Towards developing a microeconomic framework for modelling the joint choice of activity-travel behaviour and ICT use

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Abstract

Rapid development of information and communication technologies (ICT) has been argued to affect time use patterns in a variety of ways, consequently influencing travel behaviour. While there exists significant body of empirical studies, the available microeconomic time allocation models in their current forms appear not suitable to capture various aspects resulting from the increasingly digitised society. To address this gap, we present a framework, grounded in time allocation theories and goods-leisure framework, for modelling jointly the choice of mode of activity (traditional versus tele-activity), travel mode and route, and ICT bundle. By providing the expression for conditional indirect utility function, we demonstrate by means of hypothetical scenarios, how our framework can conceptualise various activity-travel decision situations involving choices regarding travel behaviour (mode, route) and ICT. In our scenarios we assume variety of situations including implications of severe weather, autonomous vehicles' introduction, and interaction between multiple decision makers. Moreover, our approach leads to microeconomic foundations for deriving subjective values of ICT qualities such as broadband speed or connection reliability. Finally, we also demonstrate means by which our framework could be linked to various data collection protocols (stated preference exercises, social diaries, laboratory experiments) and modelling approaches (discrete choice modelling, hazard-based duration models).

Keywords

ICT; tele-activities; travel behaviour; microeconomic model; travel time use; productivity

Highlights

- ICT can interact with travel behaviour via emergence of tele-activities.
- Existing time allocation paradigms can accommodate ICT-travel interactions.
- Tele-activity can be considered a special case of travel (communication) mode.
- Choice of an activity depends on the participation experience (intensity).
- Value of ICT qualities can be inferred using existing econometric tools.

1. Introduction

Developments in information and communication technologies (ICT) have brought about the idea that physical presence might not be essential for activity participation since individuals can increasingly undertake various tasks remotely, by means of ICT. This novel capability of remote participation which does not require travel relaxes the long-established spatio-temporal constraints formally defined by Hägerstrand in his concept of 'daily space-time prism' (Hägerstrand, 1970). Such activities, referred to as tele-activities, following the term *telecommuting* coined by John Nilles in 1970s, have received considerable attention from a number of researchers for almost 40 years, especially from the perspective of transport studies (Salomon, 1986; Bailey and Kurland, 2002; Mokhtarian *et al*., 2004; Andreev *et al.*, 2010). Moreover, due to their spatio-temporal flexibility, tele-activities display also higher potential for being undertaken simultaneously with other activities, thus linking to the concept of multitasking (Lyons and Urry, 2005; Kenyon and Lyons, 2007; Pawlak *et al*., 2011).

For the purpose of this paper we find it useful to provide a working definition of tele-activities *as those activities which can be conducted by means of ICT instead of the actual physical travel*. Such activities can range from simple exchange of text messages or voice call, to sophisticated, graphic-rich, immersive technologies of virtual reality. What is common is that in both cases an individual is capable of projecting his or her *tele*-presence by means of ICT medium to a location (physical or virtual) without any travel requirement (Steuer, 1992). As such the location can be company's office, but also the virtual reality of an online shop or offline computer.

Tele-activities have been the focus of considerable interest due to their potential influence on time use patterns, travel behaviour, and hence infrastructural and policy needs (Salomon, 2000; Gann *et al*., 2010). Neglecting the issue may result in the inability of the modelling frameworks to accurately capture and reflect individual time use patterns in the increasingly digitised world. In the past such a claim would be applicable only to highly-skilled and mobile professionals due to the exclusive nature and price of advanced ICT. However, falling costs leading to mass ownership of personal ICT devices such as laptops, smartphones or tablet devices together with the increased availability of mobile and wireless Internet have made the issue relevant in the context of ever-growing share of population. In such a situation, even small changes to individual behaviour, if aggregated over the whole society, can have profound implications for various systems such as transport, health care, or labour market (Golob and Regan, 2001).

While a significant number of studies have explore the field empirically, the existing microeconomic frameworks (on which most of the current understanding of the time allocation, activity scheduling and travel demand modelling rests) appears to have lagged behind, not always appropriately capturing the effects of rapid development of ICT. It is the purpose of this study to attempt addressing this gap. In section 2 we present a brief review of the studies highlighting the existing discourse on understanding the relationships between ICT and travel behaviour. Subsequently, in section 3 we develop a microeconomic framework for the joint choice of activities, travel mode, route and timing, as well as ICT use. Following that we introduce five scenarios in section 4 which demonstrate how the framework would be able to conceptualise various instances of ICT and travel behaviour interaction that have been observed in the empirical studies elsewhere. As the current paper constitutes a theoretical contribution, section 5 discusses possible ways in which the

framework could be operationalized and linked to the existing econometric tools. The final section provides conclusions and directions for further research.

2. Time use, ICT and tele-activities: a brief review

One of the earliest and most significant conceptual contributions to understanding the relationship between tele-activities (in fact, more widely ICT) and travel can be attributed to Ilan Salomon and Patricia Mokhtarian. Not only have they shed light by defining four possible relationships between ICT and travel, i.e. complementarity, substitution, modification, and neutrality (Salomon, 1986; Mokhtarian, 1990), but also subsequently produced a number of studies investigating the issue empirically (Mokhtarian and Salomon, 1996; Mokhtarian and Salomon 1997; Mokhtarian *et al*., 1998; Mokhtarian and Salomon 2002).

From the perspective of transport planners, it was initially tempting to assume that the arrival of ICT would emerge as the ultimate solution to traffic problems as people would continue to switch towards various tele-activities (i.e. substitution effects), trying to avoid the hassle of costly travel. This belief resulted from early studies based on careless generalisations and frequently untested hypotheses as noted by Salomon (1986). However, the reality proved more complex and Mokhtarian (2009) noted twelve possible reasons why simple ICT-travel substitution was not the only observed consequence. This has been confirmed in numerous studies reporting whole range of different effects, depending on the activity, context as well as ways in which ICT use, tele-activity participation, and travel behaviour were used and defined (see review by Andreev *et al.*, 2010). For instance, from an aggregate perspective of large-scale studies in Hong Kong (Wang and Law, 2007) and in the US (Choo and Mokhtarian, 2007), dominance of complementarity effects was suggested while the results of Konduri and Pendyala indicated prevalence of substitution (Konduri and Pendyala, 2011). However, in both cases authors noted simultaneous interplay of substitution *and* complementarity effects later re-confirmed in a cross-national study by Pawlak *et al.* (2014).

Other empirical studies in the field tended to be of a more disaggregate nature and dealing with specific instances of tele-activities such as tele-commuting, tele-conferencing, tele-shopping, tele-leisure, or tele-services. Those studies have considerably increased the understanding of people's motivation for participating in tele-activities (e.g. Mokhtarian and Salomon, 1997), their frequency (e.g. Singh *et al*., 2013), contextual factors (e.g. Lu and Peeta, 2009), impact on the co-operation between employees (e.g. Fiol and O'Connor, 2005), or the role of household obligations (e.g. Bailey and Kurland, 2002).

Another aspect linked to the growing proliferation of ICT and the consequent emergence of tele-activities is facilitation of simultaneous time use, otherwise referred to as multitasking, simultaneous activities, secondary activities, overlapping activities, time-sharing activities or polychronicity (Mokhtarian *et al*., 2006; Kenyon, 2010). Essentially describing the same phenomenon, the concepts refer to situations when multiple activities are undertaken *at the same time*. Since tele-activities are by definition more independent from particular physical locations, their emergence have expanded the activity choice sets individuals are facing (Mokhtarian *et al*., 2006). This process enabled participation in *combinations* of activities that might have been previously infeasible, e.g. tele-conferencing while travelling on a train or doing shopping while waiting for a bus. While the phenomenon of multitasking is firmly grounded in the existing time use studies (Hedges, 1974; Harvey, 1993; Frazis and Stewart, 2007; Kenyon, 2008), in the context of in-travel time use it has only quite recently received

renewed attention (the first treatment of the issue dates back to the study of business travellers by Hensher in 1977) due to its likely impact on the travel experience and possibly valuation of travel time savings (Salomon and Mokhtarian, 1998; Mokhtarian and Salomon, 2001; Redmond and Mokhtarian, 2001; Ettema and Verschuren, 2007). Such substantial research effort backed by empirical evidence and likely profound implications for transport investment appraisal (Pawlak *et al*., 2011) motivated inclusion of the in-travel time use possibility in the course of developing our framework.

An important aspect of the choice between participating in a tele-activity is the experience of participation, also referred to as *quality of participation* as compared to an equivalent physical-reality-based activity. The concept encompasses a number of aspects that define the experience and outcome of activity participation. For instance, in case of work one of the most important aspects would be that of productivity. In this case some empirical results supported the claim that ICT enable effective (productive) tele-work through easier reconciliation with non-work duties and making efficient use of peak productivity periods, more focused task handling (no disruptions from co-workers) and higher job satisfaction, though at a risk of blurring of the boundaries between work and non-work life, social isolation and lack of interaction with peers, lesser control over the employee and lower opportunities for promotion (Hill *et al*., 1998; Butler *et al*., 2007; Golden, 2012). On the other hand, in an extensive review Bailey and Kurland (2002) found no strong support for the productivity gains from tele-work practices though these results varied between studies conducted in different contexts (Hill et al., 1998; Westfall, 2004; Neufeld and Fang, 2005; Butler *et al.*, 2007). Additionally, a number of studies indicated that ICT lead to increase in workers' productivity also in traditional office setting through facilitation of multitasking or development of knowledge networks (Brynjolfsson and Hitt, 2003; Westfall, 2004; Aral *et al*., 2006; Grimes *et al.,* 2012). In a direct comparison of tele-work and in-office work, Dutcher (2012) found that the efficiency of participation (productivity) in the former is higher for tasks requiring creativity, while lower for dull and repetitive ones (Dutcher, 2012).

In the case of tele-conferencing, the increasing capabilities of ICT improving the quality of virtual meetings brought in the possibility of day-to-day co-operation within geographically distributed 'virtual teams' though empirical results suggested their lower efficiency, e.g. due to no response to digital messages, as compared to collocated teams (Bailey *et al*., 2011). Moreover, Lu and Peeta (2009) noted that physical participation may be essential for sensitive meetings (e.g. involving negotiations) as this frequently involves non-verbal factors and may be perceived as demonstration of respect. These aspects have to date not been achievable by means of tele-activities, i.e. the 'medium is not rich enough for the content' (Douglas *et al.*, 2013). In the context of social contacts, the emergence of the question of whether the quality of meeting someone in virtual reality is comparable to face-to-face meeting may also depend on the relationship between people, purpose of the meeting, built environment and frequency of contact which means a fairly complex interplay of factors, some of which may be difficult to observe or quantify such as the need to for 'face-to-face interaction to maintain […] socio-psychological environment' (Smoreda and Thomas, 2001: 11).

