What can we Learn from GPS Measurement of Travel?

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1 Introduction

Since the mid-1990s, Global Positioning System (GPS) technology has been applied to various aspects of the measurement of transport-related issues. Initially, GPS devices required an external source of power, which largely limited them to being used in vehicles, and sometimes only in specially-equipped vehicles (Wagner, 1997; Quiroga, 1997; Quiroga, 2000; Wolf *et al.*, 2000; Wolf *et al.*, 2003). Subsequently, versions of the devices were developed that provided an attached or built-in power source (Drajier *et al.*, 2000; Stopher *et al.*, 2005a; Wolf, 2006). These devices have been used for a number of alternative applications in transport, ranging from objective measurement of infrastructure (Baffour, 2002), to various measurements of traffic flow and related phenomena and system performance (Quiroga *et al.*, 2002; Ranjitkar *et al.*, 2002; Wee *et al.*, 2002; Bullock *et al.*, 2003; Bullock and Jiang, 2003), to validating the measurement of personal travel behaviour (Wolf *et al.*, 2003; Forrest and Pearson, 2005; Li *et al.*, 2004; Stopher and Bullock, 2001; Stopher *et al.*, 2002; Stopher *et al.*, 2003), to evaluating policies relating to behaviour change (Stopher *et al.*, 2005b; Stopher *et al.*, 2006). Although it has been suggested that GPS devices could take the place of more conventional travel surveys (Wolf *et al.*, 2001), this notion seems to have become lost subsequently in the drive to use GPS as a complement to more traditional methods of conducting personal travel surveys, and in the quest to improve methods of tracking behaviour change resulting from various policy directions.

In this paper, we use data collected from recent evaluation surveys to explore what information can be obtained from current GPS devices and the extent to which they are capable of replacing more conventional procedures for collecting personal travel data. At the outset, we need to observe that the use of GPS devices is not cheap. On the contrary, a self-powered GPS device today costs about AU$1250 to purchase. While such a device can be used many times over, so that the actual costs attributable to each day of measurement of travel become relatively small, there are other costs that are quite high on a day-by-day application of GPS technology. Also, whilst GPS technology offers far greater precision of measurement of travel, it is also not foolproof, and complete data cannot be obtained. In this paper, we start by setting out the normal requirements for data from a personal travel survey. We then examine the disadvantages of GPS devices in measuring such data, exploring specifically the limitations and problems of the technology. Subsequently, we explore what data can be obtained from GPS devices, and draw conclusions about the usefulness of GPS as a substitute for more conventional methods of measurement.

2 Data requirements for personal travel surveys

While there is not complete agreement in the profession on what data items must be measured in a personal travel survey, there is extensive agreement on certain core data requirements. In recent work for the US National Cooperative Highway Research Program (NCHRP), it has been proposed that a set of core questions need to be part of every personal travel survey (NCHRP, 2006). Whilst one or two of these questions are probably required only for surveys in North America, and some others may be required in other parts of the world, those variables for which there is probably little disagreement are shown in Table 1.

Table 1: Suggested Minimum Question Specifications

Category	*Item*	*Description*
Household	Location	Home address or home position in geographic terms
	Type of Building	Detached, semi-detached, terraced, flat, etc.
	Household Size	Number of household members
	Relationships	Matrix of relationships between all members of the household
	Number of Vehicles	Summary of number of vehicles from vehicle data
	Housing tenure	Own or rent status
	Re-contact	Willingness to be contacted again for further surveys, etc.
Personal	Gender	
	Year of Birth	(Preferable to requesting age)
	Paid Jobs	Number of paid positions and hours worked at each in the past week
	Job Classification	Employee, self-employed, student, unemployed, retired, not employed, etc.
	Driving License	Whether or not a current drivers license is held
	Non-mobility	Indication of why no out-of-home activity was performed on a survey day including work-at-home days
	Education Level	Highest level of education achieved
	Disability	Types of mobility disability, both temporary and permanent
Vehicle	Body Type	E.g., car, van, ute, etc.
	Year of Production	
	Ownership of Vehicle	Household/person, lease, institution
	Use of Vehicle	Main user of vehicle
Activity	Start Time	Start time of each activity or travel
	End Time	End time of each activity or travel
	Activity or Purpose	
	Location	Where the activity was performed, unless travelling
	Means of Travel	If activity is travel, what mode(s) was used (including specifying if a car passenger or driver)
	Mode Sequence	Unless collected as fully segmented data
	Group Size	Number of persons travelling with respondent as a group
	Group Membership	Number of persons in the group who live in respondent's household
	Costs	Total amount spent on tolls, fares and respondent's share
	Parking	Amount spent to park
	Ticket Type	Type of ticket used on public transport

