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# Development and Application of an Activity Based Space-Time Accessibility Measure for Individual Activity Schedules

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## ABSTRACT

Accessibility plays an important role in a number of existing theories of spatial and travel behaviour. It affects the rate and the pattern of land-use development as well as impacting significantly upon our notion of society equity and justice. However despite the importance of the notion of accessibility, the measures which have traditionally been used to quantify accessibility, have tended to be relatively poorly defined, excluding a wide range of observed forms of travel behaviour. This has ramifications for the implicit assumption underpinning the use of accessibility measures, namely that of a direct correlation between the measure of accessibility and individual travel behaviour.

In this paper we present a new family of space-time route benefit measures. These are used to derive an associated family of disaggregate activity based space-time utility accessibility measures. Applicable to individual activity schedules, these space-time accessibility measures implicitly acknowledge that travel is a derived demand.

The paper commences with a brief review of traditional accessibility measures, highlighting some of their principal weaknesses. The paper proceeds to provide a brief review of space-time user benefit measures highlighting their principle assumptions. Existing space-time locational benefit measures are subsequently extended to incorporate more realistic temporal constraints on activity participation and the perceived user benefit. The improved locational benefit measures incorporate a variety of factors including the utility an individual derives from activity participation, individual income, and space-time constraints. In addition travel time, route delay and schedule disutility components such as the facility and activity wait times associated with early arrival are incorporated, in addition to late start time penalties associated with late commencement of an activity.

The improved space-time locational benefit measure is applied to activity schedules incorporating a series of multiple linked activities. The paper subsequently demonstrates how the resulting user benefit measure can be shown to be part of a broader family of space-time route benefit measures, which despite their theoretical attractiveness have hitherto not been utilised by researchers. An associated family of space-time utility accessibility measures are subsequently developed and the paper proceeds to highlight how stochastic frontier models utilised in conjunction with existing travel/activity diary datasets can be utilised to operationalise the proposed measure of accessibility.

The family of accessibility measures are implemented within a point based spatial framework encompassing detailed spatially referenced land-use transportation network encompassing cycle and walk transport modes. Several practical examples are presented of the proposed family of accessibility measures in use and demonstrate the strength and potential of the methodology in developing a wide range of transport-land-use policies, including new/improved transport links, the provision of additional land-use facilities/opportunities, extended opening of facilities/opportunities, as well as the development of flexible working policies. The proposed family of accessibility measures is also used to compare alternative accessibility enhancing strategies, highlighting which policy interventions have the greatest effect on individual accessibility.

The paper concludes with a summary highlighting the principle benefits and properties of the proposed family of accessibility measures in addition to highlighting potential areas of future research.

## 1. INTRODUCTION

Accessibility is an important component of a number of existing theories of spatial and travel behaviour in particular spatial interaction, utility maximisation and information minimisation. Accessibility both impacts upon and is impacted by innovation; it is also closely related to freedom of choice, travel, land-use distribution, activity participation and trade, in addition to having strong parallels in democracy and religion. Historically transport and land-use planners have utilised accessibility to assess the effectiveness and occasionally the efficiency of transport and land-use policies. However traditional accessibility measures have hitherto lacked a sound theoretical basis. This is in part attributable to the considerable degree of confusion that exits regarding what actually

constitutes accessibility and the numerous different definitions of accessibility and measures of accessibility that this espouses.

Definitions of accessibility range from those founded on the notion of ease of reach Morris *et al* (1979), Vickerman (1974), Ingram (1971), and Hansen (1959) to those based on notions of activity participation Jones (1981), Burns (1979) and Pirie (1978). In this paper we propose that '*…accessibility is a measure of the overall utility that an individual derives from participating in one or more linked activities within an integrated land-use-transport environment…*'.

The diverse range of accessibility measures to be found within the literature possess a number of important characteristics. In particular, the majority of the measures consider only a single purpose trip or activity, often analysed at the aggregate level masking potentially important variations in individual accessibility. In addition these measures of accessibility have in the main tended to ignore the potential for trip chaining travel behaviour. The sequential linking of trips and activities within activity schedules which serves to increase an individual's overall level of accessibility which has long been recognised in the literature, Kitamura *et al* (1990), Hanson (1980) and Ben-Akiva & Lerman (1979). However to date little progress has been made towards developing the necessary theoretical or operational techniques for incorporating such factors.

In this paper a more behaviourally realistic series of schedule based space-time user benefit measures and a related family of space-time utility accessibility measures are presented which are disaggregate in nature and thus applicable to individual activity schedules.

## 2. SPACE-TIME USER BENEFIT MEASURES

In this section we present a brief review of the definition and use of space-time user benefit measures. This is followed by an extension of the benefit measures to accommodate considerations of travel delay, waiting time and late start time, associated with the travel and activity participation components of behaviour.

### 2.1. Locational and Route Benefit Measures

Burns (1979), whilst considering an individual undertaking a discretionary activity constrained by upstream and downstream mandatory activities, utilised a space-time prism depicted in figure 1, to develop a locational benefit and a route benefit measure.

Burns' (1979) locational benefit function presented in equation 1, defines the benefit ($BM_k$) to an individual of a location $k$ as a function of the spatial separation ($d_k$) existing between activity locations, the attractiveness of the opportunity ($a_k$) and the stay time ($T_k$) at the activity location.

$$BM_k = \oplus g(d_k) a_k u(T_k) \qquad (1)$$

Where $\oplus$ represents a binary operation such as addition or maximisation, denoting the manner in which the individual derives benefit from the choice set as a whole.

Burns' (1979) route benefit function presented in equation 2, defines the benefit ($BM_r$) to an individual of a route $r$ as being a function of the total aggregate spatial separation of all relevant opportunities located along the route ($d_r$), the total aggregate attractiveness of all relevant opportunities located along the route ($a_r$) and the total aggregate stay time ($T_r$) at all relevant opportunities located along the route.

$$BM_r = \oplus g(d_r) a_r u(T_r) \qquad (2)$$

Historically researchers such as Odoki *et al* (2001), Wu & Miller (2001) and Miller (1999a, 1999b) have utilised Burns' (1979) locational benefit formulation to undertake accessibility assessments. In so doing these researchers have neglected the theoretically attractive route benefit approach.

Burns' (1979) locational and route benefit measures only consider the benefit to the individual of being able to reach and stay at a particular discretionary activity location. In reality the relative timings of the arrival at the activity location, the opening/closing of the activity location and the formal earliest/latest start times of the activities, means that not all the time spent at the destination will be productive for activity participation. A simple example is arriving at a shopping center early then waiting until the shops open before formally starting shopping.

The locational benefit measures utilised to date do not assess the utility to the individual of actual activity participation, but instead assume that being able to reach and remain at a potential activity location confers an element of utility to the individual. In addition these benefit measures make no allowance for non-travel related delays such as time spent waiting for public transport, but also time spent waiting to engage in activities once one has arrived at the destination. These extra potential delays will introduce an element of disutility that will reduce the total utility derived from a particular activity

location. In addition late commencement of an activity due to late arrival will result in further disutility being incurred by the individual.

### 2.2. Incorporating Delay, Waiting Time and Late Arrival

In order to overcome the limitations associated with the stay time and travel time assumptions outlined earlier, we propose to modify Burns' (1979) locational and route benefit measures by introducing the notions of route delay, facility wait time, activity wait time and late start time. This facilitates the development of an improved, more behaviourally realistic, family of space-time user benefit and space-time utility accessibility measures.

Utilising the following formulation of the space-time prism, which represents an extension of the simple definition utilised by Kwan 1998 and Kwan & Hong 1998:

$$\mathrm{PPS}_{lS_1} = \left\{(k_1, t_1) \middle| t_i + t_{ik_1} + D_{ik_1} + w_{ik_1} + W_{ik_1} \le t_1 \le t_j - t_{k_1 j} - D_{k_1 j} - w_{k_1 j} - W_{k_1 j}\right\} \qquad (3)$$

Where:

*PPS* Denotes the potential path space or space-time prism.

*l* Denotes the individual type/person under consideration.

$S_1$ An activity schedule containing only one flexible or discretionary activity.

$(k_1, t_1)$ Denotes all possible activity locations in space-time for undertaking the discretionary activity, situated within the space-time prism and consequently satisfying an individual's coupling constraints.

$t_1$ The start time of the single discretionary activity located at $k_1$ constrained by upstream and downstream coupling activities located at i and j respectively.

$t_i$ The latest end time of the upstream coupling/mandatory activity located at i.

$t_j$ The latest start time of the downstream coupling/mandatory activity located at j.

$t_{ik_1}$ The travel time associated with the minimum time/cost routing between the upstream coupling activity location i and the discretionary activity location $k_1$ under consideration.

$t_{k_1 j}$ The travel time associated with the minimum time/cost routing between the upstream discretionary activity location $k_1$ under consideration and the downstream coupling activity location j.

$D_{ik_1}$ Delay time encountered along the route between the upstream coupling activity location i and the downstream discretionary activity location $k_1$ under consideration, which may include considerations of wait time penalties, modal interchange time penalties, parking and other non-travel related time spent in transit.

$D_{k1j}$ Delay time encountered along the route between the upstream discretionary activity location $k_1$ under consideration and the downstream coupling activity location j.

$w_{ik1}$ Wait time penalty incurred as a consequence of arrival at the discretionary activity location $k_1$ ahead of the scheduled opening times of the opportunity/facility.

$W_{ik1}$ Wait time penalty incurred as a consequence of arrival at the discretionary activity location $k_1$ ahead of the earliest scheduled start time of the activity as defined within the activity schedule.

$L_{ik1}$ Late start time penalty incurred as a consequence of arrival at the discretionary activity location $k_1$ after the scheduled latest start time of the activity.

$w_{k1j}$ Wait time penalty incurred as a consequence of arrival at the downstream mandatory activity location j ahead of the scheduled opening times of the opportunity/facility.

