A new concept of accessibility to personal activities: Development of theory and application to an empirical study of mobility resource holdings

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ABSTRACT

The notion of spatio-temporal accessibility to [potential] out-of-home activities is central to transport geography. This paper extends existing theory by proposing a new concept of accessibility, termed the 'perceived activity set' (PAS). A person's PAS is defined as the set of out-of-home activities which they view as encompassing their potential travel needs when making decisions that structurally affect their accessibility. In other words, it is proposed that a person's mobility-linked choices such as, for instance, where to live or whether to own a car, are a function of how such choices affect their ability to access out-of-home activities they consider relevant.

This paper first formalises the PAS and places it in the wider context of accessibility theory. It then presents an empirical study that makes use of the PAS concept, which analyses people's ownership of several mobility resources that each enable particular forms of travel. The PAS appears promising, as it unlocks a class of flexible techniques that relax restrictive assumptions regarding the drivers behind structural choices related to personal mobility.

The techniques were found to be analytically tractable, and the empirical analysis based on the PAS yielded a number of insights. The advantages of using long-duration diaries with PAS-based techniques, rather than more-common one-day diaries, are shown to be large. It was found that the more 'substantial' a mobility resource is (in terms of expense and commitment) the better the PAS concept is at explaining patterns of ownership.

The paper concludes with suggested directions for research to further develop the PAS concept, which include refinements to the quantitative techniques, extension to other structural mobility choices, and qualitative research into the nature of the relationship between people's perceived needs for mobility and their expected activity patterns over longer periods than are observed by most activity and travel surveys.

Key words: Accessibility, perceived activity set, mobility resource

1 Introduction

Taking part in many of life's obligations and opportunities involves traversing space, therefore understanding the nature of various types of accessibility, and the associated spatio-temporal patterns of human activities, has broad implications for economic development, resource usage, planning and designing human environments, and degradation of the natural environment.

This line of research aims to better understand how people's interactions with the environment around them are manifested in their needs/wants for personal travel. This paper introduces the *perceived activity set* (PAS), a new concept of personal accessibility to [potential] out-of-home activity locations. It is defined as:

> *the array of activities which a person views (at a particular point in their life) as encompassing their potential travel needs, when making decisions that structurally affect their accessibility*

Decisions that structurally affect accessibility would include, among others, whether to own a car, as well as where one chooses to live and the location of other anchor points such as one's place of work. The PAS concept is based on a hypothesised two-way relationship between decisions of this nature and personal travel needs. To take one example, in some cities accessibility to routine out-of-home activities such as shopping and working is shaped by whether one owns a personal car. At the same time, it is quite intuitive to hypothesise that a person's choice of whether to own a car depends in some way on the degree of access it offers to the activities they consider relevant to their life.

In this paper, the PAS concept is investigated by way of an empirical study of people's *mobility resource* holdings. A mobility resource is defined as any product, service, status, or information that enables or facilitates travel in some way. Examples include a personal car, petrol, one's health condition and functional abilities, a driver's license, a public transport ticket (whether pay-per-journey or season ticket), a bicycle, subscription to a car-sharing service, walking shoes, membership in a frequent-flyer programme, a passport, a walking stick, etc.

In addition to being able to predict whether a person owns a car or not, as in classical transport analyses, it is increasingly important to understand how people match between sets of travel needs and sets of travel tools, to, for instance, understand engagement with emerging mobility services such as bike-sharing, lift-sharing, and car-sharing. Such mobility systems generally address only a [small] part of a person's travel needs. Understanding their take-up (and knock-on effects) thus requires some assessment of how they fit in the wider context of a person's mobility needs and available resources.

The empirical study, which was designed to investigate the empirical usefulness of the PAS concept, looks at people's holdings of three widely-held, durable, market-traded and substantial mobility resources that one generally acquires in advance of (rather than at the time of) travel: personal cars, bicycles, and public transport season tickets.

The remainder of this paper is organised as follows. Section two reviews the literature first on earlier notions of personal accessibility and then on mobility resources, and draws comparisons between the former and the PAS concept. Section three outlines the analytical methods of the empirical study, with results presented in Section four. Section five concludes the paper, including a discussion of the limitations of this empirical study, and discusses directions for future research.

2 Background

2.1 Accessibility measures

In a traditional sense accessibility refers to personal accessibility – the ability to transport oneself to/from locations which, at particular times, offer the possibility of participating in life activities (e.g. shopping, employment, caring, education, socialising, etc.) Technological developments – the post, telephone, internet, card payment, and mobile telephony / computing amongst them – have however somewhat mitigated the value of physical presence for some types of human activities. On the basis of evidence of today's young people reporting a mobile phone to be a higher-priority 'must-have' than a car, it may well be that this process has accelerated in recent years (Motavalli 2010). Regardless of whether this short-term trend proves to be sustained over time, it does appear that despite the role played by other-than-personal mobilities – Urry (2002) defines and discusses *object*, *virtual*, and *imaginative* forms of travel – the ability to deliver oneself to and from particular places at particular times will remain desirable or imperative for many types of personal activities.

Hagerstrand introduced the fundamental concept of a *time-space prism*, which in principle sets the boundaries, and the time-space volume contained within, which can be reached by a person able to travel at a given fixed rate of speed and having a given amount of time before returning to their starting point (Hagerstrand 1970). A term closely-linked to the time-space prism is the *action space* in which a person operates, defined by Horton and Reynolds as 'the collection of all urban locations about which the individual has information and the subjective utility or preference he associates with these locations.' More recent research into quantifying the nature of the time-space prisms that constrain people's accessibility includes studies reported by Pendyala and colleagues (2002) and Miller (1999). The extension of these ideas to account for heterogeneity of travel speeds (in a world where much travel takes place on differentiated networks) leads to distortions in the shape of such spaces. Practical applications frequently involve analysts investigating the aggregation or patterns of such metrics across a region or population of interest.

