehicle productivity α increases, traffic volume is also likely to increase, even when the optimal toll is applied. In other words, the optimal traffic volume increases as in-vehicle productivity increases.

Dynamic models

The previous analysis is static and represents time as nothing more than a quantity; it does not take into account the timing of trips. A dynamic model is needed to analyse a number of issues related to travel time. The notion of scheduling utility can be applied to build such a model.

Consider now a traveller calculating the timing of a single trip. The traveller has a scheduling utility $U(t_{dep}, t_{arr})$ that ranks all possible ways the trip can be timed.[6] For simplicity, the scheduling utility is money-metric, such that the utility difference between two potential outcomes is a monetary value.

There are several approaches to formulate a scheduling utility. Different approaches will have different impacts on how the effect of increasing the productivity of in-vehicle time may be included.

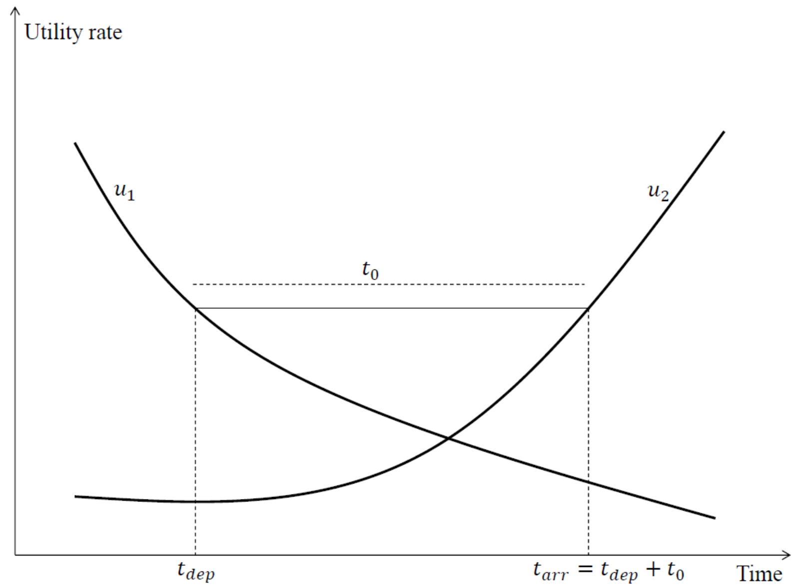
The first approach assumes the traveller accumulates utility prior to the trip at the decreasing rate $u_1(t)$ until the time of departure. Similarly, the traveller accumulates utility at the destination at the increasing rate $u_2(t)$ after the time of arrival. The scheduling utility can then be written in terms of utility rates[7] as

$$U\left(t_{dep},t_{arr}\right)=\int^{t_{dep}} u_1(t)dt+\int_{t_{arr}} u_2(t)dt\ . \qquad (1)$$

Figure 1 illustrates this formula. The scheduling utility expresses that the traveller would like to stay at home as long as possible, everything else equal, and also that he would like to be at work as early as possible, everything else equal.

The traveller chooses departure time to balance these two goals. If travel time is fixed at t_0, the optimal departure time is $u_1\left(t_{dep}\right)=u_2\left(t_{dep}+t_0\right)$. The value of travel time is the utility rate at the optimal departure time, $u_1\left(t_{dep}\right)$. It is clear that the value of travel time increases with trip length in this model.

Figure 1. Utility rates



Vickrey (1969) bottleneck model applied this kind of scheduling utility to analyse congested demand peaks. The Small (1982) analysis of commute scheduling and congestion also used it. It is also applied to assign a value to travel time variability (Engelson and Fosgerau, 2016).

