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# On the impact of vehicle automation on the value of travel time while performing work and leisure activities in a car: Theoretical insights and results from a stated preference survey – A comment

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## ABSTRACT

This note revises the theoretical insights concerning the Value of Travel Time for automated vehicles as derived in a recent paper in this journal (Correia et al., 2019). That paper concluded that Value of Travel Time in an automated vehicle should be lower than in a conventional vehicle by salary rate, if the traveller works during the trip, and unchanged compared to conventional vehicles, if the traveller engages in leisure activities while travelling. However, these conclusions have limited validity, because the models, upon which they are based, contain a term whose interpretation differs across the models. This note clarifies this interpretation and offers an alternative extended model, which allows comparison across models. The alternative model provides an intuitive result: the facilitation-level of on-board activities determines the reduction of the Value of Travel Time in the automated vehicle. If automated vehicles provide identical work or leisure experience to out-of-vehicle locations, then the opportunity costs of travel time are erased and the Value of Travel Time equals the intrinsic costs of travel, which is strictly smaller than the Value of Travel Time in a conventional vehicle.

## 1. Clarifying the theoretical insights in Correia et al. (2019)

The recent paper by Correia et al. (2019) set on an important mission to theoretically derive the Value of Travel Time (VoTT) for the Automated Vehicle (AV) era and to compare the theoretical insights with empirical results. The theoretical part of the work was based on the classical microeconomic time-use framework. In order to incorporate the possibility of future AV-users to perform activities during the trip, the authors altered the constraints of the time-use model and, after derivations, obtained the VoTT in a work- and leisure-equipped AV:<sup>1</sup>

$$VoTT_{AV-work} = \frac{\frac{\partial U}{\partial W}}{\frac{\partial U}{\partial G} - \alpha\theta} - \frac{\frac{\partial U}{\partial t_i}}{\frac{\partial U}{\partial G} - \alpha\theta} \quad (C 13)$$

and

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<sup>1</sup> Equations that are copied from Correia et al. (2019) preserve the original numbering from their paper, but are marked with a preceding ‘C’. Equations that are original in the present note are numbered as conventional.

$$VoTT_{AV-leisure} = \frac{\frac{\partial U}{\partial L}}{\frac{\partial U}{\partial G} - \alpha\theta} - \frac{\frac{\partial U}{\partial t_i}}{\frac{\partial U}{\partial G} - \alpha\theta}. \quad (C 18)$$

The notation in the equations is as follows:

- $U$  – overall utility obtained from engaging in activities and consuming goods in some time period;
- $G$  – purchased goods (in monetary terms);
- $L$  – time spent in leisure;
- $W$  – time spent working;
- $t_i$  – travel time (in mode  $i$ );
- $w$  – salary rate per time unit (e.g., an hour);
- $\alpha$  – leisure time needed to consume one (monetary) unit of purchased goods;
- $\theta$  – Lagrange multiplier of the technical constraint (see [Correia et al., 2019](#) or [Jara-D  az, 2008](#) for details).

Having obtained the results (C 13) and (C 18), the authors correctly interpreted that the VoTT in a work-equipped AV equals the utility difference between working outside the vehicle (first term of (C 13)) and working inside the vehicle (last term of (C 13)). Likewise, the VoTT in a leisure equipped vehicle could be interpreted as the utility difference between having leisure inside the vehicle, instead of outside it (C 18).

Further however, the authors deduced that (C 18) could be rewritten as (C 19):

$$VoTT_{AV-leisure} = w + \frac{\frac{\partial U}{\partial W}}{\frac{\partial U}{\partial G} - \alpha\theta} - \frac{\frac{\partial U}{\partial t_i}}{\frac{\partial U}{\partial G} - \alpha\theta}. \quad (C 19)$$

This led to the conclusion that the VoTT in a leisure-equipped AV (C 19) is identical to the VoTT in a conventional vehicle (CV) ([Jara-D  az, 2008](#)):

$$VoTT_{CV} = w + \frac{\frac{\partial U}{\partial W}}{\frac{\partial U}{\partial G} - \alpha\theta} - \frac{\frac{\partial U}{\partial t_i}}{\frac{\partial U}{\partial G} - \alpha\theta}. \quad (C 8)$$

Similarly, it was obtained that the VoTT in a work-equipped AV should be less than the VoTT in a CV exactly by the salary rate  $w$  (by comparing Eqs. (C 13) and (C 8)) (see p. 362, 375–376).