The picture emerging from the brief account of the existing discourses suggests complex pattern of interactions between the use of ICT and the joint activity-travel choices (for a more extensive review of empirical studies, see Salomon, 1986; Golob and Regan, 2001; Bailey and Kurland, 2002; Andreev *et al.*, 2010). In all cases the evidence points out towards a

conclusion that the choice between tele-activity and traditional physical-reality-based is usually *not* motivated purely by travel conditions, but may also be influenced by the quality of participation in the desired activities as well as possibility of making use of travel time, especially during longer journeys in productivity-enhancing surroundings. Consequently, our framework seeks to incorporate such effects for better understanding of joint choice decisions faced by individuals and thus contribute towards better understanding of the empirical results reported elsewhere. In doing so, the model is developed so as to provide parsimonious and tractable explanation based on basic principles of microeconomics, yet with preserving the effects discussed in the literature presented above.

3. Modelling framework

There exists a number of microeconomic models dealing with the issue of how people allocate their time, including Becker's model and subsequent modifications by De Serpa, Evans, Small, and culminating in the most recent and general formulation by Jara-Díaz (Becker, 1965; De Serpa, 1971; Evans; 1972; Small; 1982; Jara-Díaz, 2003), Tobit model by Yamamoto and Kitamura (1999), network models by Nagurney *et al*. (2002) or model of time allocation to physical versus virtual activities (Hui and Lei, 2008). Nonetheless, to the best of our knowledge the existing frameworks in their current forms do not simultaneously encapsulate the effects discussed above which appear crucial to fully understand the impacts of ICT and tele-activities on travel behaviour.

In order to address what seems to be a gap in the microeconomic treatment of the presence of tele-activities, we decided to make use of the Winston's model of time-specific analysis of household activities, itself drawing on Becker's household production theory (Becker, 1965; Winston, 1982). In the past, simplified versions of this model were employed in the contexts of modelling activity scheduling and road pricing (Polak and Jones, 1994; Ashiru *et al.*, 2003; Ettema *et al.*, 2007). The main advantages of Winston's framework over the traditional time-allocation models (see Jara-Diaz, 2007 for a summary) lie in its explicit treatment of the quality of participating in an activity *at each particular instant* as well as endogenous treatment of timing (scheduling) decisions. These features appear particularly relevant in the light of apparently relaxed timing and spatial constraints governing activity-travel behaviour as well as rich body of research concerning modelling the impact of time of day (circadian rhythm) on productivity, performance, vigour, and alertness (Spencer, 1987; Wood and Magnello, 1992; Folklard and Tucker, 2003; Klerman and Hilaire, 2007; Van Dongen and Dinges, 2007; Bryson and Forth, 2007; Dawson *et al.*, 2011).

In his model Winston made use of Gary Becker's concept of household commodity which is produced using inputs and consumed to yield certain utility such as eating breakfast (commodity) requires milk and cereals as inputs (Becker, 1965). In Winston's framework, the inputs x are assumed to be time-specific flows used to generate intensity of activity participation z, itself time-specific to reflect the preference for certain activities, such as eating a breakfast in the morning. This intensity, in turn, determines the instantaneous flow of utility u at each moment of a day. Thus utility that individual derives from participating in an activity 1 between times t_0 and t_1 is:

$$U = \int_{t_o}^{t_1} u(z(x(t), t))\, dt \qquad (1)$$

This integrated utility is in fact coincidental with the utility derived from activity participation used in the traditional time allocation models. Moreover, (1) can be extended to multiple activities during a reference period, e.g. a day or a week. For instance, in the case of a two-activity period bounded between times t_0 and t_3, where the second activity, from t_1 to t_2, is assumed to be paid work length of which an individual is assumed to choose freely and which itself is *not* a direct source of utility, a rational (in economic sense) individual will choose the timings of start and end of work, t_1 and t_2 respectively, to maximise their total utility U:

$$U = \int_{t_o}^{t_1} u_1(z_1(x_1(t)))\,dt + \int_{t_2}^{t_3} u_2(z_2(x_2(t)))\,dt \tag{2}$$

subject to resource (budget) constraint:

$$\int_{t_o}^{t_1} \bar{p}_1 x_1(t)\,dt + \int_{t_2}^{t_3} \bar{p}_2 x_2(t)\,dt = \int_{t_1}^{t_2} w\,dt + E \tag{3}$$

where p_1, p_2 are price vectors, w is a wage rate and E denotes any additional, unearned income. Note that (2) assumes that no utility is derived from work (between time t_1 and t_2), its intensity is effectively time-invariant, and hence time allocation decisions are based more strongly influenced by intensities of non-work activities. It is worth emphasizing that the integral formulation of the problem, effectively assuming unit of time equivalent to the unit of labour includes the time constraint implicitly:

$$L = L_h + L_w = (t_1 - t_0) + (t_2 - t_1) + (t_3 - t_2) = t_3 - t_0 \tag{4}$$

where L is total number of (labour hours) individual can allocate split between L_h, labour allocated to household activities (leisure/discretionary) and L_w, labour allocated to work (implicitly assuming constant productivity). Winston demonstrated that following the Lagrangian method of optimisation and principles of dynamic programming, it is possible to define a rule for activity choice which is to choose an activity k which at a particular instance maximises so-called *net value of time* μ_k defined as:

$$\mu_k(t) = u_k(t) - \lambda \bar{p}_k x_k(t) \tag{5}$$

where λ is the Lagrange multiplier associated with income constraint (3). In principle (5) is the 'rate of flow of utility yielded (at time t) by a moment of doing the activity less the reduction of utility over the rest of the consumption period consequent on its using up x consumption goods' (Winston, 1982: 184). Effectively, expression (5) is a Hamiltonian for the dynamic programming problem expressed by the above utility maximisation problem.

While Winston's formulation enables quite detailed treatment of the time allocation problem, we note that this advantage can be troublesome at the same time since the dynamic programming formulation makes it very difficult, if at all possible, to produce analytically tractable or econometrically estimable solutions. Additionally, Winston's extension accounting for the adjustment costs of switching between activities is potentially insufficient to deal with the problem of choice between a tele-activity and a physical activity (and mode of travel in that context) since it only accounts for the monetary cost of adjustment, and not any time requirements and travel-associated utilities, including in-travel activities. Finally, the assumption of time-invariable intensity of work seems implausible in the light of the

aforementioned studies on temporal variations in performance measures which can lead to biased understanding of scheduling decisions, e.g. in case of flexible tele-work participation.

In this paper, we present a framework for joint modelling of choice made by a rational (in economic sense) individual regarding participation in a traditional, physical-reality based activity requiring travel versus tele-activity participation, and the choices of travel and route, bundle of ICT, and the activities undertaken during travel. In our model, we account for the possibility of the different intensities of activity participation. These intensities are made dependent on whether activity is physical or virtual, and in case of in-travel activities, on the mode and route of travel which acknowledges the possible (in)compatibilities between activities and travel conditions such as experienced when cycling on a rainy day and travelling in 1st class compartment on a train. In doing so, we attempt to make the framework flexible enough to encompass various possibilities faced by individuals as discussed in section 4.

Consequently, our model is focused on activity choice and time allocation decisions, and constitutes a fusion of Winston's framework (Winston, 1982), more traditional time allocation theories, and Train and McFadden's goods-leisure framework (Train an McFadden, 1978), augmented with concepts borrowed from labour economics and ergonomics (work intensity and productivity), technological studies (impact of ICT on various activities) as well as biology and occupational medicine (circardian rythm).

Conceptually, let there exists an individual who seeks to maximise their utility derived during a reference period delimited by arbitrarily defined start and end times, t_0 and t_E respectively (see Figure 1). During that period an individual participates in two main activities, *A* and *B*. If *A* and *B* are performed at different locations and individual's physical presence is required, travel takes place starting at time t_1 (which is also end time for the activity A) and finishing at time $t_1+r_{ij}(t_1)$ where r_{ij} is the journey duration depending on the chosen transport mode *i*, route *j* and time of departure t_1. Such formulation enables capturing the impact of modal and route (network) characteristics as varying by time of day. Moreover, during the journey the individual may engage in travel activities *T1* and *T2*, switching between them at time t_t (while in the current formulation only two activities are assumed for tractability, there is no loss of

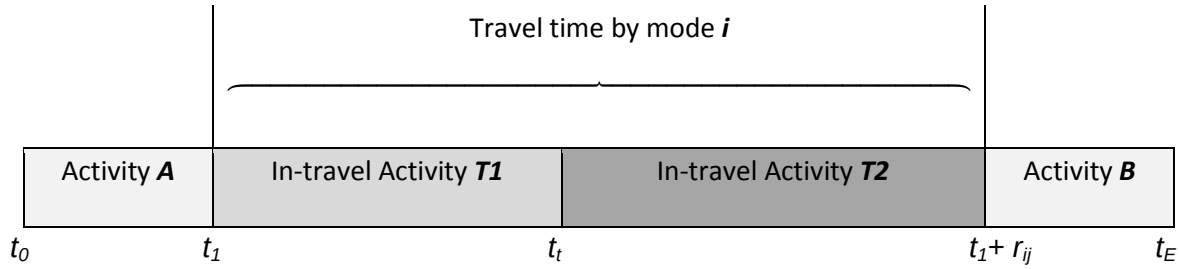


Figure 1 In-travel time allocation between activities – a conceptual representation

generality in the formulation as additional activities could be incorporated without altering the results as demonstrated later and in the appendix). Following the journey, individual engages in activity *B* from time $t_1+r_{ij}(t_1)$ to t_E. Interestingly, if activity *B* is chosen to be tele-activity *which does not require physical* travel, $r_{ij}(t_1)$ reduces to zero. Hence conceptually, tele-activity participation can be interpreted as a special case of transport (communication), or mode of activity conduct (similar conceptual interpretation was provided by Mokhtarian and Meenakshisundaram, 1999). Naturally, the quality of participation in tele-version of activity *B*

will most likely differ from the physical version as argued in section 2, which is captured by in the model by different activity intensities as discussed below. Moreover, the reference period delimiters t_0 and t_E, while assumed arbitrarily may in fact represent exogenously defined constraints, e.g. institutional. For instance, t_0 can be interpreted as the limiting case of the earliest departure time (or end time of activity *A*) defined by the time of a first train on schedule. At the same time t_E represents the latest possible arrival time, e.g. for a spectacle, or defined by workplace regulations. As such, the conceptual framework presented in Figure 1 is flexible enough to represent various situations, e.g. home-based leisure followed by a choice between traditional commuting trip or tele-commuting, or meeting with a customer followed by journey back to the office, or decision on a mode of interaction made by multiple individuals which will be demonstrated in section 4.

Participation in the activities would yield the respective instantaneous utilities (i.e. u_A for activity *A*, etc.) which integrated over the respective periods of participation yield aggregate utility of participation (i.e. U_A for *A*). These aggregate utilities are similar to those used in time allocation models originating in Becker's work, and thus the current formulation can be considered a specific formulation nested within the time allocation theory.