The second approach uses insights from the static model set the foundation for considering the impact of increasing the in-vehicle productivity of work or leisure. The scheduling utility rates should be understood as differences from the utility rate that is achieved while travelling (Oort, 1969). Lacking an explicit theory that links the static and dynamic models, one option is to simply suppose that utility rates in the scheduling model are multiplied by the productivity difference $(1\text{-}\alpha)$. An increase in in-vehicle productivity would then translate directly into a decrease in the value of travel time.[8]

The decrease would be proportionally the same for all trip lengths if the in-vehicle productivity is independent of the trip length. However, it seems more likely that the in-vehicle productivity is higher for longer trips, since longer trips allow for activities that require more time. This could be, e.g., watching a TV show or performing work-related tasks. The range of activities that are possible on shorter trips is more limited. These considerations suggest that the value of travel time decreases more on long trips.

The third approach assumes that scheduling utility is the sum of two terms: one that is related just to travel time and one that is related just to the arrival time[9], i.e.

$$U\left(t_{dep},t_{arr}\right)=U_{tt}\left(t_{arr}\text{-}t_{dep}\right)+U_{arr}(t_{arr}) , \tag{2}$$

where U_{tt} is decreasing and U_{arr} is concave with maximum at some preferred arrival time.[10] Within this model one may also suppose, for example, that in-vehicle productivity affects only the first term, as in the static model, but not the second. The two different versions will hereafter be referred to as Model 1 and Model 2.

Model 1 is separable in departure and arrival times. Both terms are scaled by $(1\text{-}\alpha)$.

Model 2 is separable in travel time and arrival time. Only the travel time term is scaled by $(1\text{-}\alpha)$.

The two models are equivalent when the travel time term $U_{tt}\left(t_{arr}\text{-}t_{dep}\right)$ in Model 2 is linear, except for the way in-vehicle productivity is included.

Congested demand peaks

Increased in-vehicle productivity is likely to have an impact on congested demand peaks. In a general version of the Vickrey (1969) bottleneck model, commuters with similar scheduling utility have to pass a bottleneck on their way to work. Ideally, many commuters would travel at the same time, but this is not possible since the bottleneck capacity is limited. This capacity constraint causes a queue to build as travellers arrive at the bottleneck at a faster rate than they can pass through it. The queue diminishes gradually at the end of the demand peak, when the arrival rate is smaller than the bottleneck capacity.

The bottleneck model considers an equilibrium where each commuter has chosen her optimal departure time, taking the behaviour of the other commuters as given. Early commuters achieve a short travel time, but pay by departing when their utility rate at home is high and arriving while their utility rate at work is low. They would prefer to depart and arrive later, but commuters departing later pay for their more convenient departure and arrival times by spending more time queueing. This correlation is reversed at the other side of the demand peak. Later commuters spend less time queueing but pay with later departure and arrival times. They would have preferred earlier departure and arrival times, but only if it had been possible without increasing travel time.

The duration of the congested demand peak is determined solely by the number of commuters and the bottleneck capacity. Increasing the productivity of in-vehicle time therefore has no direct impact on this duration. The effect of in-vehicle productivity depends on the model of scheduling preferences.

- In Model 1, if increasing in-vehicle time productivity translates into a proportional decrease in utility rates, then there is also no direct impact on the beginning and the end times of the congested demand peak. The evolution of travel time over the peak is given by a differential equation that depends on a ratio of utility rates. Multiplying these utility rates by a constant relative change $\left(1\text{-}\alpha\right)$ makes no difference for this differential equation. Thus the basic prediction of this model is that increasing in-vehicle time productivity has no direct impact on the queueing delay at any time during the demand peak. However, the equilibrium scheduling utility of commuters will increase, which will generally induce more commuting. Taking this into account, one may expect that the duration and height of the congested demand peak will increase as α increases.
- In Model 2, increasing in-vehicle productivity does not affect the arrival time term. The travel time is the same for the first and the last commuters in the peak, therefore the arrival time term determines the timing of the peak. Hence, in-vehicle productivity has no direct impact on the timing of the peak. Commuters that travel in the middle of the peak pay for their more convenient arrival times with longer travel time. As increasing in-vehicle productivity reduces the cost of queueing, the amount of queueing must increase to maintain equilibrium. The equilibrium scheduling utility of commuters will increase, but less than in Model 1, so perhaps the induced increase in the demand for commuting will be smaller than in Model 1.