The items identified in Table 1 as being about the household, the person, and the vehicle would be collected usually on forms separate from the travel information. These data items would continue to be needed in any type of personal travel survey, together with any other data items that the local agency may desire to measure. Because they are not collected by a travel diary, and would obviously still be required in a GPS-based survey, we do not consider them further. They remain a requirement that can probably best be collected by household, vehicle, and person forms. The data of interest in this paper are those items included under the category of 'Activity' in Table 1. Typically, people round their estimates of the start and end times in any form of reporting of travel information, whether to an interviewer or through a self-administered survey, such as a postal or Internet survey (Rietveld, 2002; Stopher, 2004). Rounding to the nearest 5 minutes at each end of a trip will lead to inaccuracy in the travel time estimation. Rounding to the nearest 15 minutes or even 30 minutes, which is quite common, will lead to sufficiently erroneous estimates of travel time as to be of little use to the modeller or analyst. A second problem with self-report data collection is that people often do not know the addresses of places they visit (Stopher, 2004). They may know quite well how to recognise the location, how to get there, and so forth, but are not able to state the street name or number, nor even possibly the suburb in which the place is located. As a result, the information on location is often deficient. These are probably the most serious difficulties that arise in collecting travel data from people, although there are often other problems, some of which may be less self-evident, that also afflict the collection of self-reported travel data.

3 Problems and shortcomings of GPS data collection

Basically, GPS is capable of providing second-by-second information on the exact time, the location to within about ±3 metres, and the speed and direction of movement. This means that the purpose of the travel, the means of travel (and therefore the mode sequence), and also travelling group size, travelling group membership, and any cost information are not able to be collected by the GPS device. Before pursuing these items further, it must also be acknowledged that there are various circumstances that will arise that mean that the GPS device does not always collect the position, time, speed, and direction information. In this section, we will first explore the circumstances under which the GPS does not record information as it should, and what can be done about that. We will then discuss the issue of the data that the GPS does not collect and the methods that can be used to deal with this.

3.1 Missing GPS data

GPS devices require either a clear view of the sky, so that satellites used in the satellite navigation system can be seen, or the GPS antenna/receiver must be sufficiently sensitive to be able to pick up the satellite signal information even when a clear view of the sky is not available. In the earlier devices that were used in transport applications, a clear view of the sky was essential. Latest technology, however, has provided an antenna/receiver of sufficient sensitivity that a clear view is no longer essential (Stopher *et al.*, 2005a). Indeed, the most recent technological developments permit a signal to be received inside most homes, as well as in other buildings, as long as the antenna/receiver is not more than two storeys below the roof, although accuracy of position is often compromised. This most recent technology will still lose the ability to maintain position information in a multi-storey building at any level below the top two floors, and will also lose position information in tunnels and other constructs that effectively shield the device from reception of a strong enough signal from the navigation satellites.

If one were to consider the use of a GPS tracking device to track a traveller in London, where that traveller uses the Underground system extensively, it is clear that the loss of signal would represent significant missing data. As the traveller leaves her or his origin and travels to the first Underground station, the device would be able to track the travel. Once the person enters the Underground station, assuming it is one of the many stations that are actually underground (as opposed to some sections of the system that are above ground or in cut and cover shallow segments), the signal would be lost. Eventually, this person emerges from the Underground system at another station. However, there are so many potential routes within the system, with a myriad of possibilities for transfers between lines, that no inference could be drawn accurately about the route the person traversed. Fortunately, there are not a large number of cities in the world with such complex systems offering such a variety of potential routes as the London Underground system.