Kwan (1998) highlights the dichotomy between 'place' and 'person' accessibility metrics – those that are constructed as attributes of a *location* (or frequently an aggregation of locations into a spatial zone) versus those that relate to individual people. While place-based metrics have been applied more widely, recent enquiries into person-based measures of accessibility (sometimes referred to as 'activity-based accessibility' measures as they are sensitive to people's unique activity participation patterns) have included Ben-Akiva and Bowman (1998), Dong et al. (2006), and Kamruzzaman and Hine (2011). Hagerstrand (1970) presented the *life path* notion of personal accessibility, a theoretical tracing of a person's complete spatiotemporal trajectory from birth to death, and posited three categories of constraints on a life path (a person's biological capabilities, perhaps extended by tools; 'coupling' requirements to perform some activities in tandem with other people; and the recognised authority to perform an activity at a certain place and time, both in the sense of constraints acting on the scale of an individual, and wider ones such as hours of operation.)

Schonfelder and Axhausen (2004) review concepts such as *awareness space*, *perceptual space*, and *mental maps*, which take account of people's individual life experiences and cognitive capacities.

Recent developments include efforts to take into account multiple people's time-space constraints in the case of activities undertaken jointly by two or more members of a household (Neutens et al. 2008).

The *activity repertoire* concept bears similarities to the PAS view of accessibility. Axhausen (2002) defines a person's activity repertoire as 'the set of activities (specific action streams at particular – types of – locations and times) which a person knows of, or has performed in the past.' This, like other activity-based accessibility concepts, differs from *Hagerstrandian* notions of accessibility in that time-space is viewed discontinuously, rather than as a continuous space in which opportunities are distributed. Lee-Gosselin (1990) discussed a person's 'operating envelope', also in terms of activities rather than continuous space, defined as: "a set of opportunities that [are] in some ways constrained by [spatio-temporal constraints, and social ones such as power or externally-imposed constraints]." The 'operating envelope' concept is described as having three distinct subsets of opportunities: 'normal' ones that are day-to-day activities and are seen to fall within one's 'comfort zone'; 'perceived' ones that a person does not normally participate in, but of which they are aware; and 'potential ones' which are activities for which it is feasible for the person to take part, but of which they are presently unaware.

The need for the PAS arises from the need to map between sets of activity needs and mobility resources. The accessibility notions discussed above are incomplete for this purpose, as they do not address the linkage between space-that-can-be-covered and the points in space (and time) that *one wishes* to reach. It may well be that for a particular person the capability to reach some particular locations is not viewed as especially important, whilst it may be seen as critically important to reach others. The PAS concept is (in principle) not based on an *a priori* judgment of which activity locations (in time and space) it is that a person considers important, rather It makes use of empirical observations and statistical methods to draw such inferences.

A person's PAS is not necessarily a simple undifferentiated listing of the set of activities the person considers relevant to them; the concept is flexible to accommodate several subtleties. A person may for instance place varying levels of importance on being able to access different activities. One can also imagine functional links between different activities – with a simple example that being able to access one activity may relax the need to access another 'substitute' activity. A suitable level of accessibility to, say, one type of leisure activity location, might allow a person to feel that accessibility to other similar locations is less important.

As the PAS cannot be directly observed by the researcher, an appropriate characterisation of the activities in people's PASs is a judgement of the researcher for any particular study, which would be made on the basis of their understanding of the context. Dimensions of interest could include activity purpose, scheduling, requirement for co-participants, frequency of recurrence (if any), links with other activities, spatio-temporal flexibility, etc. 'Work' for instance could be considered a unitary activity in a person's PAS, or individual working activities could be defined to be separate elements (i.e. work on 22nd Sept. 2011 from 8:30 to 17:00 would be distinct from work on 23rd Sept, etc.) Elements within a person's PAS need not necessarily be activities that a person has direct personal experience with. A footloose worker may feel that the quality of access to her/his current job is important, but that the quality of access to alternative employment sites is also relevant.

Were a person an *homo economicus*, and their forthcoming pattern of activity participation deterministically known to them without error, their PAS might be an unbiased, error-free set of activities which they are likely to do within some timescale, where the timescale might be related to the functional lifetime of the durable travel resources which they are considering acquiring (and later activities would be subject to some discounting process). *Homo economicus* is one model of human behaviour, and it is entirely plausible, in principle, that that there are systematic distortions from pure rationality in the hypothesised mental processes. To take one example, the term *perceived* activity set is proposed, rather than the more concise *activity set*, to account for the fact that a person's view of their travel needs is a matter of their perceptions, which may not align fully with an outsider's view from an 'objective' perspective. Likewise it is plausible that a person's PAS may in some way relate to their past experiences rather than being exclusively a set of prospective forthcoming activities.

2.2 Mobility resources

Whilst researchers are becoming increasingly interested in a variety of mobility resources beyond car ownership in recent years (e.g. Vovsha and Peterson 2009; Xing et al. 2008; McElroy 2009; Mulley 2011, Pooley et al. 2011), of the three mobility resources considered in this research (personal cars, bicycles, and public transport season tickets) most attention has – by some distance – been directed towards understanding people's choices relating to car ownership.

Early enquiries (e.g. Chow 1957, Mogridge 1967, Tanner 1977) investigated car ownership at the level of aggregate demand, in other words aiming to understand how many cars in sum would be owned by a given group of people. As with other sort of analyses relating to personal mobility, over time the state-of-the-art migrated to disaggregate techniques (i.e. where individual people or households are the unit of analysis). de Jong and colleagues prepared a broad review of practices for analysing car ownership in a study published in the early 2000s, which by then had evolved, in response to the changing policy agenda and increased computing power, to take in issues such as fuel type, emissions level, and timing of vehicle transactions (de Jong et al.2002). Roorda and others reported agent-based (i.e. disaggregate) analyses in which car ownership is one in a broader sequence of choices that people face related to their mobility (Roorda et al. 2009, Ciari 2010, Eliasson and Mattson 2000). Huang showed, using quasi-panel household level data, that cohort effects could be identified with regards to car ownership (Huang 2007).

The techniques which have predominantly been employed to analyse car ownership have treated the underlying demand for cars to be a function of apparently-exogenous observations such as a person's income, the type of neighbourhood in which they live, whether they are employed, the distribution of employment opportunities across a region, etc.

In the past decade, researchers have begun to explore the inter-relationships between owning a car and owning other durable travel products/services (Simma and Axhausen 2001, Scott and Axhausen 2006, McElroy 2009, Weis et al. 2010). Scott and Axhausen, for instance, specified people's holdings of both cars and public transport season tickets to be linked choices with the possibility for correlated error terms (Scott and Axhausen 2006.) Vovsha and Petersen (2009) also report partial-substitution effects between cars and public transport season tickets.