Following Winston's conceptualisation, the instantaneous utilities depend on activity-specific intensities *z*. These intensities could, on the other hand, depend on time of day *t* to reflect the natural preferences for certain timings of activities resulting from, e.g. circadian rhythm, ICT equipment possessed Ψ, conditions in which activity is performed (crowding, noise), companionship, previous activities, or attitude and subjective well-being among others. Additionally, as previously mentioned the intensities of in-travel activities are made dependent on the chosen mode of transport *i* and route *j* reflecting the compatibility of undertaking those activities with the prevailing journey conditions, e.g. impossibility to use laptop while cycling, or ease of use of a mobile phone on an empty versus congested route.

We propose to assume the intensities of activities *z* as non-negative with zero denoting a case where all effort is proving useless. In case of work activity, the intensity could under such assumptions serve as a proxy for productivity. We argue that such an interpretation provides a better intuition for the otherwise relatively intangible concept. Moreover, there is no restriction regarding the relationship between intensity (productivity) *z* and instantaneous utility. Thus a laptop-equipped individual on a quiet carriage with a table and coffee could experience higher work intensity that could also be enjoyable if such conditions constitute their *creative milieu* (Kellog, 1986). On the other hand, a bustling office with an inefficient computer but a significant workload may mean high intensity that is, however, not enjoyable. In fact, such perception of travel time as a period free from office- or home-duties, possibly useful for creative thinking as opposed to dealing with office routine has been one of the findings reported in the literature (e.g. Sipress, 1999; Watts and Urry, 2008). As such, it appears as essential component for inclusion in the framework, especially in order to understand the role of ICT in medium- and long-haul trips. Similarly, in the context of leisure activities, availability of music player can be a good example of the impact on the intensity and experience (Bull, 2000). In the case of tele-conferencing, it is the the quality, graphical richness and capability to communicate the required content, both verbal and non-verbal, which may be the determinants of activity intensity (Douglas *et al.*, 2013). In short, the concept of activity intensity is a useful construct allowing to capture different experiences obtained from participating in particular (tele-)activities.

Table 1. Notation used in the maximisation problem

Variable	Meaning	Notes
A	Pre-journey activity, e.g. leisure, meeting	Discrete decision variable
B	Post-journey activity, e.g. work, tele-work	Discrete decision variable
b	Marginal utility of goods' consumption	Assumed constant
c_{ij}	Total cost of travel by mode i on route j	Expressed in real terms
c_β	Cost of a particular quality β characterising a discrete decision variable	Expressed in real terms
c_ψ	Total cost of an ICT bundle	Expressed in real terms
E	Exogenous monetary transfers from and to the reference period	Expressed in real terms, may express expenditures made from a fixed salary
i	Mode of travel chosen, e.g. car, public transport, but also includes tele-activity mode	Discrete decision variable
j	Route of travel chosen	Discrete decision variable
M_A, M_B, M_{T1}, M_{T2}, M_T	Total contribution to the utility derived from participating in a particular activity, consisting of direct satisfaction from participation and contribution to consumption-derived utility	Defined as integral over the whole period of activity duration (see equation 11)
r_{ij}	Duration of travel on mode i and route j	Depends on time of day. Collapses to zero for tele-activity.
t	Variable describing time	
t_0	Beginning of the reference period	
t_1	End time for activity A, also departure time or commencement time if B is a tele-activity	
t_1*	Optimal value for departure time t_1	Derived from the first order conditions
$T1,T2$	In-travel activities, e.g. eating, document typing	
t_E	End of the reference period	
t_t	Switching time of in-travel activities	
t_t*	Optimal switching time t_t from in-travel activity T1 to T2	Derived from the first order conditions
U	Total utility derived by individual in the reference period t_0 - t_E	
u_A, u_B, u_{T1}, u_{T2}	Instantaneous utility derived from participating in a particular activity A, B, $T1$, or $T2$	Depends on intensity of activity z and consumption level x which are assumed to be separable.
u_T	Instantaneous utility derived from the sole act of travelling (not in-travel activities)	Depends on the intensity of travelling z_{ij}
$u(x)$	Instantaneous utility component describing the utility obtained from being at a consumption level x	Approximated by a linear function with the constant marginal utility of consumption b, assumed equal for all activities
U_A, U_B, U_{T1},U_{T2}, U_T	Total utility derived from participating in a particular activity	Defined as integral of the instantaneous variables over the whole period of activity duration (see equation 6)

$V_{A,B,T1,T2,i,j,\psi}$	Conditional truncated utility function characterising the joint choice of pre- and in- and post-travel activities (*A*,*T1* ,*T2*,and *B* respectively) as well as mode *i*, route *j,* and ICT bundle Ψ	Conditional on the optimal values t_1^* and t_t^*
w_A, w_B, w_{T1}, w_{T2}	Long run wage rates associated with participating in particular activities	Equal to zero for leisure activities
x	Variable describing a general level of goods consumption experienced by individuals reflecting the general material prosperity of an individual	Equal for all activities
z_A, z_B	Instantaneous intensity of participation in pre- and post-journey activities A and B respectively, assumed to reflect output-related productivity (for work activities)	Depend on activity, time *t* and ICT bundle
z_{T1ij}, z_{T2ij}	Instantaneous intensity of participation in in-travel activities, assumed to reflect productivity	Depend on mode *i* and route *j* chosen
z_{Tij}	Variable describing the intensity (e.g. speed, comfort) of travelling on mode *i* and route *j*	Depend on mode *i* and route *j* chosen
β	A generic variable describing particular quality of a discrete decision variable, e.g. mobile Internet's (part of Ψ bundle) bandwidth or route's *j* congestion	Assumed continuous
Ψ	Bundle of ICT chosen by individuals, e.g. laptop and smartphone characterised by specific qualities β_Ψ	Discrete decision variable

The dependence on goods in the framework is made via variable *x* which, unlike in Winston's mode, is assumed to describe a general consumption level for all activities. Furthermore, the consumption variable is assumed to enter the utility function directly, i.e. not via intensity variable. We argue that such formulation simplifies the formulation while still retaining the important dependence of the utility of activity participation on consumption of goods.

Finally, the inherent (dis)utility associated with travelling itself, reflecting (dis)liking of travel in the sense described by Ory and Mokhtarian (2005), is captured by the term U_T. This effect depends on the mode- and route-specific intensity denoted by z_{Tij}. For instance, a speed-loving person on a fast joyride in a nice surrounding may find the act of travelling itself enjoyable while a motion-sickness-stricken person would most likely not.

The formalised problem (see table 1 for notation) is thus to choose appropriate timings and consumption level (continuous) as well as activities, consumption levels, and ICT bundle (discrete) to maximise the utility derived from the whole reference period:

$$\max_{\substack{t_1,t_t,x,\\ A,B,T1,T2,i,j,\psi}} U = \underbrace{\int_{t_o}^{t_1} u_A(z_A(t,\psi),x)\,dt}_{U_A} + \underbrace{\int_{t_1}^{t_t} u_{T1}(z_{T1ij}(t,\psi),x)\,dt}_{U_{T1}} +$$

$$+ \underbrace{\int_{t_t}^{t_1+r_{ij}(t_1)} u_{T2}(z_{T2ij}(t,\psi),x)\,dt}_{U_{T1}} + \underbrace{\int_{t_1}^{t_1+r_{ij}(t_1)} u_T(z_{Tij}(t))\,dt}_{U_T}$$

$$+ \underbrace{\int_{t_1+r_{ij}(t_1)}^{t_E} u_B(z_B(t,\psi),x)dt}_{U_B}$$

(6)

subject to a budget constraint:

$$\int_{t_o}^{t_1} x\,dt + \int_{t_1}^{t_t} x\,dt + \int_{t_t}^{t_1+r_{ij}(t_1)} x\,dt +$$

$$+\int_{t_o}^{t_1} x\,dt + c_\psi + c_{ij}\big(r_{ij}(t_1)\big) = w_A \int_{t_o}^{t_1} z_A\,dt + w_{T1}\int_{t_1}^{t_t} z_{T1ij}\,dt +$$

$$+w_{T2}\int_{t_t}^{t_1+r_{ij}(t_1)} z_{T2ij}\,dt + w_B \int_{t_1+r_{ij}(t_1)}^{t_E} z_B\,dt + E$$

(7)

While time constraint is included implicitly in (6), the need for a separate constraint (7) results from the fact that without it individual could increase their utility indefinitely by choosing higher consumption level, more comfortable and costly mode, or using more sophisticated and costly ICT, all of which is in reality bounded by financial constraints. Furthermore, as previously mentioned, we assume that the intensity *z* which the activity represents in case of work activities a proxy for the productivity of an individual, and that productive output is paid for according to activity-specific wage (non-zero for work-related activities, zero for leisure). Such interpretation of *z* is similar in nature to time-of-day-specific (e.g. hourly) productivity or efficiency measures used in the engineering, economics, ergonomics, safety analysis or occupational medicine literature, especially in the context of investigating diurnal variations in performance, alertness, fatigue or cognitive abilities (Spencer, 1987; Folklard and Tucker, 2003; Nicholls *et al.*, 2004; Bryson and Forth, 2007; Dawson *et al.*, 2011). Furthermore, such interpretation enables investigation of the relationship between productivity and timing and duration of work, an issue of interest for labour economists dealing with flexible work arrangements (Golden, 2012). The flow of goods *x* is priced at price level *p* though to ease the notation, let *p* be assumed *price index* for consumption equal to unity so that c_ψ expresses relative cost of ICT and wages reflect *real* wages. Additionally, c_{ij} denote cost of travel on mode *i* and route *j,* and any external, unearned during the travel income *E*, both in real terms. The latter is included to reflect the possibility of using money earned elsewhere, e.g. during office work, which can also include be the case of a worker with fixed salary.

By including ICT bundle level as a decision variable, the framework enables what Golob and Regan indicated to be a gap in research, i.e. joint modelling of the activity choice and level of ICT use by an individual, comparing that to the case of car ownership decision and activity participation (Golob and Regan, 2001). The impact of ICT on the intensities can be seen as influencing the experience of participation, and in some case, enabling certain tasks. In the context of tele-work, ICT could serve as enablers of remote communication without which the intensity (productivity) would be so low that activities would be undesirable or infeasible. Similarly, in the context of traditional office setting, Internet-linked computer would enable easier exchange of information as well as communication with the peers and customers, possibly increasing productivity. In case of discretionary (non-work) activities, availability of Internet could make tele-leisure (e.g. gaminig) more attractive by enabling multiplayer games, though distortionary impacts on intensities could also be possible, e.g. disrupting

mobile phone during a dinner. Clearly, the interaction and choice setting will most likely be influenced by further factors such as occupation and task, companionship, time of day, socio-demographics, companionship as well as various skills and physiological capabilities. Nonetheless, the formulation presented in (6) in (7) is flexible enough to incorporate majority of such effects using variables summarised in table 1.