If our hypothetical traveller were in Sydney, for example, there are still a number of tunnels that could be travelled through. Some of these are road tunnels, and some are rail tunnels. However, in this case, the tunnel systems do not offer significant routing alternatives. If one were to know where the traveller entered the tunnel in question and where she or he exited the tunnel, then the route would be known almost with certainty. In the road tunnels, there are no options for finding destinations still within the tunnel system, so that an accurate idea of the time taken to travel through the tunnel is also provided. In the train system in Sydney, there are possibilities for a person to exit from a train at an underground station, walk to a destination, undertake an activity at that destination, and then resume travelling, all without ever being at a location where the GPS can determine position. Only in this case would it be difficult to pinpoint the location to which the person had travelled.

A second situation that is encountered in the use of GPS devices that can lead to loss of GPS data, is that of an urban canyon. An urban canyon is defined as the situation that exists when one has a road on either side of which are high-rise buildings. With older GPS devices, the only satellites in view are those that can be seen in the strip of sky that is directly above the road. This does not provide a sufficient dispersion of the satellites to obtain accurate position information. In addition, signals from satellites that are masked from view by the buildings may be reflected from the buildings to the antenna/receiver, thereby giving a false position reading, which may be 100 metres or more away from the true location of the GPS device. This is referred to as *multipath errors.* Fortunately, the increased sensitivity of the antenna/receiver also helps with this problem, by permitting the antenna/receiver to pick up signals from satellites that are masked from direct view, but without obtaining the reflected signals that produce a false reading of position. Stopher *et al.* (2006b) provide maps that show precise location of travel through the Sydney CBD, where older antenna/receivers were unable to pick up position and provided a scatter of points all around the true route at distances up to 100 metres or more from the true position.

Older GPS antenna/receivers were also found to lose signal under dense tree canopies and under shopfront awnings. Again, this is a situation that has largely been resolved by the newer more sensitive antenna/receivers. Similarly, the older antenna/receivers were not capable of picking up a signal when travelling in some types of urban vehicle. In particular, it was generally found that a signal could be obtained when in a single-decker bus, but that position was rarely obtained when in a train or a ferry. Again, however, the latest antenna/receiver has proved capable of receiving signals in most Sydney buses, trains, and ferries. Thus, with the most modern devices, the problems of missing data from urban canyons, dense tree canopies, and public transport vehicles are largely overcome by the technology. Loss of signal in underground transport facilities remains the principal issue of missing data.

In the processing software that ITLS has developed to use the GPS data, we are able to provide inferred data for any missing data areas, such as those discussed in this section. With the newest technology, we find that the urban canyon and dense tree canopy have largely disappeared as problems. Loss of signal in public transport vehicles is largely overcome by the technology, as well, although we sometimes still find signal loss in trains. Fortunately, because of the GIS rail network, it is fairly easy to see when a GPS record stops on boarding a train, and resumes after alighting from the train. Again, unless the underlying rail system is a complex network with high redundancy, it is not a problem to infer the route taken and obtain network-based distances to insert into the trip record. Our software currently performs such corrections when needed (FitzGerald *et al.*, 2006).

3.2 Position acquisition

A second problem that arises with GPS devices relates to the time required for the device to acquire position. While the specific parameters may vary somewhat from one manufacturer to another, in principal, GPS devices operate under two alternative modes. If the last time that satellites were in view was less than an hour ago (this value may vary from one device to another), then the software associated with the device assumes that the current position is the same as the last position recorded. In this case, recording of position is almost instantaneous when movement re-commences, because the starting position is considered to be known, speed and direction of movement are ascertained immediately, and the device is able to determine new positions quickly from the prior position. We have defined this condition as a ‘warm start’.