$W_{k1j}$ Wait time penalty incurred as a consequence of arrival at the downstream mandatory activity location j ahead of the earliest scheduled start time of the activity as defined within the activity schedule.

$L_{k1j}$ Late start time penalty incurred as a consequence of arrival at the downstream mandatory activity location j after the scheduled latest start time of the mandatory activity.

Figure 2 depicts the shape of a space-time prism resulting from participation in a discretionary activity. In particular the figure denotes the change in the shape and structure of the space-time prism as a consequence of the route delay, facility wait time and activity wait time encountered en-route between the constraining upstream and downstream mandatory activities. The figure shows that as these variables are increased then the potential path space and the potential path area (the space-time and spatial regions available for discretionary activity participation) decreases.

If it is assumed that:

- The discretionary activity has an associated minimum activity duration or threshold below which the individual derives no utility.
- Useful activity participation time arises only within the context of one contiguous time block during which the facility/opportunity in question is open and available for use.
- Arrival before the formal opening times of an opportunity results in an early start disutility being incurred at the activity location in question.
- Arrival after the formal scheduled latest start time of the activity results in late start disutility being incurred at the activity location in question.

It thus follows that the space-time prism can be defined by:

$$\mathrm{PPS}_{lS_1} = \left\{ (\mathrm{k}_1, \mathrm{t}_1) \,\middle|\, T_{k_1} \geq T_{1_{\min}} \right\} \qquad (4)$$

Where,

$$\mathrm{T}_{\mathrm{k}_1} = t_j - t_i - \left(t_{ik_1} + t_{k_1 j}\right) - \left(D_{ik_1} + D_{k_1 j}\right) - \left(w_{ik_1} + w_{k_1 j}\right) - \left(W_{ik_1} + W_{k_1 j}\right) \qquad (5)$$

$T_{1min}$ Minimum discretionary activity duration or threshold required for the individual $l$ to derive utility from participating in a single discretionary activity.

$T_{k1}$ Maximum discretionary activity duration for an individual $l$ participating in a single discretionary activity at location $\mathrm{k}_1$.

Equations 3-5 represent the mathematical formulation of the space-time prism associated with participation in a single discretionary activity with associated route delay, facility wait and activity wait terms introduced.

Utilising the following definitions:

$$\mathrm{t}_{\mathrm{k}_1} = t_{ik_1} + t_{k_1 j} \qquad (6)$$

$$\mathrm{D}_{\mathrm{k}_1} = D_{ik_1} + D_{k_1 j} \qquad (7)$$

$$\mathrm{w}_{\mathrm{k}_1} = w_{ik_1} + w_{k_1 j} \qquad (8)$$

$$\mathrm{W}_{\mathrm{k}_1} = W_{ik_1} + W_{k_1 j} \qquad (9)$$

$$L_{\mathrm{k}_1} = L_{ik_1} + L_{k_1 j} \qquad (10)$$

Utilising a multiplicative user benefit function of the following form:

$$BM_{PlS_1} = \sum_{k_1=1}^{m} q\left(t_{k_1}\right) g\left(D_{k_1}\right) h\left(w_{k_1}\right) v\left(W_{k_1}\right) y\left(L_{k_1}\right) z\left(a_{k_1}\right) u\left(T_{k_1}\right) \qquad (11)$$

Where, *q*, *g*, *h*, *v*, y, *z* and *u* are functions respectively denoting how spatial/temporal separation, route delay, facility wait time, activity wait time, late start time, opportunity/activity attractiveness and activity participation time are individually perceived by the individual *l*. There are a range of curvilinear deterrence functions which can be utilised to reflect the disutility associated with increased, spatial/temporal/cost separation, route delay, facility wait time, activity wait time and late start time on activity participation and spatial interaction. These include the inverse/negative power function, the negative exponential function, the negative Gaussian and the negative combined function.

The negative exponential deterrence type function, of the form used by Odoki *et al* (2001), Wu & Miller (2001), Miller (1999a, 1999b) and Burns (1979) is utilised in the following analysis to define the functions *q*, g, *h*, *v and y*. A positive power, positive

exponential or positive combined function can be utilised for *z* and *u*, reflecting the utility associated with increasing activity participation time and attractiveness at the specific activity location in question. In the following analyses a positive power function is utilised for z and u.

It is worth noting that the techniques adopted in the development of the series of space-time user benefit measures and the associated family of space-time utility accessibility measures outlined in the following discussions, can equally be applied to the alternative curvilinear functions outlined above, without any loss of generality in the use of the techniques.

Utilising the negative exponential and power function model forms, it follows that a user benefit function of the following form can be developed:

$$BM_{PlS_1} = \sum_{k_1=1}^{m} \left(a_{k_1}^{a_{l_1}}\right)\left(T_{k_1}^{b_{l_1}}\right)\exp\left[-\left(l_{l_1} t_{k_1} + m_{l_1} D_{k_1} + g_{l_1} w_{k_1} + h_{l_1} W_{k_1} + n_{l_1} L_{k_1}\right)\right] \qquad (12)$$

Where:

$a_{k1}$ Spatial component of accessibility. A finite non-negative real number, representing the relative attractiveness of the activity/opportunity location under consideration.

$t_{k1}$ Transportation component of accessibility, reflecting the temporal or cost separation associated with travel between respective upstream and downstream coupling activities.

$T_{k1}$ Temporal component of accessibility, reflecting the amount of time an individual can spend undertaking an activity at the location opportunity in question.

$D_{k1}$ Route delay component of accessibility, reflecting the amount of non-travel time (interchange time, queuing time, parking time etc) spent en-route between adjacent upstream and downstream coupling activities.

$w_{k1}$ Facility wait component of accessibility, reflecting the amount of time spent waiting for an opportunity to open.

$W_{k1}$ Activity wait component of accessibility, reflecting the amount of time spent waiting to commence an activity.

$L_{k1}$ Late start component of accessibility, reflecting the extent of the late start time at the activity location under consideration.

It can easily be shown that the improved seven term locational benefit measure presented in equation 12 has a number of properties which are analogous of those associated with Burns' (1979) three term user benefit function.

### 2.3. An Improved Space-Time Utility Accessibility Measure

In the remainder of this section the space-time locational benefit measure formulated above is used to derive three space-time utility accessibility measures applicable to an activity schedule composed of a single constrained discretionary activity. The space-time locational benefit measure is subsequently used to derive a space-time route benefit measure applicable to an activity schedule comprising of multiple linked activities and associated family of space-time utility accessibility measures.

Three space-time accessibility measures applicable to a single constrained activity can be developed by utilising three approaches for translating user benefit measures into accessibility measures, previously used by Miller (1999a, 1999b).

The user benefit translation mechanisms used to derive the accessibility benefit measures include:

- Consumer welfare or consumer surplus maximisation.
- Consumer welfare aggregation.
- Utility maximising choice behaviour implemented within a random utility framework.

Assuming Wilson's (1976) approach to the analysis of total consumer welfare developed within an aggregate based spatial interaction framework can be applied at the disaggregate level, then by adopting the following formulation:

$$a_k^a = \exp(a \ln a_k) \qquad (13)$$

$$T_k^b = \exp(b \ln T_k) \qquad (14)$$

It can be shown that equation 12 can be expressed as:

$$BM_{PlS_1} = \sum_{k_1=1}^{m} \exp\left[\left(a_{l_1} \ln a_{k_1} + b_{l_1} \ln T_{k_1}\right) - \left(l_{l_1} t_{k_1} + m_{l_1} D_{k_1} + g_{l_1} w_{k_1} + h_{l_1} W_{k_1} + n_{l_1} L_{k_1}\right)\right] \qquad (15)$$

Where:

$a_{l_1}$ A parameter defining the marginal utility of the attractiveness of the opportunity/facility.

$b_{l_1}$ A parameter defining the marginal utility of activity participation time $dU(T_k)/dT_k$.

$l_{l_1}$ Spatial/temporal based travel impedance parameter for individual *l*, positive in magnitude, used to define the effect of increased spatial or temporal separation on the user benefit measure.

$m_{l_1}$ Route delay temporal impedance parameter for individual *l*, positive in magnitude, used to define the effect of increased non-transit delay on the user benefit measure.

$g_{l_1}$ Facility temporal impedance parameter for individual *l*, positive in magnitude, used to define the effect of increased facility wait time on the user benefit measure.

$h_{l_1}$ Activity temporal impedance parameter for individual *l*, positive in magnitude, used to define the effect of increased activity wait time on the user benefit measure.

$n_{l_1}$ Late start time penalty deterrence parameter for individual *l*, positive in magnitude, used to define the effect of increased late start time on the user benefit measure.

Rearranging and removing binary addition as the binary operation and replacing the benefit measure annotation, BM, present within equation 15 with that of utility U, it can be shown that:

$$U_{PIS_1} = \exp\left[\left(l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}\right)\left(\left(\frac{a_{l_1}\ln a_{k_1} + b_{l_1}\ln T_{k_1}}{l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}}\right) - \left(\frac{t_{k_1}}{m_{l_1} g_{l_1} h_{l_1} n_{l_1}} + \frac{D_{k_1}}{l_{l_1} g_{l_1} h_{l_1} n_{l_1}} + \frac{w_{k_1}}{l_{l_1} m_{l_1} h_{l_1} n_{l_1}} + \frac{W_{k_1}}{l_{l_1} m_{l_1} g_{l_1} n_{l_1}} + \frac{L_{k_1}}{l_{l_1} m_{l_1} g_{l_1} h_{l_1}}\right)\right)\right] \quad (16)$$

This expression is analogous to Wilson's (1976) consumer welfare formulation, in which the term contained within the second closed parenthesis represents the utility or benefit derived from activity participation at the particular destination in question. The term contained within the third of the closed parentheses represents the disutility or disbenefit associated with travel time, delay time, facility wait time, activity wait time and late start time. The utility formulation presented in equation 16 together with the user benefit measures presented in equations 11, 12, and 15 are equal to zero if the attractiveness term $a_k$ or activity participation time $T_k$ are zero.