In order to provide analytical solution to the problem a number of simplifying assumptions have to be made which, though debatable, enable adjustments in the existing microeconomic models to reflect the emerging properties of (tele-)activities (see appendix for formal notation and full derivation). Firstly, the instantaneous utilities are assumed to be separable in consumption and intensity. Additionally, the consumption component of the utility function is implicitly assumed equal for all activities, and expressed as a linear function. Both assumptions yield the following result:

$$u_A(x) = u_{T1}(x) = u_{T2}(x) = u_B(x) = bx \tag{8}$$

where *b denotes* constant marginal utility of consumption. While a potentially debatable assumption (implying very flexible substitutability between consumption and other factors, including timing) it is essential in keeping the model tractable and capable of delivering indirect utility function encompassing the resource constraint. This formulation can in fact be perceived as a first-order approximation of the true utility function, traditionally assumed concave (doubling the consumption less than doubles the utility). We claim that for the short time scale problem, such linear approximation can hold as a realistic assumption as in fact similar assumptions have been followed in other models of time allocation and modal choice (Bates, 1987; Jara-Diaz, 2003, 2007). Additionally, the utility of work is assumed to depend on its intensity, though without restrictions on the direction of such impact. Finally, we assume that individuals are aware of their time-specific intensities of participation in an activity, e.g. know when their peak productivity occurs, or when they prefer to engage in leisure/discretionary activities. Since people tend to describe themselves as ‘morning birds’ or ‘night owls’ in terms of activity timing preferences, we claim this assumption is justifiable. A possible extension which is, however, not developed fully in this paper, could frame such uncertainty in terms of randomly distributed intensities, and individuals dealing with expected rather than pre-determined and fixed conditions.

Following the assumptions above, it is possible to use consumption as a pivotal variable and thus reduce the dimensionality of the optimisation problem (see detailed derivation is in the appendix). Defining the optimal switching time between in-travel time activities as t_t*, the first order conditions associated with in-travel time allocation is:

$$u_{T1}(z_{T1ij}(t_t^*)) + bw_{T1}z_{T1ij}(t_t^*) = u_{T2}(z_{T2ij}(t_t^*)) + bw_{T2}z_{T2ij}(t_t^*) \tag{9}$$

The interpretation of this expression is such that in an instant at time t_t* when activity *T1* is switched to activity *T2*, they would both yield the same utility derived from participation with particular time-specific intensities, $u_{T1}(z_{T1ij})$ and $u_{T2}(z_{T2ij})$ respectively, *as well as* from their contribution to utility derived from salaried productivity and ultimately – consumption as denoted by $bw_{T1}z_{T1ij}$ and $bw_{T2}z_{T2ij}$ respectively. This condition applies to both work and non-work activities, i.e. for leisure the respective wage rates w_{T1} and w_{T2} would reduce to zero, and the choice would only depend on the satisfaction derived from participation with particular intensity. If more than two in-travel activities take place, similar conditions would

result from the first order conditions associated with switching time for each two consecutive activities, and hence working with two-activity case provides enough generality.

On the other hand, the first order condition associated with the optimal departure time t_1^* is:

$$\begin{aligned} u_A(z_A(t_1^*)) + bw_A z_A(t_1^*) \\ &= u_B(z_B(t_1^* + r_{ij}\big|_{t_1^*})) + bw_B z_B(t_1^* + r_{ij}\big|_{t_1^*}) \\ &+ u_{T1}(z_{T1ij}(t_1^*)) + bw_{T1} z_{T1ij}(t_1^*) \\ &- u_{T2}(z_{T2ij}(t_1^* + r_{ij}\big|_{t_1^*})) - bw_{T2} z_{T2ij}(t_1^* + r_{ij}\big|_{t_1^*}) + u_T(z_{Tij}(t_1^*)) \\ &- u_T(z_{Tij}(t_1^* + r_{ij}\big|_{t_1^*})) \\ &+ \left(\frac{dr_{ij}}{dt_1}\Big|_{t_1^*}\right)\Bigg[u_B(z_B(t_1^* + r_{ij}\big|_{t_1^*})) + bw_B z_B(t_1^* + r_{ij}\big|_{t_1^*}) \\ &- u_{T2}(z_{T2ij}(t_1^* + r_{ij}\big|_{t_1^*})) - bw_{T2} z_{T2ij}(t_1^* + r_{ij}\big|_{t_1^*}) \\ &- u_T(z_{Tij}(t_1^* + r_{ij}\big|_{t_1^*})) - b\frac{dc_{ij}}{dr_{ij}}\frac{dr_{ij}}{dt_1}\Big|_{t_1^*}\Bigg] = 0 \end{aligned}$$

(10)

Where t_1^* is optima departure time satisfying the condition (10). For the purpose of clarity, let us first consider a situation where change in departure time *does not* influence travel duration, e.g. commuter train without operating in accordance with the schedule. Under such conditions, the term $\frac{dr_{ij}}{dt_1}\Big|_{t_1^*}$ reduces to null. Thus the overall utility derived from change in departure time and hence infinitesimal change in duration of activity *A* (from both satisfaction and consumption contribution) will be exactly equal to a corresponding infinitesimal change in activity *B* together with changes in utilities induced by changed timing of in-travel activities and travel itself. To provide an example, let us consider an individual departing at 9.05 AM instead of 9.00 AM and hence arriving at the destination at 10:05 AM instead of 10:00 AM (assume that 5 minutes approximates an infinitesimal change). Condition (10) states that that this individual must derive higher utility from participating in activity *A* during those 5 minutes than would have derived from activity *B* from time 10:00 AM to 10:05 AM together with any changes in in-travel activities (e.g. checking e-mail at 9:06 instead of 9:01, finishing coffee at 10:05 and not 10:00) as well as changes in travel conditions, e.g. weather or crowding. It is worth noting, that in case of tele-activities where, by the definition of tele-activity travel duration r_{ij} is fixed at null and no in-travel activities take place, (10) reduces to similar condition as (9). In other words, a minute longer participation in activity *A* is associated with the minute-long opportunity cost (change in utility) associated with *not* participating in tele-activity *B* at the same time.

In reality, however, change in the departure time usually *does* influence travel duration, i.e. $\frac{dr_{ij}}{dt_1}\Big|_{t_1^*} \neq 0$, e.g. due to changing circumstances on the network resulting from variable traffic congestion or weather conditions. In such a situation, depending on the direction of change of r_{ij}, effects resulting from shorter (longer) duration of post-travel activity *B* discounted by

longer (shorter) participation in the final in-travel activity as well travel itself would have to be taken into account (t_t could also change as a consequence of departure depending on how in-travel intensity depends on time). Furthermore, as travel time in certain contexts (modes, routes) may not always be completely predictable, r_{ij} could be framed as a random variable (with the degree of uncertainty perhaps reduced by increased use of ICT thanks to access to real-time travel information). Additional aversion to uncertainty could, on the other hand, enter the model via inherent travel utility term $u(z_{Tij})$.

Using conditions (9) and (10) it is possible to derive the expression for truncated utility function for the joint choice of activities pre- and in- and post-travel activities, as well as mode *i*, route *j,* and ICT bundle Ψ, conditional on the optimal timings t_t^* and t_1^*:

$$
\begin{aligned}
V_{A,B,T1,T2,i,j,\psi}\big|_{t_1^*.t_t^*} &= \underbrace{\int_{t_o}^{t_1^*} (u_A(z_A) + bw_A z_A)\, dt}_{M_A} + \underbrace{\int_{t_1^*}^{t_t^*} \left(u_{T1}(z_{T1ij}) + bw_{T1} z_{T1ij}\right) dt}_{M_{T1}} \\
&+ \underbrace{\int_{t_t^*}^{t_1^*+r_{ij}(t_1^*)} \left(u_{T2}(z_{T2ij}) + bw_{T2} z_{T2ij}\right) dt}_{M_{T2}} + \underbrace{\int_{t_1^*}^{t_1^*+r_{ij}(t_1^*)} u_T(z_{Tij})\, dt}_{M_T} \\
&+ \underbrace{\int_{t_1^*+r_{ij}(t_1^*)}^{t_E} (u_B(z_B) dt + bw_B z_B)\, dt}_{M_B} - bc_\psi - bc_{ij}\left(r_{ij}(t_1^*)\right)
\end{aligned}
\tag{11}
$$

where *M*-terms denote total gains in the utilities obtained from particular activities (both due to time-specific intensity as well as contribution to consumption) in the reference period. Expression (11) provides a microeconomics-grounded interpretation for systematic component of the utility function in a discrete choice model of an individual facing a choice situation described in Figure 1 in a similar manner to the existing interpretation of the systematic component of associated with mode of transport choice (Train an McFadden, 1978; Hensher and Truong, 1985; Bates, 1987). In such formalisation, an alternative would be formed from a particular *combination* of pre-, in-, and post-travel activities (*A, T1, T2, B*), mode *i*, route *j*, and ICT bundle Ψ.

The interpretation of (11) follows the intuition that the highest utility-yielding alternative will be that which maximises the sum of aggregate utilities (integrated utilities derived from time-specific intensity and contribution to consumption) of pre-, in-, and-post journey activities less the reduction in consumption due to the opportunity cost of expenditure on using ICT bundle and choosing particular transport mode on a particular route. While conceptually simple, (11) is comprehensive in that it allows incorporating any combination of activities, including tele-activities, and their associated time- and context-specific characteristics (individual experience of participation, productivity, companionship, equipment possession etc.), compatibility of in-travel activities with transport mode and route, or impacts from changes in transport network conditions. Interestingly, (11) allows for the possibility that ICT-caused better travel conditions, including expanded opportunities to make use of travel time or more

reliable travel time prediction caused by developments in transport telematics (themselves relying on ICT) as well as possible impacts of ICT on travel-requiring activities (e.g. office-based work) can *inhibit* the pace of tele-activities proliferation.

These interactions between various components of (11) demonstrate that perceiving the problem of tele-activity choice as simply an efficiency choice problem ('Am I more efficient when working at home or office?'), or 'travel or not-to travel' problem alone may be erroneous as both factors should be considered jointly. This confirms the empirical results by Ndubisi and Kahraman (2005) and is also consistent with the remarks reached by Mokhtarian (2000) warning of perceiving tele-activities in an overly simplistic manner. Additionally, the results emphasise that in a world of tele-activities enabling higher spatial but also temporal flexibility, it appears essential to relate the activity choice and time allocation to the inherent preferences for particular activity timings, among other factors resulting from individual's circadian rhythm. Being a highly individual-specific issue, such timing preferences could offer an opportunity to explain more of individual variations in activity/travel decisions which happen to constitute a large unexplained component of such choice problems (Chikaraishi *et al*., 2009).