When a period of more than an hour has elapsed since the last time that satellites were in view, the device starts over in determining current position. This means that it must first search for and find a minimum of four satellites, solve the position equations based on those four satellite positions, and then determine its current position. If the device is stationary, this process can take from 20 seconds to as much as 2 minutes, even though manufacturers may provide a position acquisition time of, say 30 seconds. The time taken actually depends on the location of the closest satellites in view, and their proximity to the current device position. If there are four well-dispersed satellites in reasonable proximity, then the position will be acquired rapidly. If the satellites that are in closest proximity (having the strongest signals) are not well-dispersed, position acquisition may require the device to acquire signals from additional, less proximate satellites, which is a process that can take much longer. If the device is in motion immediately from when satellites first come into view, then the position acquisition can take very much longer. In experiments that the authors have run, this time can be as much as 15 minutes, and is dependent on the satellite positioning, relative to the device, and the speed at which the device is moving. The higher the speed of motion of the device, the longer it will be until a position is acquired. We have defined this situation as a ‘cold start’.

In older GPS devices, where the antenna/receiver required a direct view of the sky to receive satellite signals, this property of the GPS device would lead to the start of many trips being missed, and even some entire trips being missed altogether. For example, one of the authors walked in Vienna from a residential flat to the nearby university – a distance of about 1.5 kilometres – without the device ever acquiring position during the walk. After spending several hours at the university, and then walking back, the position was again never acquired, so that the round trip from the flat to the university was entirely absent from the data. The walk was generally accomplished in about 12 minutes, but a significant amount of the distance was under a fairly dense tree canopy, and the device was in motion at about 6 km/h immediately upon leaving each of the flat and the university. In the newer devices, the improvement to this situation occurs when the origin is in a building that is not more than two storeys in height, or where the individual begins travel from a location that is not more than two floors below the roof of the building. In this case, the device may already have satellite reception prior to the trip commencing, in which case there will be minimal acquisition delay. However, if the device is unable to receive satellite position information while at the origin, then the same situation will arise as for the older antenna/receivers.

Again, we have developed fairly sophisticated procedures in our processing software (FitzGerald *et al.*, 2006) to identify when cold start problems have occurred, and to repair the data record as far as possible. This is generally done by using both the underlying GIS network and information on a mirror-image trip to the origin of the trip where the cold start problem occurs. Missing trips are more problematic. When a one-way trip is missed only, we have a break in the GPS record, which should otherwise be continuous. We can identify this as a missing trip. Without going back to the respondent, we can make an estimate of the distance and time for the missed trip. However, we cannot determine the time of day, unless the time of day of the preceding and following trips are very close to the time required for the missed trip. There is also a possibility that a repeated trip through a week or more of GPS recording will show up on some days and not on others. If this is the case, then an improved inference can be made to use data from another day as a sort of ‘hot-deck’ imputation. If a round trip is missing, there is no way to infer this from the GPS data, and it will remain missing.

3.3 Trip purpose and mode

GPS devices do not provide any information directly on purpose or mode. However, both of these can be inferred, with a very high accuracy, from the information provided by the GPS device. First, we consider trip purpose.

3.3.1 Trip purpose

To make the identification of origins and destinations easier, our approach with the GPS survey is to ask respondents to list the workplaces and their addresses for each person and each job held by members of the household. They are also asked to provide the schools for each person in the household that attends school. Finally, they are asked to provide details of the two most frequently used grocery stores. The home address of each household is known, of course, so that GPS devices and other survey materials can be delivered. On the average, about 30 percent of household trips are made either to or from either school or work (Stopher and Bertoia, 2006), while another 13 percent involve regular shopping, and about 40 percent of the remaining trips will have one end at home. As a result, asking these address questions leads to the identification of about 70 percent of the trip purposes.

For the remainder, three pieces of information can be used that are available in the GPS and which should be available for the region where the GPS survey is undertaken. First, there is the duration of the activity, which is simply the difference between the time at which the trip to the location ends and the trip from the same location starts. This is recorded by the GPS device. Second is the frequency that the location is visited within the multiple days of the GPS survey. (Any GPS survey is likely to be a multi-day survey; however, we discuss the duration of GPS surveys in more detail later in this paper.) Third, if available, is a GIS land use map, that permits identification of the land use at each end of each trip recorded by the GPS device. With these pieces of information, together with the address data discussed previously, the purpose of most trips can be inferred, at least to the level of trip purposes used in most transport planning analysis. Typically, the purpose categorisation would be something like home-based work, home-based education, home-based shopping, home-based other, non-home-based work, and non-home-based other.