### 2.4. Consumer Welfare/Consumer Surplus Maximisation

If an individual *l* is assumed to behave according to Wilson's (1976) concept of maximisation of net interaction benefits or consumer welfare, it then follows that a space-time utility accessibility measure of the following form can be derived by introducing maximisation as the binary operation:

$$STUAM_{PIS_1} = \max_{k_1}\left[\exp\left[\left(l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}\right)\left(\left(\frac{a_{l_1}\ln a_{k_1} + b_{l_1}\ln T_{k_1}}{l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}}\right) - \left(\frac{t_{k_1}}{m_{l_1} g_{l_1} h_{l_1} n_{l_1}} + \frac{D_{k_1}}{l_{l_1} g_{l_1} h_{l_1} n_{l_1}} + \frac{w_{k_1}}{l_{l_1} m_{l_1} h_{l_1} n_{l_1}} + \frac{W_{k_1}}{l_{l_1} m_{l_1} g_{l_1} n_{l_1}} + \frac{L_{k_1}}{l_{l_1} m_{l_1} g_{l_1} h_{l_1}}\right)\right)\right]\right] \quad (17)$$

Equation 17 represents the maximum locational benefit that an individual *l* derives from the available choice set located within the space-time prism P, when undertaking an activity schedule $S_1$ composed of a single discretionary activity.

## 2.5. Consumer Welfare Aggregation

If it is assumed that the individual *l* values a space-time prism according to the range of choice available, then an alternative formulation of the space-time utility accessibility measure is the sum or aggregation of the net locational benefits that are available to the individual within the space-time prism. It accordingly follows that a space-time utility accessibility measure of the following form can be derived by introducing the binary operation of addition:

$$STUAM_{lS_1} = \sum_{k_1=1}^{m} \exp\left[\left(l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}\right)\left(\left(\frac{a_{l_1} \ln a_{k_1} + b_{l_1} \ln T_{k_1}}{l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}}\right) - \left(\frac{t_{k_1}}{m_{l_1} g_{l_1} h_{l_1} n_{l_1}} + \frac{D_{k_1}}{l_{l_1} g_{l_1} h_{l_1} n_{l_1}} + \frac{w_{k_1}}{l_{l_1} m_{l_1} h_{l_1} n_{l_1}} + \frac{W_{k_1}}{l_{l_1} m_{l_1} g_{l_1} n_{l_1}} + \frac{L_{k_1}}{l_{l_1} m_{l_1} g_{l_1} h_{l_1}}\right)\right)\right] \quad (18)$$

## 2.6. Utility Maximising Choice Behaviour: Random Utility Framework

If it is assumed that an individual *l* values a space-time prism according to the expected maximum utility, Ben-Akiva & Lerman (1979), of the opportunities located within the space-time prism. If the individual undertakes a discrete choice according to a random utility maximising process (in which the random component is IID Gumbel distributed), it thus follows that a logsum space-time utility accessibility measure of the following form can be derived:

$$STUAM_{lS_1} = \frac{1}{l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}} \times \ln \sum_{k_1=1}^{m} \exp\left(\exp\left[\left(l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}\right)\left(\left(\frac{a_{l_1} \ln a_{k_1} + b_{l_1} \ln T_{k_1}}{l_{l_1} m_{l_1} g_{l_1} h_{l_1} n_{l_1}}\right) - \left(\frac{t_{k_1}}{m_{l_1} g_{l_1} h_{l_1} n_{l_1}} + \frac{D_{k_1}}{l_{l_1} g_{l_1} h_{l_1} n_{l_1}} + \frac{w_{k_1}}{l_{l_1} m_{l_1} h_{l_1} n_{l_1}} + \frac{W_{k_1}}{l_{l_1} m_{l_1} g_{l_1} n_{l_1}} + \frac{L_{k_1}}{l_{l_1} m_{l_1} g_{l_1} h_{l_1}}\right)\right)\right]\right) \quad (19)$$

Equations 17-19 inclusive are analogous to the expressions derived by Miller (1999a, 1999b) and have been derived from similar principles but the formulation has been extended to incorporate factors of non-travel delay, the actual time available for activity participation reflected in the activity duration, the facility wait time, activity wait time and the late start time terms.

## 2.7. Extension To Multi-Activity Based Activity Schedules

In the remainder of this section an outline is proposed of how a space-time route benefit measure can be developed incorporating one or more constrained discretionary activities and how this can be used to develop a series of space-time utility accessibility measures applicable to activity schedules. The space-time prism and user benefit/utility formulations presented in equations 3-5 and 15-16 are extended to the general case of an

activity schedule composed of two or more discretionary activities framed by upstream and downstream coupling/mandatory activities.

If an activity schedule $S_a$ is considered which includes $n$ discretionary activities then by considering the *a-th* discretionary activity, and treating upstream and downstream activities as temporally constraining activities, it can be shown that:

$$\mathrm{PPS}_{lS_a} = \left\{(\mathrm{k_a}, \mathrm{t_a}) \middle| \mathrm{t_{a\text{-}1}} + T_{k_{a-1}} + t_{k_{a-1}k_a} + D_{k_{a-1}k_a} + w_{k_{a-1}k_a} + W_{k_{a-1}k_a} \le t_a \le t_{a+1} - t_{k_a k_{a+1}} - D_{k_a k_{a+1}} - w_{k_a k_{a+1}} - W_{k_a k_{a+1}} \right\} \quad (20)$$

$$\mathrm{PPS}_{lS_a} = \left\{(\mathrm{k_a}, \mathrm{t_a}) \middle| T_{k_a} \ge T_{a_{\min}} \right\} \quad (21)$$

Where,

$$\mathrm{T_{k_a}} = \left(t_{a+1} - t_{a-1} - \left(t_{k_{a-1}k_a} + t_{k_a k_{a+1}}\right) - \left(D_{k_{a-1}k_a} + D_{k_a k_{a+1}}\right) - \left(w_{k_{a-1}k_a} + w_{k_a k_{a+1}}\right) - \left(W_{k_{a-1}k_a} + W_{k_a k_{a+1}}\right) - \mathrm{T_{k_{a\text{-}1}}}\right) \quad (22)$$

Implementing the improved locational benefit measure outlined in equations 11 and 12 within the context of each individual activity present within the activity chain, it then becomes possible to develop the following macro level route benefit measures:

$$\begin{aligned} BM_{RlS_{1\ldots m}} = \oplus_1 \Big[ & \left(a_{Sk_1}^{a_{l_1}}\right)\left(T_{Sk_1}^{b_{l_1}}\right) exp\left[-\left(l_{l_1} t_{Sk_1} + m_{l_1} D_{Sk_1} + g_{l_1} w_{Sk_1} + h_{l_1} W_{Sk_1} + n_{l_1} L_{Sk_1}\right)\right] \cdots \\ & \oplus_2 \cdots \left(a_{Sk_a}^{a_{l_a}}\right)\left(T_{Sk_a}^{b_{l_a}}\right) exp\left[-\left(l_{l_a} t_{Sk_a} + m_{l_a} D_{Sk_a} + g_{l_a} w_{Sk_a} + h_{l_a} W_{Sk_a} + n_{l_a} L_{Sk_a}\right)\right] \cdots \\ & \oplus_2 \cdots \left(a_{Sk_n}^{a_{l_n}}\right)\left(T_{Sk_n}^{b_{l_n}}\right) exp\left[-\left(l_{l_n} t_{Sk_n} + m_{l_n} D_{Sk_n} + g_{l_n} w_{Sk_n} + h_{l_n} W_{Sk_n} + n_{l_n} L_{Sk_n}\right)\right] \Big] \end{aligned} \quad (23)$$

Where:

$\oplus_1$ The primary binary operation (e.g. addition or maximisation) representing the manner in which the meso level route benefit measures associated with a single complete activity chain, are combined to form the overall macro level route benefit measure.

$\oplus_2$ The secondary binary operation (e.g. addition or multiplication) representing the manner in which the individual micro level route benefit measures associated with a single activity within the activity chain, are combined to form the overall meso level route benefit measure associated with a single complete activity chain.

$k_a$ Denotes the identifier/location of the *a-th* activity present within the activity schedule.

$S$ The subscript denotes the number of different routes ($m$) available within the space-time prism, which satisfy the individual's principle coupling constraints.

$a_{Sk_a}$ A scalar parameter, denoting the attractiveness of the location/opportunity in question.

$\alpha_{la}$ A parameter defining the marginal utility of the attractiveness of the activity undertaken at the opportunity/facility location for individual *l*.

$\beta_{la}$ A parameter defining the marginal utility of the activity participation time associated with the activity undertaken at the opportunity/facility location for individual *l*.

$\lambda_{la}$ Spatial/temporal based travel impedance parameter for individual *l*, positive in magnitude, used to define the effect of increased spatial or temporal separation on the user benefit measure associated with activity a.

$\mu_{la}$ Route delay temporal impedance parameter for individual *l*, positive in magnitude, used to define the effect of increased non-transit delay on the user benefit measure associated with activity a.

$\gamma_{la}$ Facility temporal impedance parameter for individual *l*, positive in magnitude, used to define the effect of increased facility wait time on the user benefit measure associated with activity a.

$\eta_{la}$ Activity temporal impedance parameter for individual *l*, positive in magnitude, used to define the effect of increased activity wait time on the user benefit measure associated with activity a.

$\nu_{la}$ Late start time penalty deterrence parameter for individual *l*, positive in magnitude, used to define the effect of increased late start time on the user benefit measure associated with activity a.

Introducing the power transformations outlined earlier in equations 13 and 14, utilising multiplication as the secondary binary operation and assuming homogeneity of the model parameters across activities, it follows that equation 23 can be expressed as:

$$BM_{RIS_{1...m}} = \oplus_1 \left| \exp\left( \left( a_l \ln a_s + b_l \ln T_s \right) - \left( l_l t_s + m_l D_s + g_l w_s + h_l W_s + n_l L_s \right) \right) \right| \qquad (24)$$

Where:

$t_S$ Total travel time encountered along the route S, reflecting the cumulative travel time required to reach all activity locations situated on the route S.