Additionally, the indirect utility function (11) provides means of obtaining estimates of the subjective values of qualities of an alternative. Assuming that a particular combination *A, B, T1, T2, i, j, ψ* is characterised by certain quality β and its cost c_β, the subjective value of β is defined as (Jara-Díaz, 2007):

$$SV_\beta = -\frac{\partial c_\beta}{\partial \beta} = -\frac{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial \beta}}{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_\beta}} \tag{12}$$

Equation (12) provides means of attaching values to changes in qualities characterising the chosen alternative such as travel time, seating availability, or broadband speed. For instance, in the case of travel time r_{ij} *reduction* (see appendix for exact derivation; note that there is no minus sign in front of the expression as *reduction* is investigated) the subjective value SV_{rij} in real terms (to convert to monetary terms the expression must be multiplied by the consumption price index *p*):

$$SV_{r_{ij}} = \frac{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial r_{ij}}}{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_{ij}}} = \frac{dc_{ij}}{dr_{ij}} + \frac{-u_{T2}(z_{T2ij}) - u_T(z_{Tij}) + u_B(z_B)dt}{b} - w_{T2}z_{T2ij} + w_B z_B \tag{13}$$

Expression (13) indicates that the value of reduction in travel time consists of the sum of change to direct cost of travel c_{ij} and the value of longer participation in activity *B* less the value due to shorter final in-travel activity *T2* (note that dividing by *b* converts utility into value

in real terms). Consequently, expression (12) follows the similar intuition to that provided by Hensher in his inquiry into valuing the savings of business travel time reduction, which incorporated not only the benefit of longer post-activity participation, but also the cost from reduced in-travel time use with potentially different-to-office productivity (Hensher, 1977). Given that (13) depends on ICT bundle (via intensities/productivities *z*), it provides also a microeconomic justification for inclusion of ICT in the context of travel time savings valuation.

Following similar logic, the subjective value $SV_{\beta\psi}$ of any quality β_ψ characterising the ICT bundle, such as bandwidth, connection reliability and quality, can be expressed in real terms as:

$$SV_{\beta_\psi} = -\frac{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial \beta_\psi}}{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_\psi}} = \frac{1}{b}\left[\int_{t_o}^{t_1^*} \frac{\partial z_A}{\partial \beta_\psi}\left(\frac{du_A}{dz_A} + bw_A\right)dt + \int_{t_1^*}^{t_t^*} \frac{\partial z_{T1}}{\partial \beta_\psi}\left(\frac{du_{T1}}{dz_{T1}} + bw_{T1}\right)dt + \int_{t_t^*}^{t_1^*+r_{ij}(t_1^*)} \frac{\partial z_{T2}}{\partial \beta_\psi}\left(\frac{du_{T2}}{dz_{T2}} + bw_{T2}\right)dt + \int_{t_1^*+r_{ij}(t_1^*)}^{t_E} \frac{\partial z_B}{\partial \beta_\psi}\left(\frac{du_B}{dz_B} + bw_B\right)dt\right] - \frac{dc_\psi}{d\beta_\psi} \quad (14)$$

The meaning of (14) is such that the value of any changes in quality of ICT will result from changes in the impact on the intensity (productivity), and thus utilities and consumption impacts, associated with particular activities, integrated over the periods of activities' duration, net of cost of that quality change. In other words, the value attached to higher processing power of a laptop will come from its impact on the intensity (and thus productivity if activity is salaried) and hence satisfaction and consumption increase, net of change in direct cost of higher processing power. This theoretical result complements the empirical findings of Maliranta and Rouvinen (2006) who noted that ICT possess certain qualities such as storage and processing capabilities or wirelss connectivity that have different impacts on productivity. Using (14) individual's values to such productivity changes could be estimated. Furthermore, (14) enables deriving microeconomic expression for the value of in-travel ICT services, such as on-board Wi-Fi. Assuming that on-board ICT affects only in-travel activities *T1* and *T2*, its value $SV_{\beta\psi WiFi}$ can be defined as (see appendix for derivation):

$$SV_{\beta_{\psi WiFi}} = -\frac{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial \beta_{\psi WiFi}}}{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_{\psi WiFi}}}$$
$$= \frac{1}{b}\left[\int_{t_1^*}^{t_t^*} \frac{\partial z_{T1}}{\partial \beta_{\psi WiFi}}\left(\frac{du_{T1}}{dz_{T1}} + bw_{T1}\right) dt + \int_{t_t^*}^{t_1^*+r_{ij}(t_1^*)} \frac{\partial z_{T2}}{\partial \beta_{\psi WiFi}}\left(\frac{du_{T2}}{dz_{T2}} + bw_{T2}\right) dt\right] - \frac{dc_{\psi WiFi}}{d\beta_{\psi WiFi}}$$

(15)

In other words, the value one attached to on-board Wi-Fi is based on its impact on the satisfaction and productivity experienced in all in-travel activities throughout their duration, less reduction in consumption due to expenditure made on such service. Another important case would be that of a tele-worker. Assuming that the initial activity is non-salaried leisure, i.e. $w_A = 0$, and also by definition travel duration $r_{ij} = 0$ without any in-travel activities, the value $SV_{\beta\psi TLW}$ of ICT quality such as higher broadband speed would be:

$$SV_{\beta_{\psi TLW}} = -\frac{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial \beta_{\psi TLW}}}{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_{\psi TLW}}}$$
$$= \frac{1}{b}\left[\int_{t_o}^{t_1^*} \frac{\partial z_A}{\partial \beta_{\psi TLW}} \frac{du_A}{dz_A} dt + \int_{t_1^*+r_{ij}(t_1^*)}^{t_E} \frac{\partial z_B}{\partial \beta_{\psi TLW}}\left(\frac{du_B}{dz_B} + bw_B\right) dt\right] - \frac{dc_{\psi TLW}}{d\beta_{\psi TLW}}$$

(16)

In other words, the value of broadband for a tele-worker would be reflected in higher utility of the initial activity, e.g. ability to listen to the music online while eating breakfast, and in any changes to satisfaction and productivity of tele-work, again net of any changes to ICT costs. The importance of (15) and (16) is such that that they conceptualise the valuation of ICT bundles in various contexts. While the former can provide a useful guidance for pricing of in-travel ICT services, such as in-train, in-plane or in-coach Wi-Fi using stated preference exercises (as shall be discussed in section 5), the latter expression could prove useful when conducting cost-benefit analyses of ICT provision to employees working under flexible regimes, including tele-workers (Butler *et al.*, 2007).

4. Implications and discussion: possible scenarios

In order to demonstrate applicability of our approach, we develop five hypothetical activity-travel choice scenarios which individuals may face in their everyday lives, and attempt their encapsulation by means of our microeconomic framework. In what can effectively be

perceived as performing thought experiments such as those in theoretical physics we assume certain values of different components of the utility (M_A, M_{T1}, M_{T2}, M_T, M_B, bc_ψ, bc_{ij}) that are associated with choices of particular way activity is conducted, i.e. tele-activity versus travelling by a particular mode *i* on route *j*. For simplicity (yet retaining generality) we assume two in-travel activities only: work and leisure. Furthermore, we also assume that any requirement for additional travel time results in reduction of the pre-journey activity duration, i.e. activity *B* always starts at the same time.

The magnitudes of the components, while arbitrary in their values, are qualitatively justified by the assumptions made in each of the scenarios. These values, when summed up according to (11) lead to choices that are consistent with some empirical results on the relationships between ICT and travel behaviour reported elsewhere. As such, the approach resembles a reversed estimation procedure where the values of specific components would be established *given* the observed choices made from a set of alternatives characterised by specific qualities (see section 5 for discussion on operationalisation of the framework). By following the thought experiment approach, we demonstrate how it is possible to move from the basic principles of microeconomics and certain real-world conditions to specific patterns of ICT use and travel behaviour, including the possibility of complementarity, substitution, modification, and neutrality relationships (Salomon, 1986; Mokhtarian, 1990).

4.1 Scenario 1: Severe weather

In the first scenario an individual needs to perform certain office duties for which physical presence is not critical, e.g. produce a report. The prevailing conditions on the transport network are expected to be poor as a result of severe weather conditions, while the individual's employer has a positive attitude towards occasional tele-work practices. Consequently, the individual is facing the following choices (summarised in Table 2):

- *Tele-activity (tele-commuting):* individual incurs no reduction in the benefit from participating in the initial activity as no travel takes place (hence also null travel cost, and null travel-specific utility). While there is no benefit from in-travel activities, there is extra productivity due to avoided travel fatigue due to difficult conditions. There are, however, extra costs to ICT required for efficient tele-work participation (Butler *et al.*, 2007).
- *Public transport*: individual needs to depart early as travel time is longest, though cost is lower than for a car. Since public transport does not require individual's effort, he or she can engage efficiently in work and leisure while travelling though the experience of travel itself is the lowest due to unpleasant waiting time and high travel time uncertainty in such weather conditions possibly leading to increased fatigue in the final activity. The cost of ICT is lower than for tele-work, though still present due to potential use of on-board ICT facilities.
- *Car (as a driver)*: individual can depart slightly later than in case of public transport, but will not be able to engage in any work-related activities during travel as driving requires full attention (leisure, e.g. listening to music, is still possible though). Travel experience is slightly better to public transport, though still negative due to weather conditions. While travel cost is the highest, there is no associated ICT cost.

Table 2 Scenario 1 choices breakdown

Mode	Component value							V
	M_A	M_{T1} *(work)*	M_{T2} *(leisure)*	M_T	M_B	bc_ψ	bc_{ij}	
Tele-activity	0	0	0	0	2	-1	0	1
Public Transport	-2	2	1	-2	1	-0.5	-0.5	-1
Car	-1	0	1	-1	1	0	-1	-1

Assuming certain values for the components which are consistent with the qualitative description above, Table 2 presents the values for utilities *V* associated with each of the alternatives, calculated using expression (11). Clearly, engaging in tele-activity emerges as the most attractive choice due to effectiveness of work for tele-work substitution while also avoiding potential travel disruptions and fatigue. Such circumstances have been quoted by Mokhtarian (2009: 11) as an example of situation where tele-activity leads to substitution of travel.

In real world context, such conditions were in fact observed following the 2010 Icelandic volcano eruption and the consequent disruptions to air travel when videoconferencing tools emerged as the most efficient backup plan (Reuters, 2010; Brightcom, 2011). Furthermore, similar conditions may emerge as a result of transport infrastructure overload as well as reduced capacity. The former situation was observed during London 2012 Olympics when employers were encouraged to allow people to make use of tele-commuting options as means of reducing pressure on public transport (BBC, 2012; Currie *et al.*, 2014). Similarly, occasional strikes by transport operators reducing transport capacity motivated promotion of tele-commuting as an alternative means of work (e.g. Stanford University, 2013).

4.2 Scenario 2: Sensitive business meeting

In this scenario, an individual is supposed to take part in an important business meeting involving sensitive negotiations. However, since the meeting is of a sensitive nature, there is a stronger preference for face-to-face environment (as in the findings of Lu and Peeta, 2009). Travel conditions (apart from the travel experience M_T which is omitted for simplicity*)* are identical to Scenario 1 in which case individual faces the following choice situation (summarised in Table 3):

- *Tele-activity (tele-conferencing):* individual incurs no reduction in the benefit from participating in the initial activity as no travel takes place (hence also null travel cost, and null travel-specific utility). However, there is a significant loss associated with the fact that such sensitive negotiations are not undertaken in the face-to-face environment.
- *Public transport*: individual needs to depart earlier but is capable of making use of travel time for preparation to the meeting, also making use of ICT (laptop, Wi-Fi). Moreover, there is a high benefit from the post-journey activity, since it takes place in the face-to-face environment.
- *Car (as a driver)*: individual can depart slightly later than in case of public transport, but will not be able to engage in any work-related activities during travel. However, the meeting still takes place in face-to-face environment, so the associated benefit is the same as in case of public transport.