Early attempts at specifying car ownership to be a function of the mobility that a car provides include Ben-Akiva and Atherton 1977 and Train 1980, though in these cases limitations of data and computing resources constrained the researchers to specifying the demand for car ownership as a function of a single commuting journey. In very recent years (e.g. Salon 2006, Pinjari et al. 2008, Dissayanake and Morikawa 2010) researchers have begun to experiment further with techniques that treat a person's car ownership as a function of the value a car would provide to perform a specific need for mobility, typically a commuting journey, though these recent studies also use *a single archetypal travelling need* to encapsulate the mobility value of owning a car.

With few exceptions (e.g. Train, 1980; Scott and Axhausen, 2006; Le Vine et al., 2009) however, a person's (or household's) choice of whether to own a car is not specified to be driven by its potential usage pattern, as is the case with the PAS notion of accessibility.

3 Methods

This analysis examines the hypothesis that the mobility resource(s) a person holds is a function of their PAS. Discrete choice techniques are employed (Ben-Akiva and Lerman 1985). Each person is specified to choose a *portfolio* from a choice set of all available portfolios, on the basis of the cost of acquiring each resource and the value the modes of travel it enables would provide them in accessing the activities in their PAS.

Mobility resources are not exclusive; a person's 'portfolio' of holdings may include none, one, or several. The three mobility resources that are the subject of this analysis – cars, bicycles, and public transport season tickets – were selected on the basis of compatibility with the available data and their nature: all three are durable, market-traded, widely-held and substantial. Six methods of travel are included in this analysis. A person wishing to drive a car must own one (recognising that this is a first-order approximation of a more complex reality), and a person wishing to cycle must likewise possess a bicycle. The third mobility resource, a public transport season ticket, allows its holder to use public transport without paying per-journey fares, as is the case without one.[1] It can be seen from Table 1 that walking, riding as a car passenger, taking public transport on a PAYG basis, and taking a taxicab are specified in this empirical study to not require mobility resources, though it is recognised that this is a simplification of a more complex reality. Pooley et al. (2011), for instance, note that even walking may require specific equipment such as an overcoat.

		Modes of Travel						
		Drive Car	Ride Public Transport without paying per journey	Ride Bicycle	Walk	Take Taxicab	Public Transport (PAYG)	Ride as car passenger
Portfolios of resources	Own Car	Yes	No	No	Yes	Yes	Yes	Yes
	Own Public transport Season Ticket	No	Yes	No	Yes	Yes	No	Yes
	Own Bicycle	No	No	Yes	Yes	Yes	Yes	Yes
	Own Car + PT Season Ticket	Yes	Yes	No	Yes	Yes	No	Yes
	Own Car + Bicycle	Yes	No	Yes	Yes	Yes	Yes	Yes
	Own PT Season Ticket + Bicycle	No	Yes	Yes	Yes	Yes	No	Yes
	Own Car + PT Season Ticket + Bicycle	Yes	Yes	Yes	Yes	Yes	No	Yes
	Own none of these	No	No	No	Yes	Yes	Yes	Yes

Table 1: The set of means of travel enabled by various mobility resource portfolios

In the most general form, where a person can choose anywhere from zero to all resources without restrictions, they face a fully-factorial choice set of 2^R separate and distinct portfolio options, where R represents the number of resources included in the system. In this study, the only restriction imposed on people's choice sets is that all portfolios that include owning a car are restricted to adults (age 16+).

The general structure of this analysis is:

$$U_d^i = V_d^{i,non-travel} + V_d^{i,travel} + \varepsilon_d^i \qquad (1)$$

where the indices i, r, d, m, j are defined to represent people, mobility resources, mobility resource portfolios, modes of travel and journeys, respectively. Equation 1 shows a person's weighing between the (dis)utility (hassle, expense, etc.) of acquiring and/or maintaining the resources contained within a portfolio and the (dis)utility of using the travel modes which it enables to access activities in their PAS.

Following the derivation in the Appendix of this paper, this weighing takes the form:

$$U_d^i = \sum_{r=0,\forall r\in d}^{R} V_r^{i,non-travel} + \left(\sum_{j_i=1}^{J_i} \gamma_{j_i} * \frac{1}{\lambda^{travel}} \ln \sum_{m\in\mu_d}^{M} e^{\left(V_{mj_i}^{i,travel} * \lambda^{travel}\right)} \right) + \varepsilon_d^i \qquad (2)$$

The first term on the right-hand-side of equation 2 $\left(\sum_{r=0,\forall\, r\in d}^{R} V_r^{i,non-travel}\right)$ shows that the fixed expense/hassle of owning some portfolio of resources is specified to come from adding up the expense/hassle of the resources within that portfolio.

The second term shows the specification for utility relating to a person's potential travel. It is hypothesised that a person views how well a portfolio would perform in providing access to a particular activity to be how well the 'optimal' mode enabled by this portfolio would perform, which is then summed across all activities within the person's PAS. The selection of the optimal mode from within the set of all modes enabled by portfolio d (μ_d) is reflected by the logsum form. The γ_{j_i} terms are 'importance' terms; they capture the possibility that people may place higher priority on being able to access certain types of activities than others.

This empirical analysis reflects a decision for a straightforward and uncomplicated specification; a minimum of free parameters is included. Whilst in practice a study of a real-world market would likely assess the effects of further descriptors (age, gender, income, etc.), this empirical analysis was intended to expose the fundamental aspects of the PAS.