Van den Berg and Verhoef (2016) undertake a more extensive analysis of the impact of self-driving cars on congestion in a bottleneck setting based on the assumptions of the present Model 2, i.e. where increased in-vehicle productivity only affects the value of travel time but not the part of scheduling utility related to arrival time. The main point of their analysis is to allow the share of self-driving cars to vary from 0 to 100%. With some share of cars being self-driving, heterogeneity is introduced, with the drivers in the self-driving cars having lower value of travel time but the same disutility of inconvenient arrival time as drivers in the manually-driven cars. The length of the demand peak is determined by the scheduling utility of arrival time and is hence unaffected in this first extension. However, people in driverless cars may use their in-vehicle time productively and hence have lower value of travel time. Therefore, they are better able to tolerate queueing and these drivers will then occupy the middle part of the demand peak where queues will be longer than if all cars were manually driven. The shoulders of the peak will be occupied by manually-driven cars and their situation will be essentially unchanged relative to the situation without driverless cars.

This conclusion changes, however, if the reduced travel cost for driverless cars induces more traffic. Drivers in manually-driven cars will then be crowded out of the most attractive trip timings and the peak will begin sooner and end later, with manually-driven cars still occupying the shoulders of the peak.

Van den Berg and Verhoef consider an opposing effect, namely that a high share of self-driving cars may increase capacity and thereby contribute to reducing congestion by reducing the length of the demand peak. This effect benefits all drivers, regardless of whether they use a driverless car or not.

Travel time variability

Traffic congestion not only causes delays; it also causes travel times to be random from the traveller's point of view. Empirical evidence shows that a large share of average delays is due to irregular delays caused by random events. It is relevant for prediction and policy evaluation to be able to assign a value to reducing travel time variability. This is often done using models that are based on a notion of scheduling utility (Engelson and Fosgerau, 2016).

In this paper μ represents the mean travel time and σ the standard deviation of travel time. It further assumes (as a rough approximation to facilitate analysis) that the travel time distribution is independent of the departure time. These models suppose that each traveller chooses departure time to maximise the expected scheduling utility, taking into account that travel time is random with some distribution known by the traveller.[11] Then the value of changing the variability of travel time can be derived.[12] This value allows that travellers compensate for changes in the random distribution of travel times by changing their departure time.

There are two main formulations of scheduling preferences that lead to simple expressions for the value of travel time variability: the step model, and the slope model. Both are special cases of Model 1 and the step model is also a special case of Model 2.

In the step model, the value of time is a constant while utility decreases linearly the more travellers arrive earlier or later than a given preferred arrival time. Holding the standardised travel time distribution fixed, Fosgerau and Karlstrom (2010) show that the scheduling utility is linear in the standard deviation of travel time, with a slope that depends only on the penalty for early or late arrival.

The impact of increased in-vehicle productivity, then, depends on whether Model 1 or Model 2 is applied. In Model 1, in-vehicle productivity scales the whole scheduling utility and hence the value of travel time variability. In Model 2, on the other hand, in-vehicle productivity scales only the travel time term. Therefore, the value of travel time variability is unaffected.

Whether Model 1 or Model 2 is more appropriate is thus very important. As travel time becomes more productive, one of two things will happen, depending on the model chosen: either travel time variability maintains its importance relative to travel time itself, or travel time variability retains its importance while the importance of travel time diminishes.

These conclusions apply to other measures of travel time variability than the standard deviation, provided that one accepts either Model 1 or 2 as theoretical foundation, and that these measures are proportional to the standard deviation. This includes the difference between two specific quantiles of the travel time distribution (Small, Winston and Yan, 2005), the difference between a quantile and the mean travel time, the buffer time index (FHA, 2006), and the mean lateness.