$D_S$ Total route delay encountered along the route S, reflecting the cumulative amount of non-travel time (interchange time, queuing time, parking time etc) spent in transit enroute between all activities situated on the route.

$w_S$ Total facility wait time encountered along the route S, reflecting the cumulative amount of time spent waiting for the schedule related opportunities to open.

$W_S$ Total activity wait time encountered along the route S, reflecting the cumulative amount of time spent waiting to commence schedule related activities.

$L_S$ Total late start time encountered along the route S, reflecting the cumulative amount of late start time associated with all the scheduled activities.

$T_S$ Total activity participation time utilised along the route S, reflecting the cumulative amount of time an individual can spend in undertaking activities present within his/her schedule.

$a_S$ Total attractiveness of facilities utilised for activity participation along the route S.

Comparing the above expression with equation 15 and considering Burns' (1979) generic locational and route benefit measures outlined earlier in equations 1 and 2 respectively, it can be seen that the above expression is a route benefit/route opportunity measure entirely consistent with Burns' (1979) proposition. This interesting result enables us to develop a series of space-time utility accessibility measures applicable to activity schedules.

Rearranging and replacing the benefit measure annotation BM with that of utility U and removing the primary binary operation notation $\oplus_1$, it can thus be shown that equation 24 can be expressed as:

$$U_{RlS_{1..m}} = \exp\left[\left(l_l m_l g_l h_l n_l\right)\left(\left(\frac{a_l \ln a_s + b_l \ln T_s}{l_l m_l g_l h_l n_l}\right) - \left(\frac{t_S}{m_l g_l h_l n_l} + \frac{D_S}{l_l g_l h_l n_l} + \frac{w_S}{l_l m_l h_l n_l} + \frac{W_S}{l_l m_l g_l n_l} + \frac{L_S}{l_l m_l g_l h_l}\right)\right)\right] \quad (25)$$

Adopting similar principles to those outlined earlier in sections 2.3-2.6 inclusive (namely consumer welfare maximisation, consumer welfare aggregation and utility maximising choice behaviour within a random utility framework) it thus becomes possible to derive the following activity schedule based space-time utility accessibility measures:

$$STUAM_{RlS_{1..m}} = \max_{S_{1..m}}\left[\exp\left[\left(l_l m_l g_l h_l n_l\right)\left(\left(\frac{a_l \ln a_s + b_l \ln T_s}{l_l m_l g_l h_l n_l}\right) - \left(\frac{t_s}{m_l g_l h_l n_l} + \frac{D_s}{l_l g_l h_l n_l} + \frac{w_s}{l_l m_l h_l n_l} + \frac{W_s}{l_l m_l g_l n_l} + \frac{L_s}{l_l m_l g_l h_l}\right)\right)\right]\right] \quad (26)$$

$$STUAM_{RlS_{1..m}} = \sum_{S=1}^{m}\left[\exp\left[\left(l_l m_l g_l h_l n_l\right)\left(\left(\frac{a_l \ln a_s + b_l \ln T_s}{l_l m_l g_l h_l n_l}\right) - \left(\frac{t_s}{m_l g_l h_l n_l} + \frac{D_s}{l_l g_l h_l n_l} + \frac{w_s}{l_l m_l h_l n_l} + \frac{W_s}{l_l m_l g_l n_l} + \frac{L_s}{l_l m_l g_l h_l}\right)\right)\right]\right] \quad (27)$$

$$STUAM_{kS_{1\_m}} = \frac{1}{l_l m_l g_l h_l n_l} \times \ln \sum_{S=1}^{m} \exp\left( \exp\left[ \left( l_l m_l g_l h_l n_l \right) \left( \left( \frac{a_l \ln a_s + b_l \ln T_s}{l_l m_l g_l h_l n_l} \right) - \left( \frac{t_s}{m_l g_l h_l n_l} + \frac{D_s}{l_l g_l h_l n_l} + \frac{w_s}{l_l m_l h_l n_l} + \frac{W_s}{l_l m_l g_l n_l} + \frac{L_s}{l_l m_l g_l h_l} \right) \right) \right] \right)$$

*(28)*

Use of the homogenous route benefit measure assumption inherent in equations 24 and 25 poses the question as how best to define an attractiveness term that is transferable across different types of activity. Whilst Burns (1979) acknowledged that the *'…notion of attribute aggregation…'* was equally applicable to a single activity location as well as a series of distinct activity types, it is apparent that the challenges associated with attribute aggregation increase, as the range of activities increases.

The original route benefit measure presented in equation 23, with its heterogeneous attractiveness terms, marginal utility of attractiveness and activity participation time, in addition to heterogeneity in the travel, route delay, facility, activity and late start temporal impedance parameters, can be utilised in this original form, to develop a similar series of space-time utility accessibility measures for individual activity schedules.

It is worth noting that the space-time route benefit measures and associated space-time utility accessibility measure presented in section 2.7 are a family of measures which when simplified can be shown to encompass the principle accessibility measures which have historically been used by transport and land-use planners. Examples include the Shimbel, gravity/Hansen, cumulative opportunity, space-time and behavioural utility accessibility measures.

**2.8. Space-Time Accessibility Measures and Financial Constraints**

In the following discussion an outline is presented of how income factors can be incorporated within space-time utility accessibility measures. To date these measures have excluded consideration of financial constraints, which in practice serve to limit the range of land-use-transport options and associated activity schedules available to the individual.

The travel time, route delay, facility wait time, activity wait time and late start time parameters can be estimated by utilising expressions similar in form to the following expression, as proposed by Odoki *et al* (2001):

$$I = w\left(\frac{c}{rI} + \frac{1}{v}\right) \qquad (29)$$

Which forms part of a negative exponential deterrence function of the form:

$$g(x) = \exp(-lx) \qquad (30)$$

Where:

- $c$ Monetary cost of travel per unit distance of travel.
- $I$ Income/monetary benefit or utility expected for the individual as a result of undertaking the activity undertaken downstream of the travel episode under consideration.
- ρ Parameter which varies according to the activity/journey purpose, mode of travel, travel time and which decreases as a function of income$^{0.25}$ as proposed by Goodwin (1976).
- ρ$I$ Denotes the value of travel time per hour to the individual under consideration.
- ω Denotes the relative effort of the individual to travel using the transport mode in question (ω ≥ 1).
- $t$ Spatial separation between the origin and destination points.
- $v$ Average speed of travel for the transport mode in question between the origin and destination points.

Equation 29 exhibits diminishing marginal utility of income properties, in which as individual income falls the velocity or speed of travel is less of a factor compared to the cost of travel, which will dominate. In contrast, as income rises the cost of travel is less of a factor with velocity or speed of travel being the determining factor. In addition higher income groups will in the main have larger travel time, route delay, facility wait time, activity wait time and late start time parameters than lower income groups.

### 2.9. Implementation of Activity Chain Utility Measures of Accessibility

The family of space-time accessibility measures can be implemented using existing travel or activity diary datasets utilised in conjunction with stochastic frontier models of prism vertices. Stochastic frontier models, formerly utilised by Kitamura *et al* (2001, 2000) and Pendyala *et al* (2002) in the context of space-time prisms are used since travel diary datasets do not contain explicit information on all temporal timings of constraining mandatory activities. The technique involves the use of observed trip start and end times as the dependent variables within the model, together with a series of socio-economic, demographic, individual and household attribute data utilised as the independent variables. The stochastic frontier model of prism vertices is used to identify

the approximate temporal location of the unobserved frontier, namely the upstream or downstream vertex.

The activity attractiveness, activity participation time, travel time, route delay, facility wait time, activity wait time and late start time penalties can be estimated using stated preference techniques or revealed preference techniques used in conjunction with travel/activity diary datasets.

## 3. CASE STUDY

The case study in question is implemented within the English county of Surrey, a region bordering southwest London with a population of over 1 million residents; and a region having amongst the highest recorded car availability rates of any part of the UK. Heathrow and Gatwick airports, the United Kingdoms two busiest airports, are both located immediately adjacent to Surrey's borders. A number of major strategic roads pass through Surrey including the M25, one of Europe's busiest motorways.

A detailed spatially referenced transport network of Surrey, encompassing cycle and walk modes of travel is utilised in the case study, with existing land-use facilities modelled within a point based spatially referenced framework.

A hypothetical activity schedule is outlined in table 1 for a working parent with child rearing responsibilities. In the following case study a heterogeneous formulation of the space-time route benefit measure outlined in equation 23 and discussed in section 2.7, together with a consumer welfare aggregation user benefit translation mechanism is considered. Table 2 outlines the hypothetical values for the activity attractiveness, the activity participation marginal utility parameters, as well as the travel time, route delay, facility wait time, activity wait time and late start time model parameters associated with each adjacent pair of activities present within the activity schedule outlined in table 1.

The hypothetical model parameters vary in accordance with the relative importance of the activity. The parameters are greatest for constraining activities such as employment, progressively falling for school related activities and home based activities which are more flexible in nature, reflecting the increased importance (namely the greater disutility of non-activity time) that the individual accords to employment activity relative to other activities. For the employment activity the late start time parameter is greater than the travel time and route delay parameters which in turn are greater than the facility and activity wait time parameters, reflecting the greater disutility of activity late

start in comparison to travel time and route delay. The facility and the activity wait time parameters are smaller in magnitude than the travel time and route delay parameters, reflecting the greater positive utility of facility and activity wait time.