Table 3 Scenario 2 choices breakdown

Mode	Component value	V

	M_A	M_{T1} (work)	M_{T2} (leisure)	M_T	M_B	bc_ψ	bc_{ij}	
Tele-activity	0	0	0	0	-1	-1	0	-2
Public Transport	-2	2	1	0	2	-0.5	-0.5	2
Car	-1	0	1	0	2	0	-1	1

Under such conditions, travel by public transport emerges as the best alternative even though the journey takes more time. The two decisive factors are, however, the poor substitution possibility for tele-activity and the opportunity to spend travel time (in case of public transport) productively which are well-combined in case of choosing public transport. As a result, the situation reflects the possibility of complementarity effect of ICT (note that travel duration is higher for public transport) partially thanks to the possibility of ICT-enhanced productive use of travel time, which coincides with some of the justifications of Mokhtarian regarding why ICT may *not* substitute for travel (Mokhtarian, 2009).

4.3 Scenario 3: Autonomous vehicles introduction

In this scenario, an additional mode of transport is introduced: autonomous vehicle (AV), which is assumed to be capable of completely automatic driving without any human intervention. By this virtue, it effectively combines the benefits of public transport (possibility to undertake in-travel activities) and private car (speed and flexibility of travel, control of the surrounding environment). In this scenario, there is no particular definition of the pre- and post-journey activities and no preference regarding the need for face-to-face versus virtual interaction. Under such circumstances, the individual faces the following choice situation (summarised in Table 3):

- *Tele-activity (tele-conferencing):* similarly to previous scenarios, the main benefit comes from reduced fatigue of the individual incurs reflected in increased M_B while there is also cost associated with ICT expenditure.
- *Public transport*: individual needs to depart earlier but is yet again capable to make use of some travel time for work and leisure purposes. There is additional loss associated with travelling itself due to fatigue, as well as cost of travel and potential on-board ICT use.
- *Car (as a driver)*: individual can depart slightly later than in case of public transport, but is not be able to engage in any work-related activities as its attention to driving is required. The travel experience is better than for public transport, though at a higher cost of travel.
- *Autonomous vehicle*: individual can capitalise on the benefit of being able to depart at time identical to that of conventional car *and* can also use travel time in a manner similar to public transport. Moreover, the utility of leisure are potentially higher as the benefits of not requiring to drive (assuming complete trust in the self-driving capabilities) *and* being in control of the surroundings add up. The cost of using that mode is slightly higher and there is also possibly some additional expenditure associated with in-travel ICT use.

Table 4 Scenario 3 choices breakdown

Mode	**Component value**							*V*
	M_A	M_{T1} (work)	M_{T2} (leisure)	M_T	M_B	bc_ψ	bc_{ij}	
Tele-activity	0	0	0	0	2	-1	0	1
Public Transport	-2	2	1	-1	1	-0.5	-0.5	0

Car	-1	0	1	1	1	0	-1	1
AV	-1	2	2	1	1	-0.5	-2	2.5

Following such scenario, autonomous vehicle appears the most attractive alternative where the benefits of quicker and flexible departure as well as in-travel time use outweigh additional direct costs as well as the opportunity cost of travel time (as compared to tele-activity). The implicit assumption is, however, that full trust can be given to the self-driving capabilities.

4.4 Scenario 4: Autonomous vehicles with some routes incapable of using AV

While autonomous vehicles are argued to be capable of navigating on their own, studies suggest that their use may (at least in the earlier phases) be limited to certain, AV-capable routes characterised by stable conditions of driving, e.g. motorways, as compared to areas with multiple users of frequently unpredictable behaviour (Fagnant and Kockelman, 2014). In the current scenario, there are two routes available to the users of cars and AV. Route 1 leading through city centre is shorter, but due to its congested nature and multi-modal character of users including pedestrians and cyclists, has been declared AV-incompatible and users of such cars are required to drive their vehicles by themselves. Route 2, on the other hand, is a motorway bypass which is longer and takes more time to drive, but is AV-compatible. In this scenario, individual faces the following choice situation:

- *Tele-activity (tele-conferencing):* conditions similar to scenario 3
- *Public transport*: conditions similar to scenario 3
- *Car (as a driver)*:
    - *Route 1:* conditions similar to scenario 3
    - *Route* 2: conditions similar to scenario 3, but since the route is longer there is an additional monetary and opportunity cost due to the need to depart earlier.
- *Autonomous vehicle*:
    - *Route 1*: conditions are the same as faced by conventional car since autonomous driving capabilities cannot be used. Additionally, the cost of AV use is assumed higher to the conventional car.
    - *Route 2*: conditions are similar to the conventional car on route 2 with higher costs of AV use, but this effect is offset by the possibility to make use of travel time in a productive and pleasant way.

Table 5 Scenario 4 choices breakdown

Mode	**Component value**							*V*
	M_A	M_{T1} *(work)*	M_{T2} *(leisure)*	M_T	M_B	bc_ψ	bc_{ij}	
Tele-activity	0	0	0	0	2	-1	0	1
Public Transport	-2	2	1	-1	1	-0.5	-0.5	0
Car: route 1	-1	0	1	1	1	0	-1	1
Car: route 2	-1.5	0	1	1	1	0	-1.5	0
AV: route 1	-1	0	1	1	1	0	-2	1
AV: route 2	-1.5	2	2	1	1	-0.5	-2.5	1.5

Note: route 1 is shorter but AV operation incapable (through city centre), route 2 is AV capable but longer (motorway bypass)

Under such conditions, the use of autonomous vehicle on the longer, AV-compatible route emerges as the most desired alternative. This result is of particular interest as it

demonstrates (within the frames of the proposed framework) that developments in ICT facilitating travel time use as well as autonomous capabilities of private vehicles may in fact lead to modification (different route) as well as consequent generation (complementarity) of travel. While such effects have been hypothesised by some researchers (for discussion see Fagnant and Kockleman, 2014), the actual evidence for the likelihood of such outcome is still to emerge as AVs have not been commercially available yet.

4.5 Scenario 5: Lazy friends

Certain activities, such as meetings, by their very nature require co-participation of other individuals. This requirement leads inevitably to the need for co-ordination of activity choice, timing, and location. In this final scenario, such possibility is framed by means of a simple two-agent strategic game (for introduction to game theory, see Osborne, 2004).

Let us assume two persons, identical in terms of preferences and conditions faced in (11), who seek to meet. Such a meeting is possible either in physical or virtual (tele-conference) reality. The former, face-to-face meeting can take place at either person's place (in which case the other one needs to travel), or in a neutral destination assumed to be half-way between people's locations. Tele-conferencing, on the other hand, does not require any travel but is less preferred to face-to-face meeting. For simplicity, we ignore modal split and assume that people travel by public transport only. Consequently, each person faces the following, symmetrical choice set (Table 6):

- *Travel to neutral destination:* in this case the meeting takes place in the face-to-face environment, but the utility is reduced (for both individuals) by the requirement to travel (partially offset by in-travel activities) and expenditure associated with the transport cost.
- *Travel to other person's location:* in this case the meeting takes place in the face-to-face environment, but the utility is reduced by even more for the individual as it has to travel the whole distance and bear the cost of travel, both monetary and opportunity.
- *Stay, with the other person travelling:* the meeting still takes place but the person does not need to incur any travel-related cost. From that individual's point of view, this outcome is the most desirable.
- *Stay, and engage in tele-conference:* in this case both individuals choose not to travel and engage in tele-conferencing which, though avoiding travel costs does not yield utility as high as that of face-to-face meeting.

Table 6 Scenario 5 choices breakdown

Mode	Component value							*V*
	M_A	M_{T1} *(work)*	M_{T2} *(leisure)*	M_T	M_B	bc_ψ	bc_{ij}	
Travel: neutral destination	-1	0.5	0.5	0	2	0	-1	1
Travel: other's destination	-2	0.5	0.5	0	2	0	-2	-1
Stay: other person travels	0	0	0	0	2	0	0	2
Stay: no one travels, tele-conferencing	0	0	0	0	1	-1	0	0

Note: neutral destination is closer than destination of the other person

In this situation, however, the outcome of the decision does not depend on the individual him/herself only, but also on the decision of the other one. This situation is represented in a form of payoff matrix (Figure 2) which represents the values of utilities for individuals given their own and other person's decision.

		Person 2	
		Travel	**Stay**
Person 1	**Travel**	V_1=3, V_2=3 Meeting in a neutral place	V_1=1, V_2=4 Meeting at Person 2's place
	Stay	V_1=4, V_2=1 Meeting at Person 1's place	V_1=2, V_2=2 Tele-conferencing

Note: shaded cell indicates Nash Equilibrium

Figure 2 Lazy lovers game payoff matrix

It can be seen that travelling to the neutral location would be the most equitable and efficient (from the aggregate point of view) outcome. However, given that person 2 chooses to travel, there is an incentive for person 1 *not* to travel (a symmetric logic applies to person 2's position). However, in this case person 2 would need to travel the whole distance which, given that person 1 now does not want to travel, is less desirable than staying at their own place and engage in tele-conferencing. The latter case is in fact Nash equilibrium situation, as no person is willing to change their decision, given the behaviour of the other person. The situation mirrors the famous Prisoner's Dilemma situation in that lack of co-operation (both people travelling) leads to less efficient outcome (tele-conferencing).

While an example is simple in nature, it provides a clear example of how the relationships between ICT and travel behaviour in the context of interactions between people (household members, members of social networks, employer and employees) could be framed by means of linking the proposed microeconomic framework with methods employed by game theorists. In fact, games similar to those presented in Figure 2 could be extended to allow heterogeneous agents (e.g. by employment status), asymmetric conditions and information (e.g. ICT skills, availability of modes of transport) or multiple games (e.g. to reflect multiple occurrences of interactions). Such approach reinforces the link between microeconomic theory to modelling the digitisation of social contacts (Castells, 2010) and help in understanding phenomena such as uptake of Internet based communication tools (Skype, Viber) or social network platforms (Facebook, LinkedIn). The approach proposed in this paper suggests means by which understanding of such phenomena can be achieved in relation to travel behaviour, relative changes in cost of communication (both travel and digital), as well as perceived quality (intensity) of participation in tele-activities.

5. Towards operationalisation of the framework

The theoretical contribution presented in the sections above can be operationalised by a number of econometric means which this section seeks to suggest. The first aspect that emerges is that of data needs and collection protocols. In that sense, stated preference exercises would appear effective solution for situations similar to those in scenarios 1-4 (Rose and Bliemer, 2008) methods while laboratory experiments such as those used by

experimental economists could be utilised for obtaining well-controlled and efficient designs for interactive situations similar to scenario 5 (Smith, 1991; Greiner *et al.*, 2014). Additional possibility in the latter case could be collection by means of social diaries in which individuals record their social interactions (both physical and virtual) as well as information on location, relationship to other people or travel conditions (van den Berg *et al*., 2008, 2014). Such data collection protocols should, however, reflect possible factors that would enter different components suggested by the framework, i.e. M_A, M_B, M_{T1}, M_{T2}, M_T.