The empirical dataset is a randomly-selected sub-sample of 300 households living in Greater London that took part in Great Britain's National Travel Survey in 2004/05 (Abeywardana et al. 2006), a sample size dictated by the *a priori* estimate of per-household time requirements for processing data through online travel planning services, as described later in this section. Each person's PAS is specified to be the set of out-of-home activities they undertook during the survey's seven-day diary period. It is recognised that specifying a person's PAS to be their revealed pattern of behaviour may introduce bias, as the set of activities they were observed to perform during some time period may differ from the set of activities they consider when making structural mobility choices. Alternative methods of specifying a person's PAS exist, which would sidestep this potential for endogeneity, though there are inherent trade-offs. Specifying a person's PAS to be a function of the revealed behaviour of other people with similar observable demographic characteristics, for instance, rather than their own revealed behaviour would introduce a larger amount of random error into the analysis in exchange for less bias. Another possibility would be to find a suitable way of asking people to state information regarding their PAS, though this would be subject to self-reporting biases. A further consideration is that rare-but-important activities may play a significant role in shaping structural mobility choices. For instance, a person might decide to buy a larger car than needed for their day-to-day travel if they envision using it on occasional family driving holidays. In summary, it would appear that research into alternate methods for specifying people's PASs, including qualitative enquiry into the relationship between people's perceived travel needs and their observed travel pattern, would be fruitful to further develop the PAS concept introduced here.

The dataset for this study contains:

- 738 people (561 adults age 16+, 177 children aged 5 – 16; average household size of 2.46)[2]
- 10,428 diary journeys (8,658 on diary days one through six; 1,770 on diary day seven. Walking journeys under 1 mile in length are only reported on day seven)

The NTS' diary dataset indicates the journey characteristics (time, cost, etc.) of travel modes that people reported using to access each of their activities, however this analysis also required information about the characteristics of the itineraries of other competing travel modes that a person could have used but did not. If a person drove to a shop, for instance, this analysis requires knowledge of how long it would have taken to walk, how long it would have taken them if they had used public transport and how much it would have cost, etc.

In the case of repeated behaviour (e.g. commuting journeys), each instance of the behaviour is included as an item in the person's PAS. The γ_{j_i} 'importance' terms are freely-estimated, however. The relative weighting of repeated behaviour in a person's PAS is thus estimated rather than imposed *a priori*.

It should be noted that the journey purpose classes recorded in the NTS are quite broad; shopping, for instance, is only disaggregated into food and non-food shopping, leaving as unobserved much relevant information within each of these two categories (e.g. bulk food shopping activities have different transport requirements than convenience food shopping.)

This information was synthesised via online travel planning services. The origin, destination, day-of-week, and time-of-day of each journey were input into the Journey Planner (journeyplanner.tfl.gov.uk) and Transport Direct (www.transportdirect.info) services in an automated manner. The services provided recommended journey itineraries for 'non-chosen' travel modes for each observed journey (see Le Vine 2011 for details).

4 Results

The principal results are shown in Table 2. The results provide general support for operationalising the PAS concept, as the estimation algorithms run successfully and the free parameters are statistically identifiable.

As is typical in discrete choice analyses with a large number of alternatives, the ρ^2 values of the models are rather low; this is due to the ρ^2 values reflecting how well the models are predicting each person's precise portfolio of holdings, rather than how well they predict each person's holding of the individual resources (the latter is discussed further below.) There are large improvements in likelihood between the null specification, the restricted model forms, and the least-restricted form (Model 5), however, and an Akaike Information Criterion test (which compares gains in goodness-of-fit against the undesirability of including a larger number of free parameters) finds that Model 5 is the preferred specification.

Models 1 and 2 show a large improvement in goodness-of-fit from adding the 'holding cost' parameter to specification of only alternative-specific error terms (Model 1). Interestingly, the ASC for owning a car becomes very large, and in fact very nearly counterbalances (+9.38 v. -9.73) the disutility arising from the expense of owning a car. This is not very surprising, as there is great heterogeneity in the ownership costs of a car, whilst this was treated in this analysis as a single point value (£4,000/year).

Model 3 is arrived at by adding into the specification information on each person's PAS. All parameters are signed as expected, and with one exception all are statistically-significant. This model provides much better goodness-of-fit than Model 2, which contains no information on people's PAS. The mode-specific travel time parameters are ordered, from smallest [least negative] to largest: Ride a bicycle, followed by drive a car, and then followed by the 'shared' modes that are common to all portfolios.[3] Taken as a whole, the results of Model 3 show that the central hypothesis of this research – that a person's choice of 'portfolio' of mobility resources can be considered as a function of the travel value its constituent elements provide in performing – appears to be supported.

Model 4 is an extension of Model 3 in which the logsum parameter is allowed to be estimated freely; doing so yields a further large increase in goodness-of-fit.

In Model 5 the 'importance' parameters for different activity purposes within people's PASs are estimated; all but one are found to be statistically-significant. The estimates of the importance terms are found to be ordered, from smallest to largest: Escort, social, leisure, shopping/personal-business/other, work/education. In other words, the empirical evidence – which makes intuitive sense – is that, on average, the need for suitable access to a given out-of-home episode of work or education[4] plays a larger role in explaining a person's holdings of mobility resources than the need to access individual episodes of other types of activities. It was found that this difference is moderate in magnitude – neither negligible nor large. For instance, suitable access to a work/education activity episode was found to have roughly 70% greater effect in explaining a person's resource portfolio as access to each otherwise-identical shopping activity episode.

Model 5 is the source of the results discussed further below.

Model #	1	2	3	4	5
Null log-likelihood	-1,364.0				
Log-likelihood	-1,302	-1,236.3	-1,162.3	-1,134.7	-1,121.3
ρ^2 / adjusted ρ^2	0.05 / 0.04	0.09 / 0.09	0.15 / 0.14	0.17 / 0.16	0.178 / 0.167
Smallest singular value in Hessian matrix	99.97	0.34	0.35	0.37	0.38
(Portfolio Choice level) ASC Own a bicycle	-0.75	-0.140 (0.21)	-0.754	-0.766	-0.899
(Portfolio Choice level) ASC Own a car	-0.35	9.38	8.12	8.82	9.44
(Portfolio Choice level) ASC Own a public transport season ticket	-0.30	2.25	1.95	1.50	1.50
(Mode Choice level) ASC Ride a bicycle	--	--	-2.14	-0.161	-0.481 (0.12)
(Mode Choice level) ASC Drive a car	--	--	-0.973	0.112	0.431 (0.09)
(Mode Choice level) ASC Shared modes	--	--	0[a]	0[a]	0[a]
Fixed holding costs in GBP per month	--	-0.0292	-0.0313	-0.0338	-0.0355
Fare costs in GBP per journey	--	--	-0.0396 (0.27)	-0.182	-0.918
Travel time in minutes (Generic)	--	--	--	--	--
Travel time in minutes (Drive a car)	--	--	-0.021	-0.00458	-0.0184
Travel time in minutes (Ride a bicycle)	--	--	-0.014	-0.00323	-0.0129
Travel time in minutes (Shared modes)	--	--	-0.024	-0.00492	-0.0204
Importance parameter (γ) for 'escort' journey purpose	--	--	1[a]	1[a]	0.0847 (0.27)
γ(leisure)	--	--	1[a]	1[a]	0.194
γ(shopping, personal business, and other)	--	--	1[a]	1[a]	0.232
γ(social)	--	--	1[a]	1[a]	0.134
γ(work and education)	--	--	1[a]	1[a]	0.335
Logsum term (λ^{travel})	--	--	1[a]	4.21	1[a]