As one can see, the categorisation between home-based and non-home based is easy, because we know the home address, and we know whether each trip has one end at home. The home-based work and home-based education trips will be obvious from the address at the non-home end of the trip, together with the time spent at the location. (For people whose work involves visiting numerous different addresses during the course of their day, this is more difficult. Fortunately, such people are relatively rare in any urban population. Usually, they are not modelled in any current modelling applications, and travel diaries usually do not collect the data on their origins and destinations throughout the working day.) Similarly, the most frequently-performed shopping trips will be identifiable from the shop locations provided by the respondent. Non-home-based work trips are easily identified, because one end is at one of the workplaces provided by the household, whilst the other end of the trip is anywhere other than the person's home. If the trip is made from home to a location for which the respondent did not provide an address, and the land use map indicates that the activity undertaken at the unidentified trip end is retail, then it is fairly sure that this will be a home-based shopping trip, although some of these trips could be for personal services. All other trips that have one end at home and one end that is not at retail or any of the addresses provided is most probably a home-based other trip. Any trip that has neither end at home or work is a non-home-based other trip. As a result of these fairly simple steps, the trip purpose can be inferred from the data quite readily, with the only requirement being that households provide these additional addresses in the survey.

The ITLS processing software is currently undergoing development to produce trip purposes using this logic. The software is at an advanced stage of development at this time (FitzGerald *et al.*, 2006).

3.3.2 Mode

Mode of travel is a little bit more difficult. However, at ITLS, we have devised a matrix approach to identifying mode, based on average and maximum speed recorded within a trip, distance, routing, and whether or not the household reports owning cars and bicycles. Through this approach, we are able to deduce the mode of travel in almost all cases. Again, this method relies principally on information already available in the GPS record, together with a GIS street network, with bus routes also included. Although we have not used it to date, there is the potential, with the more sensitive antenna/receiver, to check for bus trips by determining that the vehicle keeps stopping at mid-block locations that are usually where the bus stops are located.

Based on the procedures outlined here, although GPS does not collect data on trip purpose or mode, it is possible to deduce this to a high degree of reliability. Therefore, although one might argue that GPS does not provide this information, it is possible to gain it with probably at least as much accuracy as conventional surveys. The ITLS processing software incorporates this logic at present (FitzGerald *et al.*, 2006).

3.4 Costs and accompanying persons

There is no way to deduce the cost information from the GPS record. Costs such as tolls may be possible to determine, simply by location and facility driven on. However, neither public transport fares nor the ticket type used will be able to be determined. With some considerable effort, parking costs could be determined, although it would not be known what amount, if any, of parking was paid for by a third party. This would involve knowing the parking charge structure for each parking location, determining from the GPS record where the vehicle was parked, and for how long, and then estimating the total parking cost. We have not attempted to do this, thus far, with GPS records that we have obtained. In theory it can be done, but may be prohibitive in cost. GIS data on parking costs and locations is not generally available at this time, and collection of such data would have to be included as part of the costs of a survey if it was desired to develop this information.

Determining data about accompanying persons is partially possible and partially not possible from the GPS records. If accompanying persons are from the same household and are also carrying GPS devices, then it is possible to match the records of household members and determine that two or more household members travelled together on a particular trip. However, if the additional household members are children who are too young to use the devices (we limit the use of devices to those who are 14 years old and over), or if they decide not to carry their devices because someone else is doing so, this information cannot be obtained from the GPS record. Except in rare instances, determining accompanying persons from different households will not be possible.

3.5 Demographics of respondents to GPS surveys

One issue that has been raised a number of times concerning the possible use of GPS as a substitute for more conventional interview or self-administered surveys is the question of biases that might arise between those who are willing to undertake the GPS survey and those who are not. First, it is important to keep in mind that there are biases in all household travel surveys. Some biases arise from coverage problems (e.g., recruiting by telephone which excludes households without phones, or sampling from rate-payer address lists, which under-represents renters, etc.). Other biases arise from differential non-response. NCHRP (2006) documents a number of findings with respect to biases in CATI household travel surveys conducted in the US. Space does not allow us to expand on these in this paper. However, typically, standard household travel surveys under-represent one-person and large households, those who travel very little and those who travel a great deal, public transport users and non-car owners (who may be the same or at least overlapping groups), and renters.