The main alternative to the step model is the slope model, which also leads to a tractable expression for the value of travel time variability. This model is a special case of Model 1, in which utility rates vary linearly over time. If the utility rate at the origin is constant, then, mathematically, it is also a special case of Model 2.

In this model, the marginal utility per unit of travel time *variance* is constant, equal to the slope of the utility rate at the destination. The more important are deviations in arrival time: the larger is the value of travel time variance.

The effect of a change in in-vehicle productivity depends on which interpretation of the model is correct. In Model 1, larger in-vehicle productivity leads to lower value of travel time variability, where there is no effect in Model 2.

Monocentric cities

This section discusses the impact of increasing in-vehicle productivity on urban form using the classic monocentric city model (Alonso, 1964). The model describes a stylised city with a central business district in which all employment takes place. Residents choose where to live and how much of their income to spend on housing and consumption. In the simplest version of the model, residents are taken to be identical. Then various conclusions may be derived concerning an equilibrium where all residents attain the same utility level.

The main stylised fact emerging from the monocentric city model is that the residential density decreases with the distance from the centre. Residents face a trade-off between transport costs and housing costs. Near the centre, transport costs are low but the cost of housing is high. Consequently, residents there consume less housing and the residential density is higher. Further out, transport costs are higher but housing costs lower. This allows each resident to occupy more space and, therefore, the residential density is lower. Altogether, the model predicts that the residential density decreases as the transport cost to the city centre increases. As the transport cost is positively related to distance, the density gradient with respect to distance is negative.

A general decrease in transport costs due to increased in-vehicle productivity will then make the density gradient less steep. Holding the city population constant, one may expect that the residential density decreases near the centre and increases further out. Cities will become more sprawled.

There is a balancing mechanism, however, which is that reduced transport costs allow cities to become larger. Due to agglomeration forces, one may predict that large cities will attract population from smaller cities and become even larger, while smaller cities will lose population (Rappaport, 2016).

These conclusions carry over to the case of the bottleneck model, which takes into account that congestion is dynamic (Gubins and Verhoef, 2014; Fosgerau, Kim and Ranjan, 2018).

Some observations on self-driving cars

The value of travel time in a self-driving car

What will the value of travel time be in a self-driving car? Self-driving cars currently are not widely available yet, so the trade-offs between time and money made by travellers in such vehicles cannot be observed. Instead, other comparisons may reveal something about the value of freeing drivers' time spent travelling.

In stated preference data from the Danish value of time study, respondents completed choice exercises both for the current mode of transport as well as for an alternative mode (Fosgerau, Hjorth and Lyk-Jensen, 2010). This design makes it possible to compare the value of travel time in different transport modes for the same individual. This comparison is important, as confirmed by the study, because of the fact that people self-select into travel modes affected by their value of travel time making it impossible to infer modal differences from simple differences in the average value of travel time across modes.

The study's main finding on comfort effects is that current bus passengers retain their (low) value of travel time in different alternative modes. It seems that only respondents with high value of travel time are affected by the experiment mode. Among those, the value of travel time is significantly lower in cars than in trains, which is consistent with cars being more comfortable than trains. There is no evidence that the value of travel time is lower in trains due to the ability to conduct activities other than driving. Hence, this study does not support the idea that car drivers have significant willingness-to-pay for not having to drive. It should be considered, however, that the data in the Fosgerau, Hjorth and Lyk-Jensen study are from 2004 and the present availability of mobile technology may change the conclusion.

Comparing car drivers to car passengers (in manually driven cars) is also informative. Self-driving technology will enable car drivers to behave like car passengers. The higher potential in-vehicle productivity of car passengers should then be reflected in a lower value of time. There are, however, other factors influencing the difference in the value of travel time between car drivers and car passengers. First, the car driver is unlikely to be randomly designated: the selection of who drives the car will most likely correlates with the individual value of travel time. Second, a car passenger is not the same as a single user of a self-driving car.