Table 3 outlines the attractiveness of the activity locations associated with the activity schedule under consideration, together with details of the opening and closing times of the activity locations. For the purposes of the case study it is assumed that all employment activity locations have identical attractiveness. The attractiveness of primary schools on the other hand is assumed to be a function of the size (i.e. the pupil roll) of the school. Table 4 outlines the five scenarios considered whilst tables 5, 6 and 7 contain details of the activity schedule and land-use characteristics associated with the scenario options 3 and 4.

### 3.1. Case Study Results

Figures 3a and 3b depict the space-time utility accessibility measure associated with consumer welfare aggregation route benefit translation mechanism for uni-modal travel by walk and cycle modes (for the current analysis the model parameters are assumed to be independent of mode of travel). The figures indicate that in the study area space-time utility accessibility is lowest for walk only travel, due to the lower rate at which the mode of travel overcomes space, in comparison to cycle travel. The two figures also show that space-time utility accessibility is greatest for the regions located between the Surrey towns of Guildford and Woking, indicating the that individuals undertaking the activity schedule in question would have the opportunity of undertaking activities in both Guildford and Woking were their homes to be located between the two town centres. In contrast alternative locations on the periphery of Guildford and Woking do not offer such opportunities for the individual.

Figures 4 to 7 inclusive depict the change in space-time accessibility, relative to the base case scenarios depicted in figure 3a and figure 3b for the scenario options 1 to 4 inclusive outlined in table 4.

Figures 4a and 4b indicate that the greatest improvement in accessibility as a consequence of the introduction of new walk and cycle links to the north-east of Guildford, arises in the immediate vicinity of the new links, but also extends further into adjoining regions along the transport corridors. Individuals located in the vicinity of the new transport links would experience a significant improvement in space-time utility

accessibility relative to other parts of the study area as a consequence of the new transport infrastructure.

Figures 5a and 5b demonstrate that the introduction of a new employment location to the west of Guildford, in a region formerly devoid of such a facility improves space-time utility accessibility greatest in the immediate vicinity of the new facility. The figures also indicate that home and primary school locations in the vicinity of the new employment location become increasingly accessible from the perspective of the individual's overall activity schedule, with the improvement in accessibility extending eastwards along the transport corridors towards Guildford and Woking. However comparison of figures 4 and 5 reveals that the magnitude and extent of the accessibility improvement are lower than that associated with the introduction of new transport infrastructure.

Figures 6a and 6b illustrate the beneficial effect of the extension of the opening time of employment and school facilities in association with an earlier start time of a number of activities present within the activity schedule. The two figures show that the majority of regions within the study area benefit from an increase in accessibility as a consequence of the facility and schedule related timing changes. For walk only travel the greatest accessibility improvements occur around Guildford and Woking whilst for cycle travel the greatest improvement in accessibility occurs in the region located between Guildford and Woking. Comparison of figures 4 and 6 reveals that the magnitude and the extent of the accessibility improvement are greater than that associated with the introduction of new transport infrastructure.

Figures 7a and 7b highlight the accessibility benefits for the individual of undertaking a modified activity schedule encompassing flexible working benefits with a half-hour extension of the latest start time of the employment activity. The figures reveal that the majority of areas located within the study area experience an improvement in accessibility as a consequence of the implementation of flexible working policies. For walk only travel the greatest accessibility improvements occur between Guildford and Woking as well as on the periphery of the two towns. The lowest improvement in walk accessibility arises within the two towns. For cycle travel the greatest improvement in accessibility occurs on the periphery of Guildford and Woking with the region located between the two towns experiencing the lowest improvement. Comparison of figures 6

and 7 reveals that the magnitude and the extent of the accessibility improvement are greater than that associated with the facility and schedule related timing changes.

For all four options considered the magnitude of the accessibility improvement and the associated spatial coverage of this improvement is greatest for cycle travel in comparison to walk travel. It is also evident from figures 4 to 7 inclusive that flexible working policies and extended opening times of facilities offer a greater opportunity to improve the magnitude and spatial coverage of individual accessibility than is possible with new transport infrastructure or with new land-use facilities. The benefit-cost ratio (e.g. the ratio of accessibility improvement to cost of implementation) is far greater for flexible working and extended opening than for the more expensive introduction of new transport and land-use infrastructure.

## 4. SUMMARY

The family of space-time user benefit and space-time utility accessibility measures outlined in this paper, represents a significant advance on existing measures of accessibility. These existing measures have in the main tended to consider single disjointed activity/trip episodes often analysed at an aggregate level in addition neglecting the constraining effect of time and income on individual accessibility as well as the utility of activity participation.

In particular the incorporation of route delay, facility wait, activity wait and late start temporal terms within the underlying locational and route benefit measures facilitates the determination of more robust and realistic series of space-time utility accessibility measures, hitherto unused by researchers. The case study analysed illustrates that the user benefit measures and associated accessibility measures respond in the anticipated manner to the range of transport, land-use, activity schedule and travel cost related measures considered. The case study presented demonstrates the strength and potential of the family of space-time user benefit and related space-time utility accessibility measures for developing a wider, more holistic range of transport, land-use, activity schedule and travel cost related solutions to increase individual accessibility thereby promoting an improved potentially more socially inclusive land-use transport environment.

In particular the family of space-time route benefit measures and related space-time utility accessibility measures can be utilised in the development of equitable land-use transport policies, new/improved transport networks, reliable integrated transport

networks, new/improved land-use facilities, new/improved forms of service delivery, extended facility opening, improved scheduling of transport and land-use services, flexible working policies, concessionary fare schemes, transport pricing regimes, salary/taxation changes amongst others.

### 4.1. Future Research

Despite the advantages of the proposed approach for determining individual space-time utility accessibility, there are a number of assumptions and areas for future research that can be identified:

- The technique, while satisfying a number of axioms present within Weibull's (1976, 1980) axiomatic framework, also violates several axioms. Weibull's axiomatic framework provides a mechanism for ensuring that accessibility measures are both internally and externally consistent. However the framework excludes a number of observed forms of spatial choice behaviour, one of which is multi-stop travel. A fruitful area of future research could involve the extension of Weibull's axiomatic framework to encompass multi-stop travel.
- The route benefit based logsum space-time utility accessibility measure presented in equation 29 is based upon a multinomial logit decision making process and is thus likely to violate the axiom of independence from irrelevant alternatives (IIA). In addition the existence of non-linear income effects present within the model parameters, violates the requirement identified by McFadden (1998) for log-sum benefit measures to be linear functions of income. An area of future research is to apply the family of route benefit measures outlined herein to alternative choice mechanisms for instance generalisation of the random utility framework beyond IID using the mixed multinomial logit, McFadden & Train (2000), or the competing destinations choice model, Fotheringham & O'Kelly (1989).