However, there are two reasons why the above conclusions have limited validity. The first of these lies in the transition from (C 18) to (C 19), which affects the comparison between VoTT in CVs and leisure-equipped AVs. This transition assumes that terms  $(\partial U/\partial L)/(\partial U/\partial G - \alpha\theta)$  and  $w + (\partial U/\partial W)/(\partial U/\partial G - \alpha\theta)$  are equal – but they are in general not so for the present model. The correct relationship between the two terms follows from the first order condition of the model, which can be obtained from Eqs. (C 6) and (C 7) of [Correia et al.](#) (not repeated here):

$$\frac{\partial U}{\partial G}w - \frac{\partial U}{\partial L} + \frac{\partial U}{\partial W} - \theta(1 + \alpha w) = 0. \quad (1)$$

Re-arranging the terms in (1), we can obtain

$$\frac{\frac{\partial U}{\partial L}}{\frac{\partial U}{\partial G} - \alpha\theta} = w + \frac{\frac{\partial U}{\partial W}}{\frac{\partial U}{\partial G} - \alpha\theta} - \frac{\theta}{\frac{\partial U}{\partial G} - \alpha\theta}. \quad (2)$$

Having (2), we can see that (C 18) is equal to (C 19) only when  $\theta = 0$ , that is, when the technical constraint connecting leisure time and consumed goods is not binding.<sup>2</sup> However, the VoTT is derived for the binding case  $\theta > 0$  and, due to being more general, it also applies to the non-binding case. Therefore, to incorporate all cases to which the VoTT applies, Eq. (C 19) should be corrected as follows:

$$VoTT_{AV-leisure} = w + \frac{\frac{\partial U}{\partial W}}{\frac{\partial U}{\partial G} - \alpha\theta} - \frac{\frac{\partial U}{\partial t_i}}{\frac{\partial U}{\partial G} - \alpha\theta} - \frac{\theta}{\frac{\partial U}{\partial G} - \alpha\theta}. \quad (3)$$

Consequently, the conclusion of unchanged VoTT in leisure-equipped AVs (as compared to CVs) has limited validity. If the comparison is performed (while accounting also for the second reason, explained below), then it should be based on Eqs. (C 8) and (3), which differ by the last term  $\theta/(\partial U/\partial G - \alpha\theta)$  in (3). This means that the VoTT in AVs with leisure activities would be smaller than the VoTT in CVs, if consumption is limited by the leisure time, and equal to the VoTT in CVs, if the leisure time exceeds the time

<sup>2</sup> The general inequality of these terms, given the present model specification, is discussed by [Jara-D  az \(2008\)](#) on p. 372: ‘If consumption is limited by time (...), the marginal utility of leisure is smaller than the total value of work given by the wage rate plus work itself.’ The equality holds for the non-binding case as well as for other model specifications, where no constraint connects the goods consumption and leisure time (see, e.g., the first model presented by [Jara-D  az, 2008](#) on p. 365).

needed to consume purchased goods. Note that the former case – consumption being limited by the leisure time – can be expected to be rather rare; it would imply that individuals are earning money faster than they are able to spend it, which would hold presumably only for a small share of high-income individuals (Evans, 1972). Therefore, empirically, the first limitation of the comparison is less severe than the second one.

The second and most important reason, which limits the comparison of VoTT between CVs and both AVs, lies in the term  $\partial U/\partial t_i$ , defined in the paper as the utility of ‘spending time inside a car’ (p. 362). This utility can be expected to be influenced by the activities performed inside the car – none in the CV and work or leisure in the AV. Therefore, the term  $\partial U/\partial t_i$  has different interpretations in the three equations used for comparison: (C 8), (C 13) and (C 18). A direct comparison across the VoTT results is possible only by assuming that the utility differences are negligible, which is limiting.<sup>3</sup>

In addition to the so-far outlined concerns, we would like to highlight two other details that might cause confusion for the readers of the original paper.