There are not many studies of the passenger value of travel time. The consensus seems to be that car passengers value travel time at about 75% of the rate of car drivers, even if that assessment does not take into account the interactions between the occupants of a car (Ho et al., 2015). Such a difference in the value of travel time is not universally found. For example, a recent large-stated preference study in

Copenhagen (Lu et al., 2018) found no difference between car drivers and passengers in the value of travel time. These studies do not control for self-selection, so it is possible that any difference between drivers and passengers is due to a tendency for the driver to be the person with the highest value of travel time. Altogether, these observations suggest an upper bound of 25% for the reduction in the value of travel time from not having to drive. This suggests that $\alpha=0.25$ is a large number.

Willingness-to-pay for self-driving technology

Self-driving cars are coming, it seems, although it will probably take many years before they have an impact on traffic volume. As there is very limited experience with self-driving cars, any conclusions regarding their impact on the value of travel time will be highly speculative. It is still worth putting some thoughts forward to stimulate further thinking and discussion.

One can try to make a small back-of-the-envelope calculation to get some idea about the potential willingness-to-pay for self-driving technology. One can estimate the total cost of the time spent driving a car during its lifetime and use that figure to suggest an upper bound for the willingness-to-pay for fully self-driving technology.

If a car drives 300 000 km at a time cost (for the driver) of EUR 10 per hour and an average speed of 60 km per hour, that time is worth EUR 50 000, or perhaps just EUR 25 000, allowing for discounting.

Taking such a figure as the willingness-to-pay for self-driving technology is, of course, extreme. It supposes that all driving time can be converted to fully productive use such that travel time will cease to be a constraint at all. Less extremely, self-driving technology will more likely lead to *some* productivity increase and only for *some* of the kilometres driven by the car. If we suppose that the willingness-to-pay were 10% of the value of travel time for 50% of the kilometres, which does not sound unrealistic, then the estimated total willingness-to-pay would be just EUR 1 250.

This simple analysis suggests that self-driving technology will have to become very cheap in order to break through at a large scale. This is much lower than the price that is currently anticipated.

Small travel time savings

The issue of small travel time savings has two parts. The first is that large, and hence valuable, aggregate savings of travel time, which may result from certain transport projects, is actually composed of lots of small travel time savings of a few seconds. These small travel time savings may seem virtually worthless from the perspective of current individual travellers. Thus it may seem paradoxical that they are assigned a large value in the aggregate. The second part is that stated preference data seem to support that small travel time savings are worth less per minute than large travel time savings. As a result, some have suggested that small travel time savings below a certain threshold should not be included in cost-benefit analysis at all.

Regarding the first part, the established and well-founded point of view is that this objection to valuing small travel time savings is misguided. Travellers who have already committed to their daily schedule may have difficulty seeing how they could use a few extra seconds. However, as the goal is to evaluate long-term effects, the short-term perspective of individual travellers with committed activity schedules is just not relevant. Furthermore, evaluating small and large time savings differently is nonsensical, as any large project can be decomposed into a sequence of small projects.

An increase in the productivity of in-vehicle time would not have any effect on this discussion. The conclusion would remain that small and large time savings should be assigned the same value for policy evaluation purposes.

Regarding the second part, evidence from stated preference data shows that small time differences are valued less than large time differences. This is inconsistent with neoclassical utility maximisation but consistent with reference point effects according to prospect theory (De Borger and Fosgerau, 2008). For anything but the very short-term, reference points are irrelevant; therefore any effect deriving from reference points is also irrelevant. The main takeaway from this research is that: 1) stated preference data are highly problematic for measuring the value of travel time because of these reference point effects; and 2) it is strongly advisable to develop revealed preference data and methods for measuring the value of travel time.

To conclude, small travel time savings is unrelated to the effect of increasing in-vehicle productivity.