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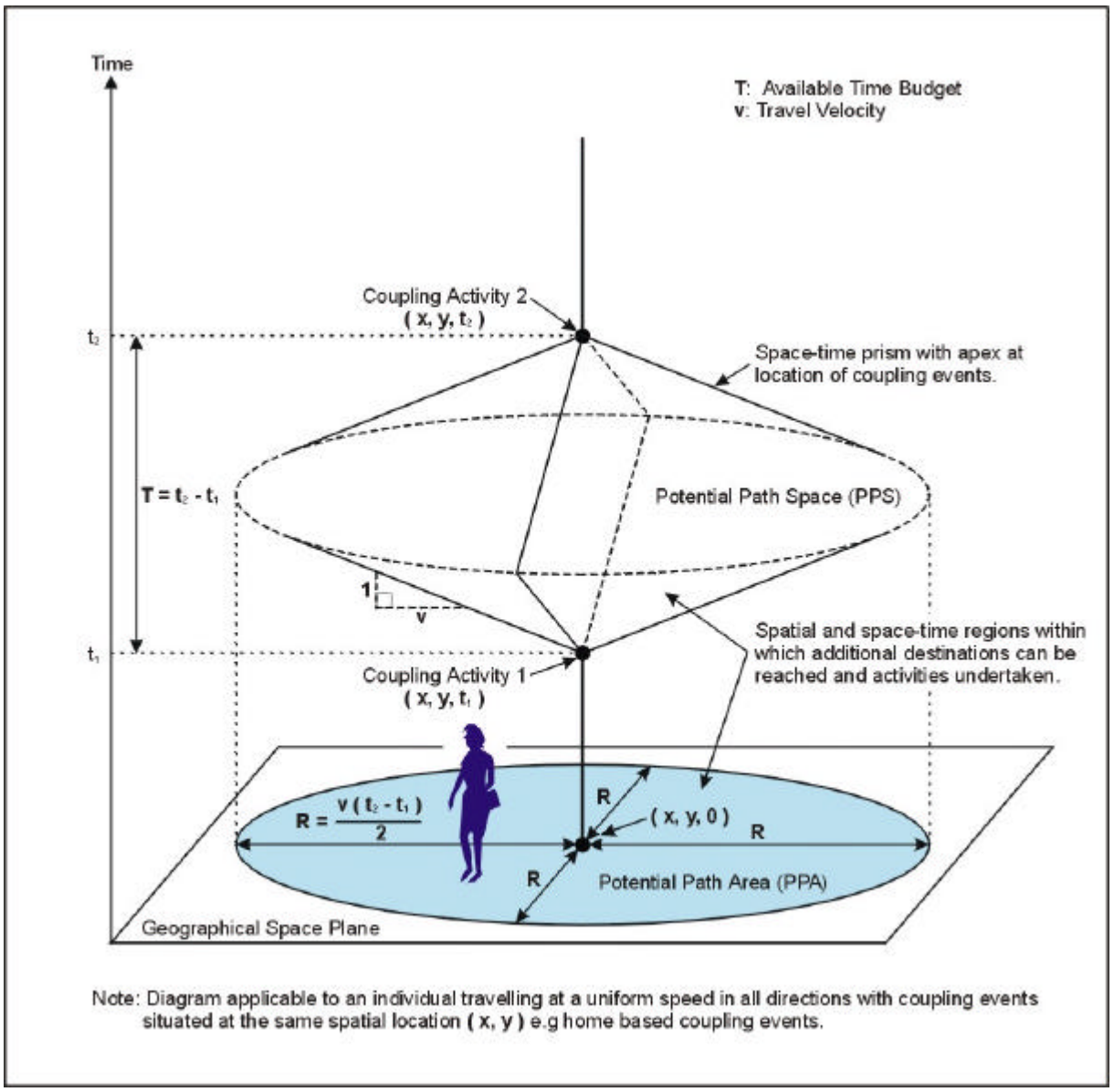
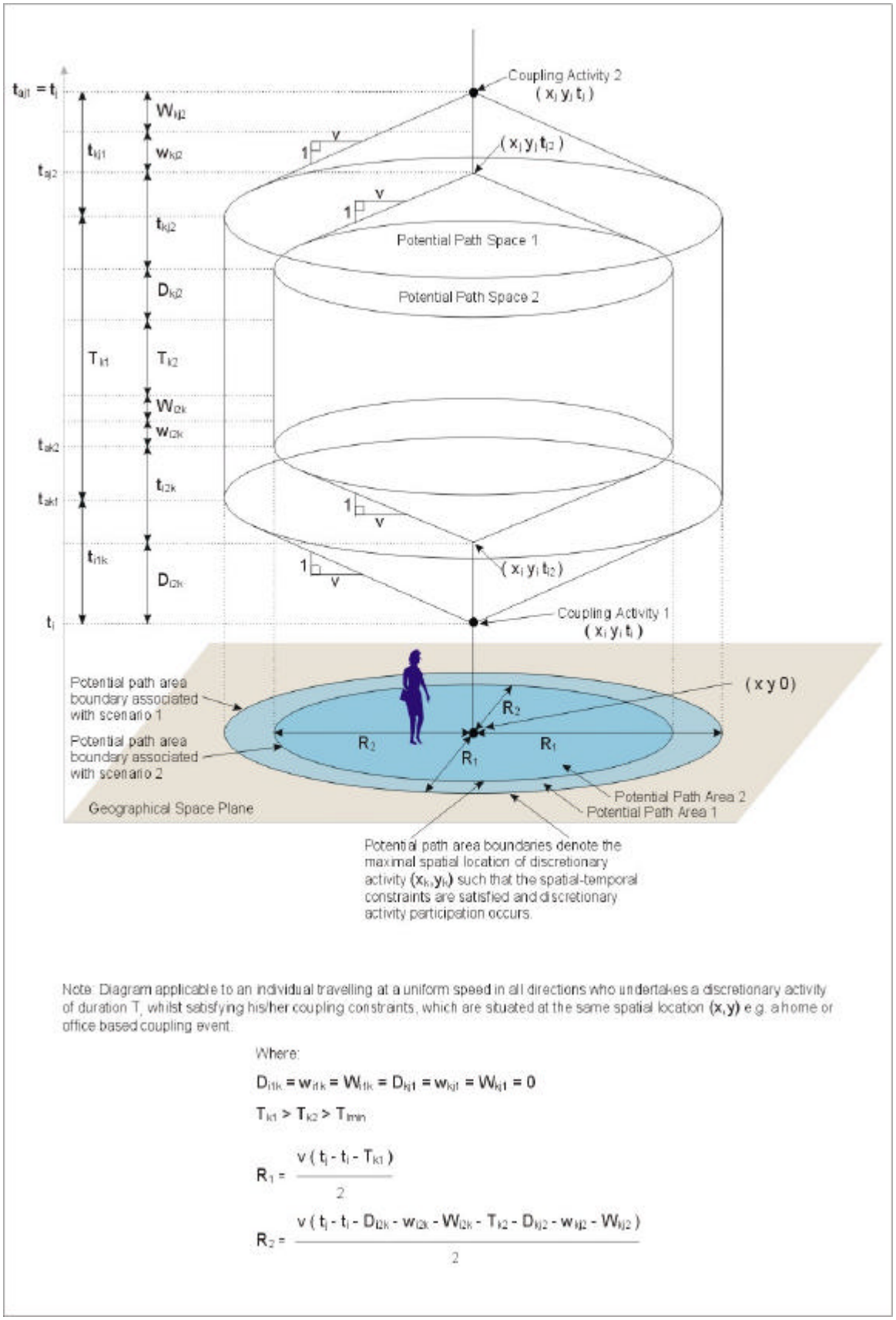
**Figure 1: Space-Time Prism For An Individual Constrained By Two Coupling Events**




Note: Diagram applicable to an individual travelling at a uniform speed in all directions with coupling events situated at the same spatial location ( x, y ) e.g home based coupling events.

**Figure 2: Space-Time Prism For An Individual Undertaking A Discretionary Activity Constrained By Two Coupling Events**




Note: Diagram applicable to an individual travelling at a uniform speed in all directions who undertakes a discretionary activity of duration $T_k$ whilst satisfying his/her coupling constraints, which are situated at the same spatial location **(x,y)** e.g. a home or office based coupling event.

Where:

$$D_{i1k} = w_{i1k} = W_{i1k} = D_{kj1} = w_{kj1} = W_{kj1} = 0$$

$$T_{kj1} > T_{kj2} > T_{kmin}$$

$$R_1 = \frac{v\,(t_j - t_i - T_{kj1})}{2}$$

$$R_2 = \frac{v\,(t_j - t_i - D_{i2k} - w_{i2k} - W_{i2k} - T_{kj2} - D_{kj2} - w_{kj2} - W_{kj2})}{2}$$