1. The unchanged VoTT for leisure-equipped AV (as compared to CV) is explained as follows (p. 362): ‘It seems that consumption  $G$  yielded from the salary is constraining the leisure time formed by the normal leisure ( $L$ ) and the travel time in mode  $i$  which is also counting as leisure in this scenario. A person will not be able to consume while traveling if the income is not enough.’ This analysis suggests that insufficient income limits the time which an individual can spend in leisure activities during travel, and therefore the VoTT for leisure-equipped vehicle does not change. However, this reason does not fit with the time-use model for leisure-equipped AVs: leisure is performed during travel by construction. Furthermore, the time-use model assumes that leisure is possible ‘for free’: you do not need income or goods in order to engage in leisure. What could be said instead, is – if goods consumption is not bound by the leisure time in the CV case, then the individual does not gain any benefit from having extra leisure time during travel for goods consumption. This corresponds to the non-binding case ( $\theta = 0$ ), for which the equations of VoTT in AV and CV models are the same. (Though, as discussed before, even if equations are the same, the interpretation of terms and hence the values of VoTT differ in both models.)
2. There is an inconsequential error in (C A6). The last term should have ‘+’, not ‘–’ in front.

## 2. An extended time-use model and VoTT for automated vehicles

Having outlined the difficulty in comparing the VoTT results of AVs and CVs in the original work, we propose an alternative extended model that permits such a comparison. The key differences between the new and the old model are two: first, the utility of on-board activities is made explicit rather than being part of  $\partial U/(\partial t_i)$ ; second, the utility of on-board activities accounts for the quality of activity-facilitation on board. Both are achieved by including travel time in the objective function also as work or leisure time:  $U(G, L, W + \beta t_i, t_i)$  and  $U(G, L + \zeta t_i, W, t_i)$  for work- and leisure-equipped AVs, respectively.<sup>4</sup> The parameters  $\beta, \zeta \in [0, 1]$  represent the facilitation levels of activities in AV: the share of the work- or leisure-utility that the traveller gains while performing activities during travel.<sup>5</sup> Note that in practice this facilitation level is determined by the vehicle and by the activities that the traveller performs on board: reading a book would likely be associated with a much higher  $\zeta$  than doing sports.

The time-use model for work-equipped vehicles becomes as follows (bold parts highlight the differences with the models in the original paper):

$$\text{Max}U(G, L, W + \beta t_i, t_i), \quad (4)$$

subject to:

$$G + c_i = wW + \gamma w t_i, \quad (5)$$

$$L + W + t_i = \tau, \quad (\text{C } 11)$$

$$L \geq \alpha G. \quad (\text{C } 12)$$

In addition to the notation presented earlier,  $c_i$  are travel costs and  $\tau$  is the total available time. Parameter  $\gamma \in [0, 1]$  specifies the salary-share obtained from work during travel. The salary could be lower during travel than at the work place, if, for example, per-piece work of an individual is slowed down due to any disturbances during travel.

Similarly, the time-use model for leisure-equipped vehicles is as follows:

$$\text{Max}U(G, L + \zeta t_i, W, t_i), \quad (6)$$

subject to:

<sup>3</sup> To highlight that  $\partial U/\partial t_i$  differs in these vehicles, we could replace the term  $t_i$  with  $t_i^w$  in (C 13), with  $t_i^l$  in (C 19), and with  $t_i^n$  in (C 8), where indexes  $w, l, n$  would stand for work, leisure, and no-activity, respectively.

<sup>4</sup> The double-counting of travel time in this approach reflects the idea that activities during travel is a type of multitasking (as opposed to the complete experience being regarded as modified travel or modified activities). This classification can be supported by observing that both travel and on-board activities typically require some mental and/or physical resources (Circella et al., 2012).