NB: Values in parentheses are p-values; values smaller than 0.05 are suppressed. [a] Value is fixed

Table 2: Results from model estimation

Figure 1 shows how goodness-of-fit varies with the number of days of travel diary data that are used to form the empirical representation of people's PASs. For instance, when each NTS respondent's first day during their diary week is included in the analysis, the adjusted ρ^2 (with the same number of parameters) improves to 0.12 from 0.08 when no travel diary data are included. Adding people's second diary day into the specification improves this to 0.14, and so on.

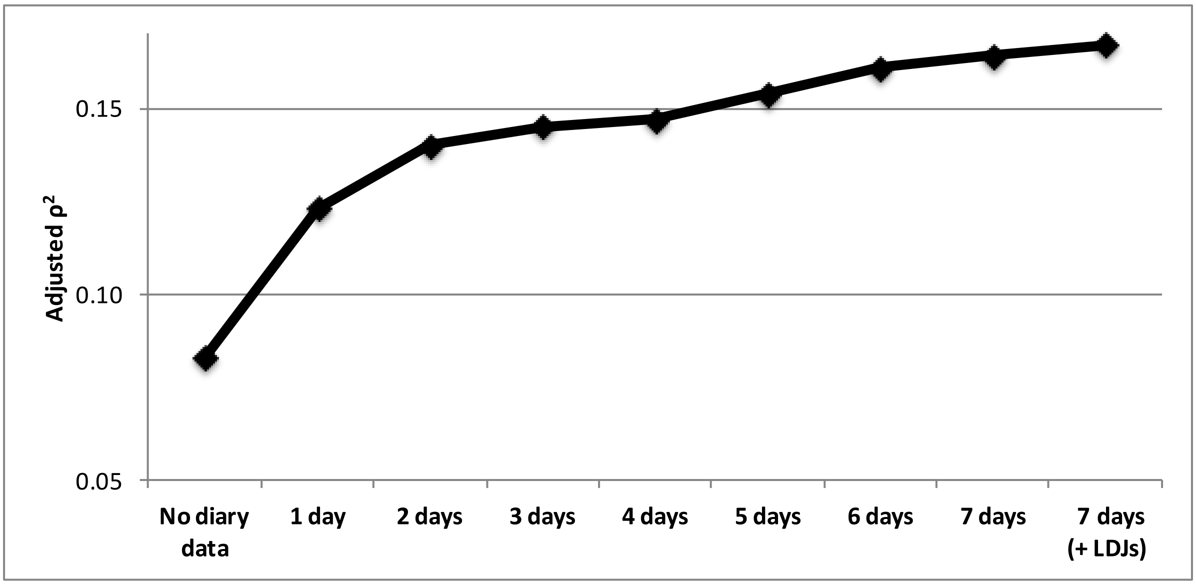

Figure 1: Response of adjusted ρ^2 to successive increases in the number of days of travel diary data observed for each person (i.e. the representation of their PAS)

Figure 1 shows relatively modest improvements in the quality of predictions after the addition of the second diary day to the representations of people's PASs. It can however be seen that 'data saturation' does not occur: predictions continue to monotonically improve as the representation of people's PAS becomes richer. This occurs across all seven days of the NTS' main travel diary, plus the long-distance journeys (LDJs) recorded during the NTS' additional three-week LDJ reporting period (Abeywardana et al. 2006).

Thus the empirical evidence indicates that the largest gains in explaining people's holdings of mobility resources come from using two days worth of travel diary data rather than a more-typical one-day diary instrument, whilst at the same time that – at least up to the week-long extent of the NTS diaries – any and all increases in the amount of diary data quite clearly improve the quality of predictions.

A simulated portfolio choice was generated for each person in the NTS data sample. An interesting pattern emerges when looking at how well the model is able to predict people's ownership of the three different types of mobility resources; this result is obtained via a simple bivariate correlation between people's observed and predicted ownership of each of them, as shown in Table 3.

	Correlation coefficient between observations and predictions
Owning a personal car	0.41
Owning a public transport season ticket	0.20
Owning a bicycle	0.06

Table 3: Correlation between people's observed and predicted holdings of mobility resources

It is found that the empirical analysis based on the PAS concept is best able to predict whether a person owns a personal car, then whether one owns a public transport season ticket, and performs worst at predicting whether a person owns a bicycle. This is a plausible finding, as a car is arguably likely to require the highest level of advance commitment of these three resources, and to offer the most in terms of extending one's access to life opportunities and obligations. Thus the predictive capacity of the PAS theory in this application appears to correlate with how 'consequential' a type of mobility resource is. It was recognised, however, that this finding could be an artefact of the experimental design, as all children under age 16 were observed to not own a car and were also so predicted. The correlation coefficient between observations and predictions of car ownership was therefore re-calculated for adults only, and found to be 0.28. Thus the structure of the pattern discussed above held and it was concluded that it was not simply an artefact of this aspect of the experimental design.