**Figure 3: Consumer Welfare Aggregation Space-Time Utility Accessibility By Transport Mode**

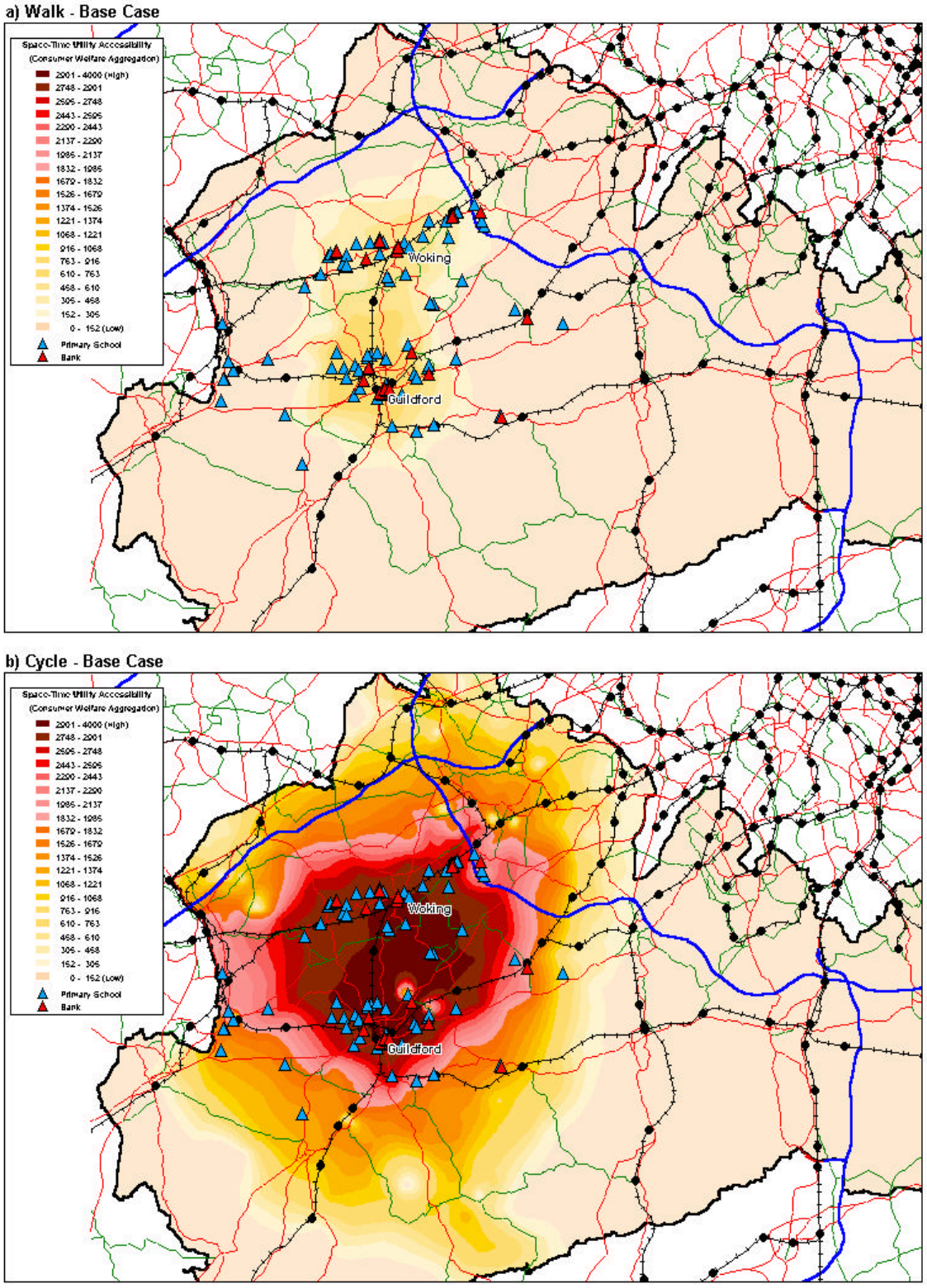


**Figure 4: Improvement In Space-Time Utility Accessibility For Walk & Cycle Travel - Option 1**

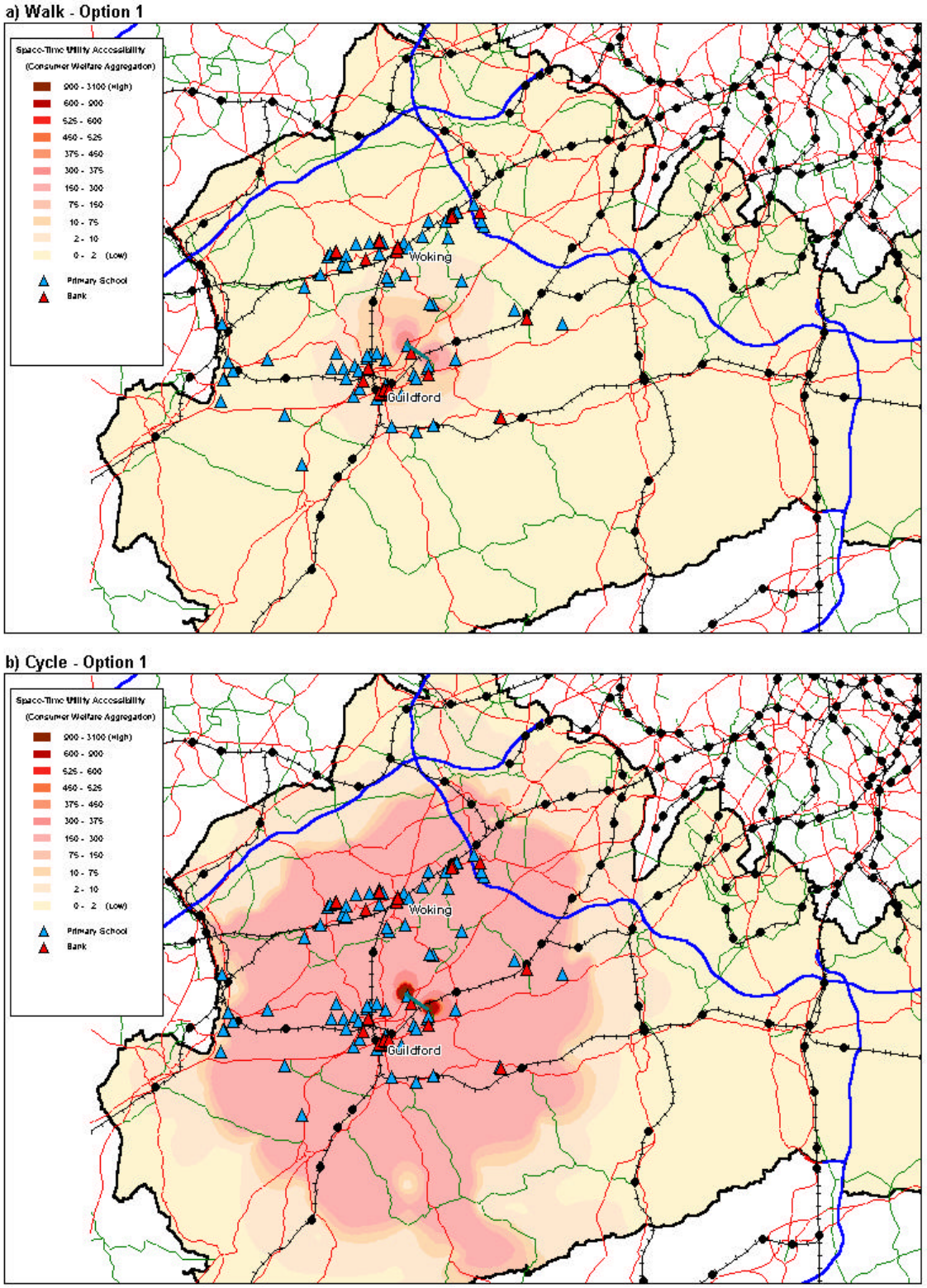


**Figure 5: Improvement In Space-Time Utility Accessibility For Walk & Cycle Travel - Option 2**

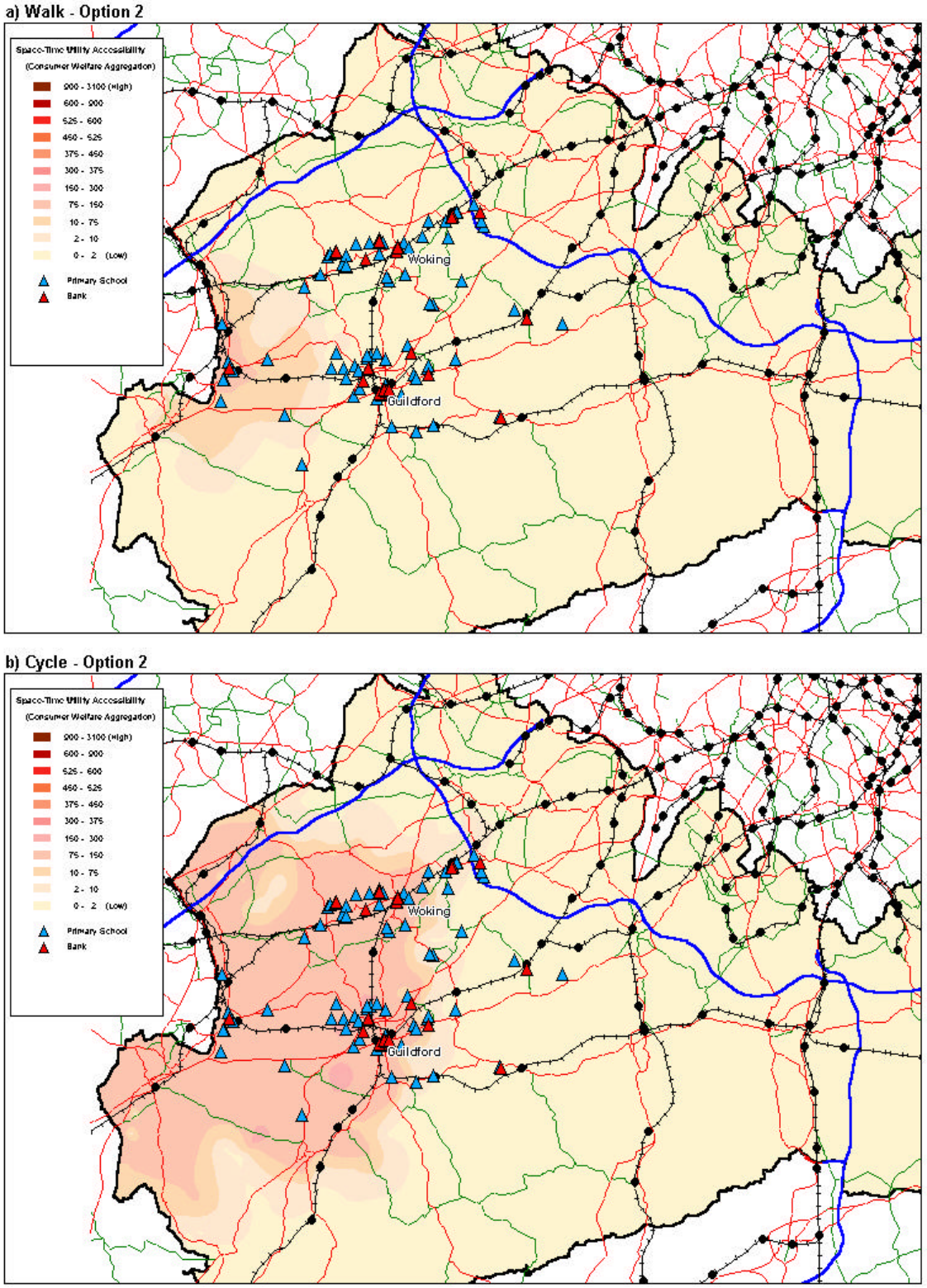


**Figure 6: Improvement In Space-Time Utility Accessibility For Walk & Cycle Travel - Option 3**

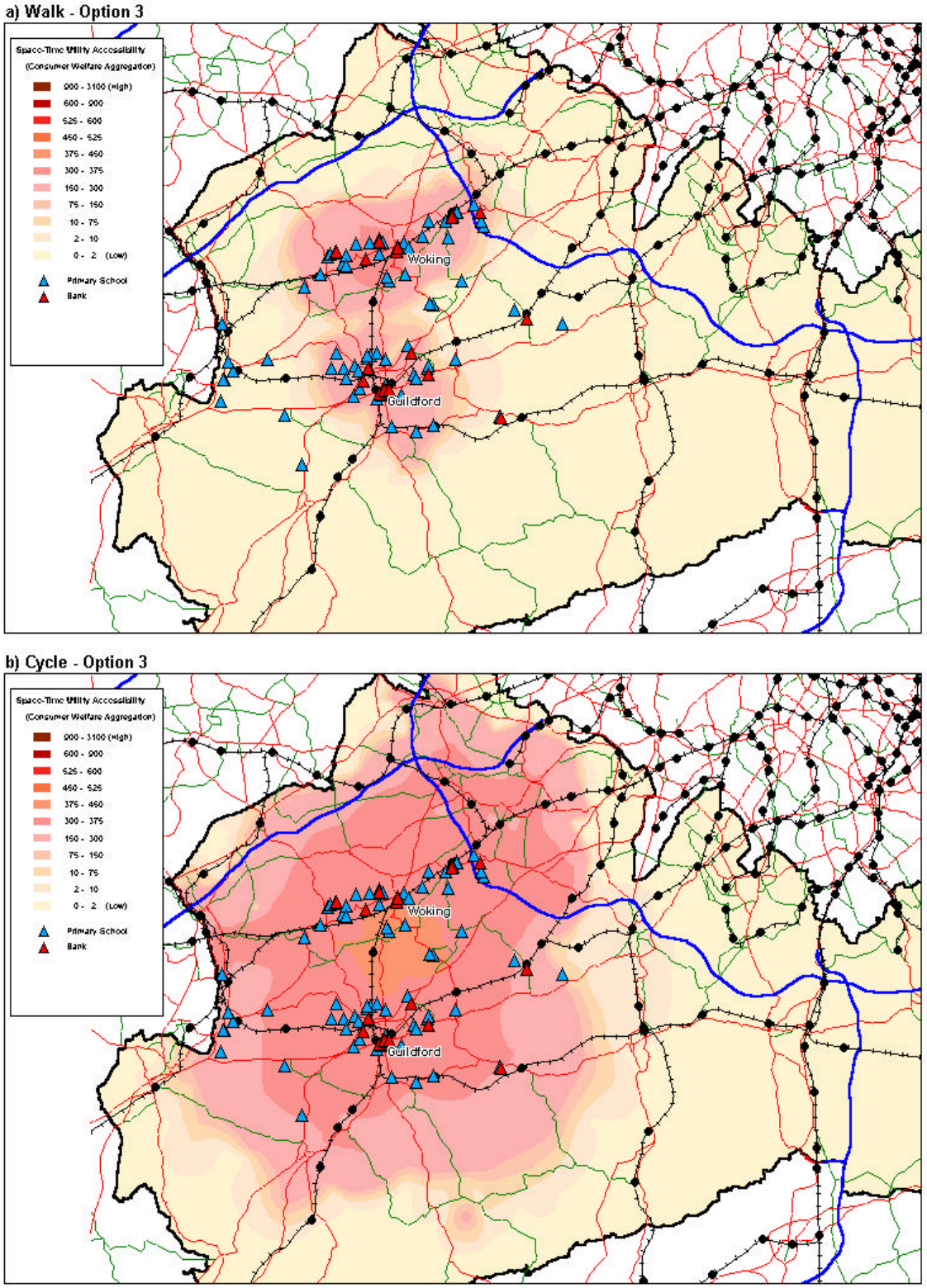


**Figure 7: Improvement In Space-Time Utility Accessibility For Walk & Cycle Travel - Option 4**

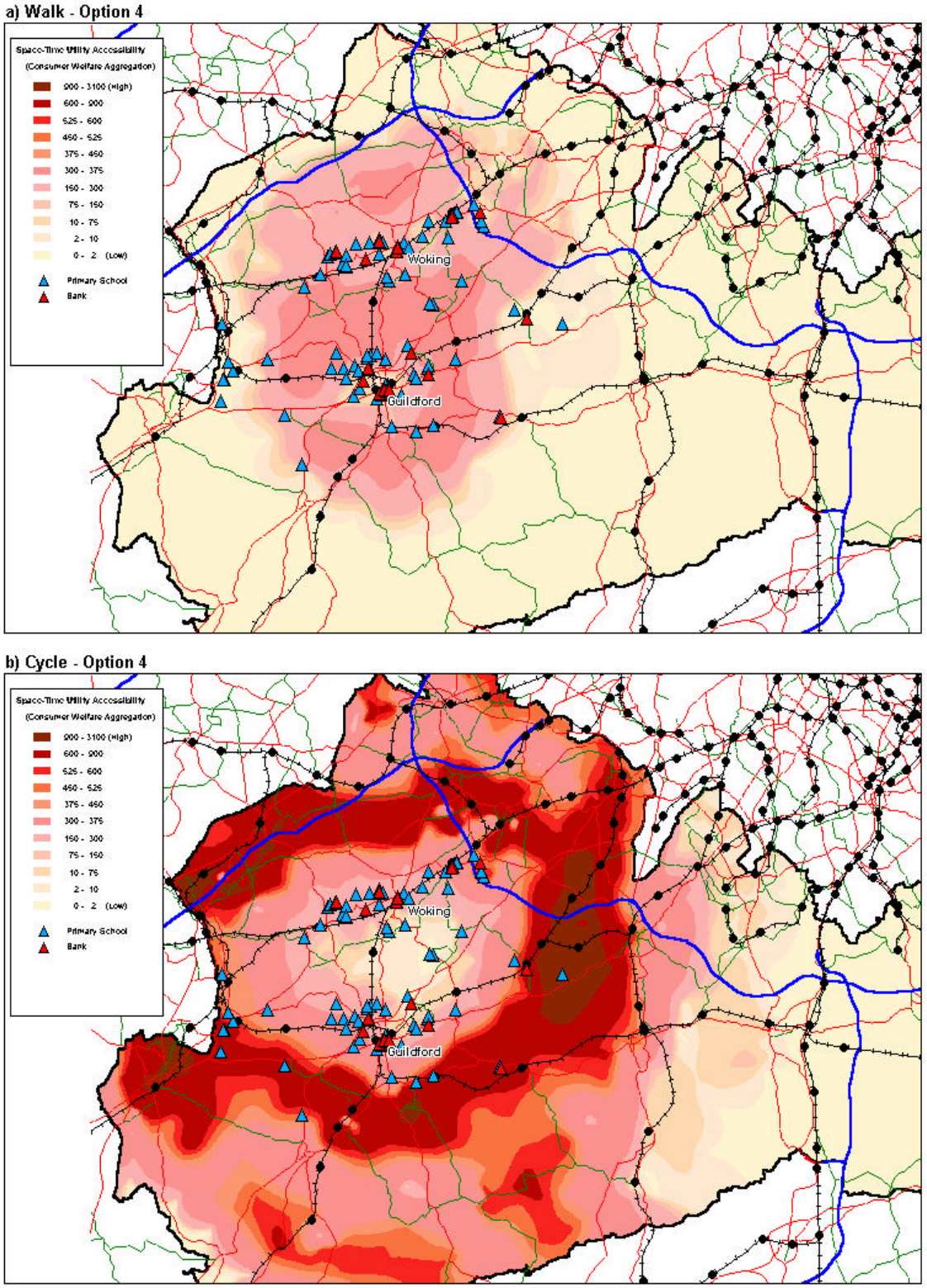


**Table 1: A Hypothetical Activity Schedule - Base Case**

| Activity No. | Activity Description | Earliest Start Time | Latest Start Time | Activity Duration (mins) |
|---|---|---|---|---|
| 1 | Home, prepare for the day. | 06:45 | 06:45 | 60 |
| 2 | Drop child at primary school. | 08:45 | 09:00 | 5 |
| 3 | Undertake part-time employment at a bank. | 09:00 | 09:30 | 300 |
| 4 | Collect child from primary school. | 15:15 | 15:30 | 5 |
| 5 | Home, prepare for the evening. | 16:30 | 17:00 | 30 |

**Table 2: Space-Time Route Benefit Activity Schedule Model Parameters**

| Activity No. | Activity Description | Attractiveness ($\alpha$) | Participation Time ($\beta$) | Travel Time ($\lambda$) | Route Delay ($\mu$) | Facility Wait Time ($\gamma$) | Activity Wait Time ($\eta$) | Late Start Time ($\nu$) |
|---|---|---|---|---|---|---|---|---|
| 1 | Home, prepare for the day. | 0.15 | 0.20 | 0.25 | 0.10 | 0.10 | 0.15 | 0.10 |
| 2 | Drop child at primary school. | 0.40 | 0.30 | 0.40 | 0.10 | 0.15 | 0.15 | 0.15 |
| 3 | Undertake part-time employment at a bank. | 0.40 | 0.35 | 0.65 | 0.65 | 0.50 | 0.50 | 0.80 |
| 4 | Collect child from primary school. | 0.40 | 0.30 | 0.40 | 0.10 | 0.15 | 0.15 | 0.15 |
| 5 | Home, prepare for the evening. | 0.15 | 0.20 | 0.25 | 0.10 | 0.10 | 0.15 | 0.10 |

**Table 3: Attractiveness & Opening & Closing Times Of Land-Use Facilities**

| Land-Use Facility Description | Opening Time | Closing Time | Attractiveness |
|---|---|---|---|
| Primary School | 08:45 | 15:30 | Proportional to pupil roll. |
| Bank | 09:00 | 17:00 | Constant for all banks. |