<sup>5</sup> Taken plainly, utility of  $W + \beta t_i$  would be interpreted as utility obtained while working longer by share  $\beta$  of travel time, while work yields its full utility on board. However, we suggest that utility in such case is equivalent to the utility obtained while working the entire  $t_i$ , but in imperfect conditions represented by  $\beta$ .

$$G + c_i = wW, \quad (C\ 15)$$

$$L + W + t_i = \tau, \quad (C\ 16)$$

$$L + \eta t_i \geq \alpha G. \quad (7)$$

Parameter  $\eta$  corrects the rate, in which the individual can consume the purchased goods during travel. For example, it may take longer to read a book in the car, if the motion of the car interrupts the reading at times. Performing the same steps as [Correia et al. \(2019\)](#) and [Jara-D  az \(2008\)](#), we can derive the VoTT for work- and leisure-equipped vehicles:

$$VOTT_{AV-work} = w(1 - \gamma) + \frac{\frac{\partial U}{\partial W}}{\frac{\partial U}{\partial G} - \alpha\theta}(1 - \beta) - \frac{\frac{\partial U}{\partial t_i}}{\frac{\partial U}{\partial G} - \alpha\theta} \quad (8)$$

and

$$VOTT_{AV-leisure} = \frac{\frac{\partial U}{\partial L}}{\frac{\partial U}{\partial G} - \alpha\theta}(1 - \zeta) + \frac{\theta}{\frac{\partial U}{\partial G} - \alpha\theta}(1 - \eta) - \frac{\frac{\partial U}{\partial t_i}}{\frac{\partial U}{\partial G} - \alpha\theta}. \quad (9)$$

As could be expected, the different facilitation levels are attached to the corresponding terms. Share  $1 - \gamma$  of the salary and share  $1 - \beta$  of the work utility is lost when working in AV as compared to the work place. Share  $1 - \zeta$  of the leisure utility is lost due to it being performed in the AV and not at another (stationary) place; factor  $1 - \eta$  determines the lost value due to potentially lower rate of goods consumption during leisure on board (if the goods consumption is bound by the leisure time:  $\theta > 0$ ). At an extreme, if work or leisure experience during travel is identical to work or leisure experience at their stationary locations  $\beta = \gamma = \zeta = \eta = 1$ , then VoTT is as follows:

$$VOTT_{AV-work} = VOTT_{AV-leisure} = -\frac{\frac{\partial U}{\partial t_i}}{\frac{\partial U}{\partial G} - \alpha\theta}. \quad (10)$$

This is an intuitive result. It expresses that the opportunity costs (the first two terms in (8) and (9)) would be eliminated given an ‘ideal’ AV and only intrinsic costs of travel would enter the VoTT.<sup>6</sup>

Hereby, we have introduced a way to explicitly model the utility obtained from performing activities during travel. Note that much work can still be done to improve the new model. Among the first priorities could be modelling the possibility to engage in both work and leisure activities during travel, as well as accounting for different types of work and leisure activities. The latter would require that parameters  $\beta$ ,  $\gamma$ ,  $\zeta$ ,  $\eta$  are treated as endogenous.

### 3. Conclusions

This note highlights a subtlety, which however has crucial importance, in the interpretation of the theoretical VoTT results for the AV era, as obtained by [Correia et al. \(2019\)](#). This subtlety relates to the fact that one term – the utility of spending time in the vehicle – has different interpretations in the separate models in this paper, which limits the validity of a direct comparison between the derived VoTT for conventional and automated vehicles. In addition, this note reports few other (less crucial) oversights in the derivations and interpretations. Nevertheless, it should be emphasised that the theoretical revisions do not challenge the empirical results of [Correia et al. \(2019\)](#). Rather, the extended model provides more flexibility that could help in understanding these and other empirical results.

The second half of this note presents a new, extended model, which circumvents the interpretation difficulty in the original work. The VoTT results obtained from the new model will likely confirm some intuitions that have been often verbally expressed when discussing the benefits of AVs: future AVs are expected to provide an opportunity to use travel time for various activities and thereby to reduce or even eliminate the opportunity costs of travel. In a nutshell, AVs may ‘give back’ the travel time to the travellers.

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<sup>6</sup> Note that the interpretation of  $\partial U/(\partial t_i)$  differs here from the original work: it represents the intrinsic utility here, but joint utility from spending time in the vehicle in [Correia et al. \(2019\)](#).

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