Conclusions

Driverless technology and mobile communication technology promise to increase the ability of travellers to perform productive activities while travelling. The unsurprising theoretical prediction that follows is that this will be reflected in a lower willingness-to-pay of travellers for reducing travel time, i.e. a lower value of travel time. This is true for both private and business travel.

The first-order effect of this is to reduce the case for investing in infrastructure in order to reduce travel times. However, the reduction in the cost of travelling will induce more traffic and the net effect on the benefits of infrastructure investment is ambiguous.

The economic efficiency argument for road pricing is unchanged. Increased in-vehicle productivity will lead to increased traffic volume, even in the presence of the optimal congestion toll. The optimal congestion toll may increase or decrease as in-vehicle time becomes more productive. A reduction in the value of travel time will not have a direct effect on the duration of commuting peaks. Driverless cars will tend to concentrate in the middle of the peaks and queue lengths may increase due to the reduced cost of travel time. A large share of driverless cars may improve capacity, thereby reducing travel cost for everybody. This will induce more traffic. It is possible that users of non-driverless cars will be worse off.

The value of travel time variability may or may not be reduced by increased in-vehicle productivity. There are competing theories and little empirical evidence to distinguish between them. There is no indication, however, that the value of travel time variability will increase.

The impact of increased in-vehicle productivity on urban form is a tendency for cities to become more dispersed in relative terms. Larger cities may become even larger and it is possible that some large cities will become denser at all distances from the centre. These effects hinge on the assumption that the value of travel time will actually decrease. One can guess how much by comparing the value of time in cars to that in buses and trains and by comparing car drivers to car passengers. Evidence suggests that the reduction in the value of travel time due to increased in-vehicle productivity might be less than 25%.

Taking into account how much time a car is actually driven and making some back-of-the-envelope calculations suggests that the average willingness-to-pay for self-driving technology might be as low as EUR 1 000 to 2 000. This is very low compared to the current predictions of the cost of providing self-driving technology. This, in turn, suggests that the market share of self-driving cars will be fairly small.

Notes

1 This paragraph was in fact written on a laptop in a plane and with (partially successful) internet access during the flight.

2 Mackie, Jara-Diaz and Fowkes (2001), Gálvez and Jara-Diaz (1998)

3 The microeconomic formulation of the theory of the value of travel time savings was fundamentally formulated by Becker (1965), Johnson (1966), Oort (1969), and DeSerpa (1971). Jara-Diaz (2000) provides a review.

4 Gender of representative person was chosen at random.

5 Considering the arguments made in this paper and elsewhere, it would be good practice to report the value of travel time relative to the net wage rate.

6 It would be of interest to have a theory that unifies the static and the dynamic perspectives on the value of travel time.

7 This generic form for scheduling utility was first formulated by Vickrey (1973). It can be derived from a broader model in which consumers derive utility from leisure and consumption, and travel time (Fosgerau and Small, 2017).

8 This observation indicates that it would be nice to have a more extensive theory that could account for the idea that in-vehicle time is more productive on longer trips. The static and dynamic models, as formulated here, do not allow such an effect to be represented.

9 This paper ignores the symmetric possibility that scheduling utility could be separable in travel time and departure time.

10 Like the first formulation above, this formulation generalises the popular α-β-γ preferences (Vickrey, 1969; Small, 1982; Arnott, de Palma and Lindsey, 1993).

11 What travellers really know and take into account is an important issue. Fosgerau and Jiang (2017) present a model in which travellers choose how much information to acquire.

12 Using the envelope theorem.

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Automation and the Value of Time in Passenger Transport

This paper reiterates the basic principles and rationale for valuing travel time savings. It explains the type of impacts that the valuation of travel time savings intends to capture and discusses whether and how those fundamental principles continue to hold with automation and increased possibility of productive time use while travelling. The paper also discusses implications for traffic management and urban form that follow from increased in-vehicle productivity.

All resources from the Roundtable on Zero Value of Time are available at: www.itf-oecd.org/zero-value-time-roundtable.

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