## Table 4: Summary Of Analysed Case Study Scenarios

| Scenario | Scenario Description |
|---|---|
| Base Case | A hypothetical activity schedule in conjunction with the existing land-use-transport environment. |
| Option 1 | A hypothetical activity schedule with no changes to the existing land-use facilities in conjunction with the incorporation of improvements to the transportation network. |
| Option 2 | A hypothetical activity schedule with no changes to existing transport network in conjunction with the incorporation of a new employment facility. |
| Option 3 | A hypothetical activity schedule with no changes to existing transport network in conjunction with an extension of the earliest start time of several activities commensurate with an extension of the opening time of existing land-use facilities. |
| Option 4 | A modified hypothetical activity schedule incorporating flexible working benefits (extension of latest start time of employment activity) with no changes to existing land-use transport network. |

## Table 5: A Modified Hypothetical Activity Schedule - Option 3

| Activity No. | Activity Description | Earliest Start Time | Latest Start Time | Activity Duration (mins) |
|---|---|---|---|---|
| 1 | Home, prepare for the day. | 06:45 | 06:45 | 60 |
| 2 | Drop child at primary school (an early morning pre-school club is available). | 08:30 | 09:00 | 5 |
| 3 | Undertake part-time employment at a bank. | 08:30 | 09:30 | 300 |
| 4 | Collect child from primary school. | 15:15 | 15:30 | 5 |
| 5 | Home, prepare for the evening. | 16:30 | 17:00 | 30 |

## Table 6: Extended Opening Times Of Land-Use Facilities - Option 3

| Land-Use Facility Description | Opening Time | Closing Time |
|---|---|---|
| Primary School | 08:30 | 15:30 |
| Bank | 08:30 | 17:00 |

**Table 7: A Modified Activity Schedule Incorporating Flexible Working - Option 4**

| Activity No. | Activity Description | Earliest Start Time | Latest Start Time | Activity Duration (mins) |
|---|---|---|---|---|
| 1 | Home, prepare for the day. | 06:45 | 06:45 | 60 |
| 2 | Drop child at primary school. | 08:45 | 09:00 | 5 |
| 3 | Undertake part-time employment at a bank (flexible working). | 09:00 | 10:00 | 300 |
| 4 | Collect child from primary school. | 15:15 | 15:30 | 5 |
| 5 | Home, prepare for the evening. | 16:30 | 17:00 | 30 |