What follows naturally from the discrete nature of the choice problem is the possibility of application of discrete choice models. Given the fact that the alternatives in the choice situations constitute combinations of alternatives, complex correlation structure is likely to underlie such situations and hence Network Generalised Extreme Value (GEV) models (Bierlaire, 2002) could provide a flexible way of obtaining closed form expressions for probabilities of choice (mixed GEV models could also serve similar purpose, though with potentially greater degree of computational complexity). In these cases, (11) would emerge as a microeconomically-founded systematic component of the utility associated with each alternative. Additionally, Bresnahan and Reiss (1991) provided econometric means for linking the discrete choice theory to games such as in scenario 5, and could consequently be used for operationalisation of the currently presented framework.

Alternative means of operationalisation of the model could be based on the models of activity scheduling (Polak and Jones, 1994; Ashiru *et al.*, 2004; Ettema *et al.*, 2007). In such models, themselves based on Winston's concept of instantaneous utility, the utility functions are defined explicitly. Given that Spencer *et al.* (1987) provided evidence that people's circadian rhythm approximately follows sinusoidal shape, it would appear convincing to model the instantaneous time-dependent intensity (productivity) as a symmetrical Cauchy distribution due to its single peak time and existence of analytical solution to integration exists (cf. Ettema *et al*., 2007). On the other hand, duration dependence could follow the formula proposed by Bhat and Misra, thus yielding time-dependent expression for *z*:

$$z(t,\psi,\theta) = \frac{1}{\pi f(\psi,\theta)\left[\left(\frac{t-t^*}{f(\psi,\theta)}\right)^2 + 1\right]} * z_{MAX} + \frac{\eta f(\psi,\theta)}{t} \tag{17}$$

In this formulation, $f(\Psi, \theta)$ reflects possible dependence of the intensity on ICT bundle Ψ and other factors θ other than time, t^* is the optimal activity timing while z_{MAX} is an arbitrary maximum value of intensity *z*. Additionally, η reflects the impact of duration of the activity on the intensity, potentially reflecting fatigue or boredom.

In such a case, and following the assumption of non-negative intensity *z*, natural logarithm could be used to reflect diminishing marginal utility of activity intensity:

$$u\big(z(t,\psi)\big) = \gamma_1 \ln(\gamma_2 z(t,\psi,\theta) + 1) \tag{18}$$

where γ_1 is a scaling parameters and γ_2 indicates the direction and sensitivity of the utility to activity intensity. The latter coefficient would thus capture the effect of productivity on

satisfaction derived from work. Additional advantage of (18) lies in the possibility to use the Taylor series (Mercator series and Euler transform in this particular case) to approximate the otherwise cumbersome expression and integrals. However, while working with the explicit utility expressions appears conceptually straightforward, its implementation in terms of computing analytical solutions as well as estimating highly non-linear expressions with entangled parameters could prove challenging (though employing approximating methods such as the aforementioned Taylor series and numerical integration could prove useful to cope with such issues).

Furthermore, Pawlak *et al.* (2013, 2014) demonstrated how condition (9) can be used to estimate relevant parameters influencing in-travel activity choice together with productivity impacts by means of multi-spell hazard-based duration models estimated jointly with binary choice models and ordered regression. While their study was limited to the case of two in-travel activities only (work and non-work), the study clearly demonstrated the possibility to link the theoretical results with empirical data. Moreover, such an approach (both theoretical and econometric) can be in principle extended to any number of possible activities using competing risk hazard model of Ettema *et al.* (1995) which can also be linked to models of discrete choice enabling valuation of on-board ICT services.

Regarding limitations of the framework presented in the current paper, one concerns the fact that the framework presented here considers only a single episode within the reference period. It is however possible to extend equation (6) to include the sum (or product) of n period-specific utilities U_n in which case it is the sum, denoted by $\widehat{U}$:

$$\widehat{U} = \sum_{n=1}^{N} U_n \tag{19}$$

that would be maximised by the individual subject to respectively modified resource constraint. In this case, however, the analytical solution and hence scenario analysis might be obscured by the complexity while estimation could prove infeasible. This motivation has been behind the parsimonious approach followed in the current paper.

A number of further possible ways of improving the formulation exist that have not been explicitly addressed in this paper. For example period-specific utilities could include terms reflecting dependence between them which is essential in modelling situations where occasional tele-activity is desirable while permanent is not, e.g. permanent tele-workers may experience sense of isolation and reduced opportunity for promotion. This could be possibly framed as appropriate backward- and forward-looking variables entering the intensity z yet this again would obscure tractability of the problem.

Additionally, more explicit treatment of the stochastic processes such as intra-individual heterogeneity of timing preferences or travel time variability could be included in the framework. As mentioned earlier in the paper, such effects could be captured by allowing some variables (z, r_{ij}) to be randomly distributed. Finally, additional layer of simultaneous activities concurrent to in-travel ones could be incorporated together with terms capturing compatibility (or its lack) between them, e.g. listening to relaxing as compared to loud and disturbing music while attempting to have a nap.

6. Conclusions

Understanding the relationship between ever-more prevailing information and communication technologies and travel behaviour has continuously motivated researchers since 1970s. While empirical studies in the domain have flourished, theoretical developments in the form of microeconomic models seem to have lagged behind in addressing the possibility to undertake activities at a distance yet without the need to travel, or undertake them simultaneously.

Our current contribution demonstrates that despite additional complexity coming from the specificity of tele-activities, possibility of in-travel time use, and time-of-day and ICT impacts on the experience (intensity, productivity), the known time allocation frameworks and goods-leisure paradigms can still prove useful in understanding the interaction between ICT-based, digital reality and physical world. Within our framework the decision on the choice of activities, mode and route of travel as well as ICT is made endogenously, given individual time-specific intensities (or productivities) and the associated utilities as well as wage. Such approach leads to obtaining an expression for indirect utility associated with particular combinations of pre- in- and post journey activities, mode and route, and ICT bundle. Furthermore, it also provides means of arriving at expressions for valuation of travel time reduction, or changes in the ICT qualities such as increase in broadband speed or availability of on-board Wi-Fi.

While we do not provide empirical estimation of the framework, we demonstrate by means of thought experiments, how it could be used to conceptualise five possible choice scenarios that could be faced by individuals in real lives, including use of autonomous vehicles or dealing with interaction between people. In doing so, we demonstrate exemplary situations that could be tested by means of appropriate data, including stated preference exercises, laboratory experiments, or social diaries. Progressing along such research path could help in improving the framework and in the process of doing so, improve understanding of the mechanisms behind ICT and travel behaviour relationships. Therefore, as our final contribution we discuss possible ways of operationalising the framework such as discrete choice models, hazard based duration models, or direct specification of the intensity and utility functions.

While we acknowledge the inherent simplicity of our formulation, we also note its comprehensiveness and parsimony in formalising the notoriously complex phenomenon and demonstrating various possible outcomes of interactions between ICT and travel behaviour noted in other empirical studies. We hope that by such theoretical contribution, better explanation and reconciliation of some seemingly contradictory empirical results can be achieved. Such understanding appears essential in the wake of ever-increasing proliferation of and people’s reliance on ICT in everyday life.

Technical Appendix

Utility maximisation problem and derivation of conditional truncated utility function

Equations (6) and (7) from the paper state the following utility maximisation problem of an individual:

$$\max_{\substack{t_1,t_t,x,\\ A,B,T1,T2,i,j,\psi}} U = \underbrace{\int_{t_o}^{t_1} u_A(z_A(t,\psi),x)\,dt}_{U_A} + \underbrace{\int_{t_1}^{t_t} u_{T1}(z_{T1ij}(t,\psi),x)\,dt}_{U_{T1}} +$$

(6) (A.1.)

$$+ \underbrace{\int_{t_t}^{t_1+r_{ij}(t_1)} u_{T2}(z_{T2ij}(t,\psi),x)\,dt}_{U_{T1}} + \underbrace{\int_{t_1}^{t_1+r_{ij}(t_1)} u_T(z_{Tij}(t))\,dt}_{U_T}$$
$$+ \underbrace{\int_{t_1+r_{ij}(t_1)}^{t_E} u_B(z_B(t,\psi),x)dt}_{U_B}$$

Subject to:

$$\int_{t_o}^{t_1} x\,dt + \int_{t_1}^{t_t} x\,dt + \int_{t_t}^{t_1+r_{ij}(t_1)} x\,dt +$$
$$+ \int_{t_o}^{t_1} x\,dt + c_\psi + c_i(r_i(t_1)) = w_A \int_{t_o}^{t_1} z_A\,dt + w_{T1} \int_{t_1}^{t_t} z_{T1ij}\,dt +$$
$$+ w_{T2} \int_{t_t}^{t_1+r_{ij}(t_1)} z_{T2ij}\,dt + w_B \int_{t_1+r_{ij}(t_1)}^{t_E} z_B\,dt + E$$

(7) (A.2)

Let us assume that as an approximation, the utility components associated with consumption and intensity are separable:

$$u(z(t,\psi),x) = u(x) + u\big(z(t,\psi)\big)$$

(A.3)

Moreover, let further be assumed that the utility derived from consumption can be approximated by a linear function with constant marginal utility of consumption *b*, equal for all activities:

$$u_A(x) = u_{T1}(x) = u_{T2}(x) = u_B(x) = bx$$

(A.4)

Thus (A.1) can be rearranged to yield (note simplified notation for the:

$$U = \int_{t_o}^{t_1} u_A(z_A)\,dt + \int_{t_1}^{t_t} u_{T1}(z_{T1ij})\,dt + \int_{t_t}^{t_1+r_{ij}(t_1)} u_{T2}(z_{T2ij})\,dt + \\ + \int_{t_1}^{t_1+r_{ij}(t_1)} u_T(z_{Tij})\,dt + \int_{t_1+r_{ij}(t_1)}^{t_E} u_B(z_B)dt + bx(t_E - t_0)$$

(A.6)

While (A.2) yields:

$$w_A \int_{t_o}^{t_1} z_A\,dt + w_{T1} \int_{t_1}^{t_t} z_{T1ij}\,dt + w_{T2} \int_{t_t}^{t_1+r_{ij}(t_1)} z_{T2ij}\,dt + w_B \int_{t_1+r_{ij}(t_1)}^{t_E} z_B\,dt + E \\ - c_\psi - c_{ij}\left(r_{ij}(t_1)\right) = x(t_E - t_0)$$

(A.7)

(A.7) can now be substituted to (A.6) using the term $x(t_E\text{-}t_0)$ as a pivot which accounts for the budget constraint, and consequently reduce the dimensionality of the problem:

$$U = \int_{t_o}^{t_1} u_A(z_A)\,dt + \int_{t_1}^{t_t} u_{T1}(z_{T1ij})\,dt + \int_{t_t}^{t_1+r_{ij}(t_1)} u_{T2}(z_{T2ij})\,dt \\ + \int_{t_1}^{t_1+r_{ij}(t_1)} u_T(z_{Tij})\,dt + \int_{t_1+r_{ij}(t_1)}^{t_E} u_B(z_B)dt + bw_A \int_{t_o}^{t_1} z_A\,dt \\ + bw_{T1} \int_{t_1}^{t_t} z_{T1ij}\,dt + bw_{T2} \int_{t_t}^{t_1+r_{ij}(t_1)} z_{T2ij}\,dt + bw_B \int_{t_1+r_{ij}(t_1)}^{t_E} z_B\,dt \\ + E - bc_\psi - bc_{ij}\left(r_{ij}(t_1)\right)$$