With regard to the particularly low goodness-of-fit of patterns of bicycle ownership shown in Table 3, it is noted that the models in this study were specified parsimoniously, without demographic explanatory variables such as age, gender or income, attitudinal ones, as well as other relevant variables that are unobserved such as confidence in one's cycling abilities. The simple and straightforward specification was selected in the interest of illustrating the explanatory power of PAS-based techniques independent of such other effects. Thus the finding here is that the combination of the PAS concept, this empirical dataset, and the explanatory variables specified here serves as a poor predictor of patterns of bicycle ownership. This is unsurprising, as the links between bicycle ownership and usage were relatively weak in the dataset: 32% of people owned a bicycle, but only 4% were observed to cycle at least once during their diary week. This finding led to an interesting question: are PAS-based techniques generally better at predicting ownership of heavily-used resources than lightly-used ones? This was investigated by comparing the average number of journeys observed in the NTS sample that were made using resources (e.g. car driving journeys in the case of cars, etc.), for both 'correctly-predicted' and 'incorrectly-predicted' resources. It was found that correctly-predicted resources were used an average of 9.2 times (std. error = 9.3) per week, whilst incorrectly-predicted resources (those observed to be owned but not so predicted) were used an average of 5.2 times (std. error = 6.5); this difference is highly-significant ($p<0.01$)[5].

Thus an issue raised for further enquiry is how techniques based on the PAS concept, where latent travel needs are specified to drive resource ownership, can be extended to produce better predictions for widely-held but lightly-used resources. One possibility would seem to be hybrid methods, in which a PAS-based specification is paired with terms incorporating traditional demographic explanators; another would be to treat 'regularly-used' and 'lightly-used' resources as related-but-distinct elements.

Table 4 shows how a people's predicted 'portfolio' holdings align with their observed portfolios. For instance, the cell at the top-left of the matrix shows that, of the 84 people observed to own a car and nothing else (the sum of the top row), 25 were 'correctly' predicted to also own a car and no other mobility resources. It can be seen that the model does best when making predictions for people observed to own portfolios with fewer resources, and relatively poorer at predicting the precise holdings of those people holding a larger number of mobility resources:

- People observed to hold no mobility resources: 30% 'correctly' predicted
- People holding one: 24%
- People holding two: 18%
- People holding all three: 7%

		Predicted 'portfolio' holdings								
		A	B	C	AB	AC	BC	ABC	None	Sum
Observed 'portfolio' holdings	A	**25**	9	5	19	11	3	7	5	84
	B	20	**39**	16	28	13	23	9	25	174
	C	8	17	**20**	2	8	10	4	24	93
	AB	8	7	0	**15**	2	7	8	5	53
	AC	16	5	4	15	**9**	5	7	2	63
	BC	2	10	4	5	4	**5**	4	9	45
	ABC	4	3	4	7	4	2	**2**	3	29
	None	13	30	33	7	9	17	5	**49**	164
	Sum	97	120	87	98	61	72	46	122	704

Codes: A: Owning a personal car
B: Owning a public transport season ticket
C: Owning a bicycle

Table 4: Cross-tabulation of observed and predicted portfolio holdings

Another way to characterise the predictions is to look at cases where the model correctly predicted a person's precise holdings together with cases where the prediction was a near-miss. For the purposes of this analysis, a near-miss is defined to be a person for whom their predicted portfolio would match their observed one if one resource was added or removed. For instance, a person observed to own only a car (code 'A' following the convention in Table 4) would be characterised in the following way: A (correct prediction); AB, AC, or None (near-misses); B, C, BC, ABC (neither correct nor near-misses).

The following pattern is found when considering both correct predictions and near-misses:

- People observed to hold no mobility resources: 77% correct or near-misses
- People holding one: 68%
- People holding two: 61%
- People holding all three: 52%

It can be seen that the same general pattern was found to hold for near-misses as for correct predictions: the predictive capacity of the PAS-based technique is inversely related to the number of resources a person owns.

The relationship between goodness-of-fit and a set of demographic explanators was then investigated, in order to assess whether the accuracy of estimates from this class of techniques is different for different types of people. The predicted probability of each person's observed portfolio was converted into a log-odds ratio, such that it was no longer bounded below by zero and above by one. This was treated as a dependent variable, against which were regressed a number of explanators. Following a specification search, the results showing effects found to be significant at the 0.10 level are shown in Table 5.[6]

	r^2= 0.16	
	Mean	**Significance level**
Constant	-1.48	<0.01
Child (Age < 16)	0.73	<0.01
Income quintile	-0.048	0.05
Employed	-0.20	0.02
Married	0.14	0.08
Female	0.20	<0.01
Living in a flat/apartment	0.18	0.02
Living in Inner London	-0.19	0.01
Any self-reported travel difficulties	0.45	<0.01

Table 5: Results from regression analysis of log-odds ratio of correct predictions. Positively-signed effects are associated with better goodness-of-fit.

The variables listed in Table 5 were found to explain a rather small portion of the variance in goodness-of-fit in predicting different people's holdings (r^2=0.16). It was found that GOF was lower for those in employment, but that at the same time it decreased in line with household income. This income effect means that these PAS-based techniques, which posit that people optimise their resource holdings with respect to their travel needs and the fixed costs of owning them, seem to be a poorer fit for people with higher-than-average household income. An intuitive interpretation of this finding would be that 'pure functionality' tends to be relatively more important for people facing tighter financial constraints. In other words, different choice-making processes or motivations for acquiring mobility resources, as opposed to functionality (in the narrow terms of the journey times and costs of travelling) appear to be somewhat more prevalent amongst those with higher incomes.

Better GOF was found for married people and for women than single people and men, respectively. Living in a flat (as opposed to a house) led to better quality of predictions, though living in Inner London had the opposite effect. Having difficulties with one or more means of travel was found to lead to better goodness-of-fit; interestingly 73% of such people owned a car and/or a public transport season ticket, whilst only 49% of people without travel difficulties did. This finding can be interpreted in a similar manner to the income effect noted above: 'pure functionality' seems to better explain the resource holdings of people facing constraints on personal mobility than the holdings of other people.

5 Conclusions

This paper presents a new concept of a person's level of accessibility to life opportunities and obligations, termed the *perceived activity set*, and the set of findings from the first empirical study to make use of it. The main distinctive feature of the PAS concept is that it encompasses all activities (at particular places and times) that a person considers *relevant* to their life.

The principal finding reported here is that the simple notion underpinning the PAS proved analytically tractable: that people have in mind some idea of their needs for mobility, which is coupled with their structural mobility choices such as acquisitions of resources for travelling. This is a departure from prevailing techniques, and opens a promising direction of enquiry given the pressures for analyses of people's travel to be sensitive to ever-subtler policy measures and market stimuli. For instance, existing techniques to analyse people's use of transport modes are challenged by emerging forms of personal mobility such as car clubs and bikesharing, where the classical techniques of analysing 'ownership' and 'usage' sequentially and independently are not tenable. Recent analysis by the authors finds that a framework where people are seen to consider multiple travel needs, resources, and methods of transport simultaneously appears promising with regard to people's take-up of such services (cf. Le Vine et al. 2011.)

The empirical analysis using the PAS concept yielded several noteworthy insights, both regarding the PAS concept and people's holdings of mobility resources.

First, whether a person owns a car or not was predicted more accurately than whether they own a public transport season ticket, and whether they own a bicycle was predicted least well. Thus it would appear that there is an inverse relationship between the level of 'commitment' that a mobility resource involves and the usefulness of the PAS concept in explaining patterns of ownership. Second, the quality of predictions was improved by extending the scope of each person's PAS beyond the small number of activities observed in a typical one- -day diary, with the largest gains coming from the addition of a second day's worth of data and smaller improvements from subsequent data. This was found to hold throughout the week-long NTS diary instrument: even after accounting for all of the first six days of diary data, adding the seventh and final day's worth of data still led to better predictions. An interesting issue for further enquiry would be identifying the optimal trade-off between the expense of collecting long-duration travel diaries and the value of improved prediction quality for different circumstances and various types of mobility resources.

Third, it was found to be feasible to estimate independent 'importance' parameters for different sorts of activities with people's PASs, and the pattern between them was found to be broadly intuitive. Work/education activity episodes were found to be most 'important' in explaining people's resource holdings, with other types of activities somewhat less. An inverse relationship was found between the number of resources owned by a person and the accuracy of their predicted holdings. The holdings of people observed to own no resources or just one were successfully predicted at a higher rate than those of people observed to own two or three resources. Finally, certain demographic characteristics seem to lead to better goodness-of-fit, such as being female, having lower-than-average household income, and having personal mobility difficulties.

The empirical application incorporates an important assumption, in that each person's PAS was specified to be defined by their actual activity/travel pattern during a randomly-observed week. There is thus a substantial potential for unaccounted-for endogeneity (i.e. two-way causality, rather than unidirectional as is assumed implicitly in this empirical application) between this representation of a person's [latent] PAS and their [observed] choices such as activity locations, frequencies, scheduling, methods of access, etc. There could also be systematic mis-perception – as well as possibly variability in perceptions of travel needs – that should be investigated as future research.

The specification reported here could thus have important repercussions in, for instance, failing to capture how people might restructure their patterns of activity participation (e.g. choosing, to take one familiar type of personal activity, to re-allocate food-shopping responsibilities amongst family members, or to shop at different grocery stores, perhaps with different frequency or qualities of the purchased food or of the experience) in order to take advantage of the opportunity to use new types of mobility resources , and remains a logical avenue for further research. Due to these limitations, it cannot be asserted that the PAS theory is fully settled on the basis of this limited empirical study; it remains a matter for future research to further develop the PAS notion, including alternative sampling methods, and test it in ways beyond those reported here in the initial empirical study.

It is suggested that, in addition to such questions of endogeneity between the specification of a person's PAS and their structural mobility-linked choices, the research agenda also include investigating similar structural choices (other than mobility resource ownership) using PAS-based techniques, qualitative research into the three-way links between actual executed activity patterns, expected future activity patterns and perceived needs for travel capabilities, further study of the issue of heavily-used versus lightly-used or unused resources (including any held for 'mobility insurance' purposes rather than regular use), the evolution of a person's PAS through their life course, and pairing PAS-based methods with demographic explanators typically used in prevailing methods for analysing people's resource ownership. It would also be worth investigating whether PAS-based techniques can be made compatible with traditional short-duration travel diaries – thus greatly broadening the scope for practical application.

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Appendix

We begin from equation 1 in the main text:

$$U_d^i = V_d^{i,non-travel} + V_d^{i,travel} + \varepsilon_d^i \qquad \text{(A1)}$$

The utility of portfolio d to person i includes a systematic component of utility associated with acquiring and/or maintaining the portfolio $\left(V_d^{i,non-travel}\right)$, a second systematic component of utility which relates to the use of modes of travel enabled by portfolio d to access activities in their PAS $\left(V_d^{i,travel}\right)$, and an error term ε_d^i.

In the interests of simplicity, the $V_d^{i,non-travel}$ term is specified here to be additive with respect to all resources within a portfolio:

$$V_d^{i,non-travel} = \sum_{r=0,\forall\, r\in d}^{R} V_r^{i,non-travel} \qquad \text{(A2)}$$

We now turn to the $V_d^{i,travel}$ term, which relates to the usage of transport. For use in a compensatory utility-based analytical framework, the performance of the transport modes enabled by a resource portfolio in accessing each activity in a person's PAS must be aggregated into a single scalar utility metric. This implies two dimensions of aggregation: the first across modes of travel to access each activity, and the second across activities.

It is hypothesised that the mental process associated with the first dimension is a form of maximisation. In other words, it is specified that a person views how well a portfolio would perform in accessing a particular activity to be how well the 'optimal' mode enabled by this portfolio would perform.[7] This is written formally as:

$$U_{dj_i}^{i,travel} = \max_{m\in\mu_d}\left(U_{mj_i}^{i,travel}\right) \qquad \text{(A3)}$$

Equation A3 shows that the utility of portfolio d to person i for performing journey j_i (alternatively: accessing the activity/activities associated with j_i) is equal to the utility of the 'optimal' mode m enabled by portfolio d for performing the journey.