(A.8)

There are two first order conditions associated with the formulation, one describing the timing of travel activities switch (which needs to occur between departure and arrival times):

$$\frac{\partial U}{\partial t_t} = 0 \qquad t_1 < t_t < t_1 + r_{ij}(t_1)$$

(A.9)

And the second one related to the choice of departure time:

$$\frac{\partial U}{\partial t_1} = 0$$

(A.10)

Thus (A.9) yields:

$$\frac{\partial U}{\partial t_t} = u_{T1}(z_{T1ij}(t_t^*)) + bw_{T1}z_{T1ij}(t_t^*) - u_{T2}(z_{T2ij}(t_t^*)) - bw_{T2}z_{T2ij}(t_t^*) = 0$$

(A.11)

And after rearranging, equation (9) from the paper is obtained:

$$u_{T1}(z_{T1ij}(t_t^*)) + bw_{T1}z_{T1ij}(t_t^*) = u_{T2}(z_{T2ij}(t_t^*)) + bw_{T2}z_{T2ij}(t_t^*)$$

(9) (A.12)

Where t_t* denotes the optimal time for in-travel activity switching. Note that if more in-travel activities are included in the formulation (*T3*, *T4*, *T5*, etc.), optimal switching times would be defined by similar corresponding conditions. As a result, working with two-activities case does not impair generality of the formulation.

Noting that $\frac{\partial U}{\partial t_1} = \frac{\partial U}{\partial (t_1^* + r_{ij}|_{t_1^*})} \frac{d(t_1^* + r_{ij}|_{t_1^*})}{dt_1}$, (A.10) results in:

$$\begin{aligned}\frac{\partial U}{\partial t_1} = {} & u_A(z_A(t_1^*)) + bw_A z_A(t_1^*) - u_{T1}(z_{T1ij}(t_1^*)) - bw_{T1}z_{T1ij}(t_1^*) - u_T(z_{Tij}(t_1^*)) \\ & + \left(1 + \frac{dr_{ij}}{dt_1}\Big|_{t_1^*}\right)\Big[u_{T2}(z_{T2ij}(t_1^* + r_{ij}|_{t_1^*})) + bw_{T1}z_{T1ij}(t_1^* + r_{ij}|_{t_1^*}) \\ & - u_B(z_B(t_1^* + r_{ij}|_{t_1^*})) - bw_B z_B(t_1^* + r_{ij}|_{t_1^*}) + u_T(z_{Tij}(t_1^* + r_{ij}|_{t_1^*}))\Big] \\ & + b\frac{dc_{ij}}{dr_{ij}}\frac{dr_{ij}}{dt_1}\Big|_{t_1^*} = 0\end{aligned}$$

(A.13)

Where t_1* expresses the optimal departure time (or optimal switching time to tele-activity *B*). After rearranging, (A.13) gives the equation (10) from the paper:

$$
\begin{aligned}
&u_A(z_A(t_1^*)) + bw_A z_A(t_1^*) \\
&\quad = u_B(z_B(t_1^* + r_{ij}\big|_{t_1^*})) + bw_B z_B(t_1^* + r_{ij}\big|_{t_1^*}) \\
&\quad + u_{T1}(z_{T1ij}(t_1^*)) + bw_{T1} z_{T1ij}(t_1^*) \\
&\quad - u_{T2}(z_{T2ij}(t_1^* + r_{ij}\big|_{t_1^*})) - bw_{T2} z_{T2ij}(t_1^* + r_{ij}\big|_{t_1^*}) + u_T(z_{Tij}(t_1^*)) \\
&\quad - u_T(z_{Tij}(t_1^* + r_{ij}\big|_{t_1^*})) \\
&\quad + \left(\frac{dr_{ij}}{dt_1}\Big|_{t_1^*}\right)\Bigg[u_B(z_B(t_1^* + r_{ij}\big|_{t_1^*})) + bw_B z_B(t_1^* + r_{ij}\big|_{t_1^*}) \\
&\quad - u_{T2}(z_{T2ij}(t_1^* + r_{ij}\big|_{t_1^*})) - bw_{T2} z_{T2ij}(t_1^* + r_{ij}\big|_{t_1^*}) \\
&\quad - u_T(z_{Tij}(t_1^* + r_{ij}\big|_{t_1^*})) - b\frac{dc_{ij}}{dr_{ij}}\frac{dr_{ij}}{dt_1}\Big|_{t_1^*}\Bigg] = 0
\end{aligned}
$$

(10) (A.14)

Assuming that t_t^* and t_1^* are optimal times for in-travel activity switching and departure time respectively that are defined by the conditions (A.12) and (A.14), it is possible to define the truncated utility function *V* for joint choice of particular combination of activities (*A*, *B*, *T1*, *T2*), travel mode *i*, route *j*, and ICT bundle using equation (A.8):

$$
\begin{aligned}
V_{A,B,T1,T2,i,j,\psi} = &\underbrace{\int_{t_o}^{t_1^*} (u_A(z_A) + bw_A z_A)\, dt}_{M_A} + \underbrace{\int_{t_1^*}^{t_t^*} \left(u_{T1}(z_{T1ij}) + bw_{T1} z_{T1ij}\right) dt}_{M_{T1}} \\
&+ \underbrace{\int_{t_t^*}^{t_1^* + r_{ij}(t_1^*)} \left(u_{T2}(z_{T2ij}) + bw_{T2} z_{T2ij}\right) dt}_{M_{T2}} + \underbrace{\int_{t_1^*}^{t_1^* + r_{ij}(t_1^*)} u_T(z_{Tij})\, dt}_{M_T} \\
&+ \underbrace{\int_{t_1^* + r_{ij}(t_1^*)}^{t_E} (u_B(z_B) dt + bw_B z_B)\, dt}_{M_B} - bc_\psi - bc_{ij}\left(r_{ij}(t_1^*)\right)
\end{aligned}
$$

(11) (A.15)

Note that the term *E* is not influenced by any of the choice variables, and hence can be removed ('truncated') from the expression for *V*.

Derivation of subjective value of travel time reduction

Travel time reduction can be defined as as:

$$
SV_{r_{ij}} = -\frac{\dfrac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial r_{ij}}}{-\dfrac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_{ij}}} = \frac{\dfrac{\partial M_{T2}}{\partial r_{ij}} + \dfrac{\partial M_T}{\partial r_{ij}} + \dfrac{\partial M_B}{\partial r_{ij}} - b\dfrac{dc_{ij}}{dr_{ij}}}{-b}
$$

(A.16)

Note that by definition of derivatives, the infinitesmall differentials are *positive* whereas reduction in travel time implies *negative* change and hence requires minus sign in the denominator. Using expression for the indirect utility function (11) (A.15) and following the fundamental theorem of calculus as well as envelope theorem yields:

$$SV_{r_{ij}} = \frac{dc_{ij}}{dr_{ij}} + \frac{-u_{T2}(z_{T2ij}) - u_T(z_{Tij}) + u_B(z_B)dt}{b} - w_{T2}z_{T2ij} + w_B z_B$$

(13) (A.17)

Derivation of subjective value of change in ICT quality

The subjective value of modification in the quality β_ψ of ICT bundle ψ is defined as:

$$SV_{\beta_\psi} = -\frac{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial \beta_\psi}}{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_\psi}} = -\frac{\frac{\partial M_A}{\partial \beta_\psi} + \frac{\partial M_{T1}}{\partial \beta_\psi} + \frac{\partial M_{T2}}{\partial \beta_\psi} + \frac{\partial M_B}{\partial \beta_\psi} - b\frac{dc_\psi}{d\beta_\psi}}{-b}$$

(A.16)

which can be obtained using (11):

$$SV_{\beta_\psi} = \frac{1}{b}\left[\int_{t_o}^{t_1^*} \frac{\partial z_A}{\partial \beta_\psi}\left(\frac{du_A}{dz_A} + bw_A\right)dt + \int_{t_1^*}^{t_t^*} \frac{\partial z_{T1}}{\partial \beta_\psi}\left(\frac{du_{T1}}{dz_{T1}} + bw_{T1}\right)dt + \int_{t_t^*}^{t_1^*+r_{ij}(t_1^*)} \frac{\partial z_{T2}}{\partial \beta_\psi}\left(\frac{du_{T2}}{dz_{T2}} + bw_{T2}\right)dt + \int_{t_1^*+r_{ij}(t_1^*)}^{t_E} \frac{\partial z_B}{\partial \beta_\psi}\left(\frac{du_B}{dz_B} + bw_B\right)dt\right] - \frac{dc_\psi}{d\beta_\psi}$$

(14) (A.17)

Note that in case of change in on-board Wi-Fi:

$$\frac{\partial z_A}{\partial \beta_{\psi WiFi}} = 0$$

(A.18)

as well as:

$$\frac{\partial z_B}{\partial \beta_{\psi WiFi}} = 0$$

(A.19)

And thus we obtain expression (15) from the paper

$$SV_{\beta_{\psi WiFi}} = -\frac{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial \beta_{\psi WiFi}}}{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_{\psi WiFi}}}$$
$$= \frac{1}{b}\left[\int_{t_1^*}^{t_t^*} \frac{\partial z_{T1}}{\partial \beta_{\psi WiFi}}\left(\frac{du_{T1}}{dz_{T1}} + bw_{T1}\right)dt + \int_{t_t^*}^{t_1^*+r_{ij}(t_1^*)} \frac{\partial z_{T2}}{\partial \beta_{\psi WiFi}}\left(\frac{du_{T2}}{dz_{T2}} + bw_{T2}\right)dt\right] - \frac{dc_{\psi WiFi}}{d\beta_{\psi WiFi}}$$

(15) (A.20)

On the other hand, in case of tele-worker:

$$t_1^* = t_1^* + r_{ij}(t_1^*)$$

(A.21)

In which case in-travel activities do not exist which results from (A.9), and neither is there any inherent travel-associated utility u_T. Consequently:

$$SV_{\beta_{\psi TLW}} = -\frac{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial \beta_{\psi TLW}}}{\frac{\partial V_{A,B,T1,T2,i,j,\psi}}{\partial c_{\psi TLW}}}$$
$$= \frac{1}{b}\left[\int_{t_o}^{t_1^*} \frac{\partial z_A}{\partial \beta_{\psi TLW}}\frac{du_A}{dz_A}dt + \int_{t_1^*+r_{ij}(t_1^*)}^{t_E} \frac{\partial z_B}{\partial \beta_{\psi TLW}}\left(\frac{du_B}{dz_B} + bw_B\right)dt\right] - \frac{dc_{\psi TLW}}{d\beta_{\psi TLW}}$$

(16) (A.21)

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