The notation μ_d represents the set of modes enabled by portfolio d. If a person's judgment of how each travel mode would perform for some journey j_i were knowable to the outside analyst with certainty, the analyst could proceed by identifying the mode of travel within μ_d which provides the person i with the largest value of utility. The analyst's knowledge is, however, incomplete due to the latency of a person's PAS, meaning that a systematic component of utility [$V_{mj_i}^{i,travel}$] can be inferred by the analyst, but there remains an unobservable error component [$\varepsilon_{mj_i}^{i,travel}$], as shown in equation A4.

$$U_{dj_i}^{i,travel} = \max_{m\in\mu_d}\left(V_{mj_i}^{i,travel} + \varepsilon_{mj_i}^{i,travel}\right) \qquad \text{(A4)}$$

Equation A5 presents the form of the $U_{dj_i}^{i,travel}$ term. This convenient relationship arises, if the analyst is prepared to assume that the $\varepsilon_{mj_i}^{i,travel}$ terms are Gumbel-distributed with variance λ^{travel}, from the properties of that distribution (Ben-Akiva and Lerman 1985).[8]

$$U_{dj_i}^{i,travel} = \left(\frac{1}{\lambda^{travel}} \ln \sum_{m \in \mu_d}^{M} e^{\left(V_{mj_i}^{i,travel} * \lambda^{travel}\right)} \right) + \varepsilon_{dj_i}^{i,travel} \quad \text{(A5)}$$

The second dimension of aggregation – across journeys – is different from the first. Whereas it is conjectured that a person identifies the 'optimal' mode from amongst the available options enabled by a portfolio, in the second dimension it is specified that, by definition, a person wishes to be able to access *each* activity within their PAS. It is thus specified that there is a summation of utility across activities within their PAS:

$$V_{d\theta_i}^{i} = \sum_{j_i=1}^{J_i} \left(V_{dj_i}^{i} + \varepsilon_{dj_i}^{i}\right) \quad \text{(A6)}$$

Here the notation θ_i is introduced to represent the set of activities forming person i's PAS. Equation A6 leads to equation A7 as the individual $\varepsilon_{dj_i}^{i}$ terms are unidentifiable and the $\varepsilon_{d\theta_i}^{i}$ represents their sum into a single term:

$$U_{d\theta_i}^{i} = \left(\sum_{j_i=1}^{J_i} V_{dj_i}^{i} \right) + \varepsilon_{d\theta_i}^{i} \quad \text{(A7)}$$

This specification accounts for the possibility that a person may place a higher priority on accessing certain activities within their PAS than on accessing others. For instance, it is plausible that a person may place a higher importance on being able to get to an ill relative to assist with their care than on being able to get to the pub to see their friends. The opposite is also plausible, as is a possibility that a person places equal priority on being able to access each of these two prospective activities. Such systematic variations in the 'importance' of accessing different sorts of activities can, expanding on Equation A7, be represented as:

$$V_{d}^{i,travel} = \left(\sum_{j_i=1}^{J_i} \gamma_{j_i} * \ln \sum_{m \in \mu_d}^{M} e^{\left(V_{mj_i}^{i,travel}\right)} \right) \quad \text{(A8)}$$

where the γ_{j_i} terms may be specified in any of a number of ways. Specifying the γ_{j_i} 'importance' terms to be functions of activity/journey characteristics, where the parameters of these functions are freely-estimated, would in principle allow insights to be drawn regarding how various activity/journey characteristics correlate with people's holdings of travel resource portfolios. In this empirical study, the γ_{j_i} terms are specified to vary according to activity purpose, where each activity is classified into one of five categories: Escort, Shopping/personal-business/other, social, leisure, or work.[9]

Mapping a set of personal activities into a set of travel needs [prospective journeys] is a non-trivial process. One possibility would be to assume that a person considers their level of accessibility to out-of-home activities to be based on the spatio-temporal proximity of each out-of-home activity location to their home. Another treatment would be to specify accessibility to be in keeping with the real-world journey-sequencing of their tours. This recognises the fact that any tour of three or more journeys must involve accessing at least one out-of-home activity from a previous out-of-home activity location, rather than directly from one's home. The latter specification was chosen here, though it is recognised that further research on this point may yield insights into such specifics of how people perceive their mobility needs.

Endnotes

[1] Note that public transport is treated throughout this paper as a single unitary means of travel, disregarding the diversity amongst the various means of travel which fall under the term such as overground rail, bus, and Tube.

[2] 34 [29] of these people [adults] were not observed to make any journeys during their diary weeks

[3] For reasons of parameter identifiability, the travel time parameters for modes of transport common to all portfolios (walking, public transport, taxi, and car passenger) are constrained to be equal to each other.

[4] The term *episode* is used here to refer to an instance of taking part in an activity. A person who works five days during a given week is thus defined to perform five work activity episodes during that week.

[5] The Mann-Whitney (M-W) test was used to determine whether the difference between the two means is statistically significant. The distributions of the two statistics are truncated at zero; unlike a t-test, M-W does not require an assumption of normality. (Mann and Whitney 1947)

[6] The specification search also considered the following variables, which were not found to have significant effects: employment on part-time basis, employment on full-time basis, being retired, age, age-squared, ethnic group, owning one's residence, population density of postcode sector of residence.

[7] Implicit in this specification is an assumption that a person is only interested in the performance of the *optimal* mode of transport enabled by a given portfolio to access a given activity, and that the performance of all other [sub-optimal] modes which it enables are not utility-relevant. Relaxing this specification to account for possible 'insurance effects' (i.e. utility-relevance of 2nd/3rd/nth-best modes) is possible in principle, though is left as an avenue for further research.

[8] Readers may recognise equation A5 as the *logsum* form which arises frequently in the case of choice model forms that include 'nests' of alternatives; in this class of models the term sets the scale of the distributions of the error terms between upper and lower levels. In a simple two-level nested-logit application the upper bound of all nesting terms (in the form shown in equation A5) is 1.0, as larger values would imply [illogical] larger within-nest variance than between-nest variance. In this application, however, there is no *a priori* belief about the scale of the variance and hence also none about the λ^{travel} term (beyond that it must be positively-signed.)

[9] The five composite activity classes arise from grouping the NTS' activity classes as follows:

<u>Escort</u>: Escort commuting, Escort business & other work, Escort education, Escort shopping/personal business / Escort home (not own) and other escort

<u>Shopping/personal-business/other</u>: Food shopping, Non-food shopping, Personal business: medical, Personal business: eat/drink, Personal business: other, Other non-escort

<u>Social</u>: Visit friends at private home, Eat/drink with friends, Other social

<u>Leisure</u>: Entertainment/public social activity, Participate in sport, Holiday base, Day trip, Just walk

<u>Work/Education</u>: Commuting, Education, Business, Other Work