In a recent study using GPS to validate responses to the Sydney Continuous Household Travel Survey, Hawkins and Stopher (2004) reported that those who responded to this GPS survey were biased against larger households, as well as households with older children. In addition, there were slight biases against lower income households and against people who were recent immigrants from non-English speaking countries. It must be kept in mind that these comparisons were to those who agreed to participate in the household travel survey, and are simply differences between the travel survey respondents and those who agreed also to undertake a short GPS survey. On the other hand, we have found different biases in GPS surveys currently being conducted in Adelaide, South Australia. Table 1 summarises the results from our two panels in South Australia. The first is a panel of 200 households that was recruited in September-October 2005, and the statistics are from that time. The second is a panel of 50 households that was recruited in October-November 2005 and then re-surveyed, with replacement for households that did not continue into the second wave. The second wave was undertaken in April-May 2006.

Table 1: Comparison of the Demographics for the Three GPS Waves in South Australia with 2001 Census Data for All Households*

Demographic (per household)	**South Australia Statistics**				
	2001 Census – All Households	**Adelaide Household Travel Survey (1999)**	**Wave 1 – 200 Household Panel**	**Wave 1 – 50 House-hold Panel**	**Wave 2 – 50 Household Panel**
Average Number of Persons	2.37	2.46	2.61	3.09	2.61
Average Number of Vehicles	1.36	1.56	1.84	1.91	1.87
Average Number of Adults	1.90	1.82	2.05	2.11	2.00
Proportion of Population Adults	80.3%	75.6%	82.3%	71.6%	74.1%
Average Number of Children	0.47	0.59	0.49	0.84	0.70
Proportion of Population Children	19.7%	24.3%	16.7%	28.5%	25.9%
Average Number of Males	1.15	1.16	1.27	1.19	1.35
Average Number of Females	1.22	1.25	1.35	1.33	1.53
Average Number of Full-Time Workers	0.62	0.70	0.88	0.91	0.76
Average Number of Full-Time Students	0.40	0.47	0.53	0.98	0.74

* The South Australia census statistics are obtained by aggregating the Western Adelaide Statistical Subdivision (SSD 40510) with the Statistical Local Areas of Holdfast Bay North (SLA 405202601) and Holdfast Bay South (SLA 405202604) to approximate the evaluation zone.

The differences between the 200 household panel and the Adelaide Household Travel Survey (AHTS) are very small, as are the differences between this panel and census data. The biggest (proportional) difference is on full-time workers, which is very likely to be a difference in employment in the economy between the census in 2001 and the panel in 2006. The AHTS is also higher in 1999 than the 2001 census, but lower than the panel in 2006. The 50 household panel is a little more different, which is almost certainly due to the small size of the panel. Overrepresentation of two households in either wave would change the percentages by 5 percent, and make similarly large changes in the averages. The biases reported in the Sydney project by Hawkins and Stopher (2004) are not evident in this analysis for Adelaide. In fact, there appears to be a slight bias towards larger households (not against as in Sydney) and to households with more children. Immigrant and language status were not collected in the Adelaide surveys. There is also a slight bias towards households with cars, which is also commonly the case in household travel surveys, as is evident in the AHTS data. It appears that, in comparison to the census, the GPS panels and the AHTS are both biased against one-person households and towards car-owning households.

3.6 Summary of shortcomings

In this section, we have identified a number of shortcomings of GPS records, both in terms of the completeness that is possible to obtain from a GPS device, and also the required data for a travel survey. We have also concluded that most of these shortcomings can be dealt with by software processing, most of which we have already developed for our present applications. The principal areas that are not subject to this sort of repair and correction are missing round trips, transport and parking costs, and accompanying persons, where these are from different households, such as a group of people going from work to lunch.

Finally, concerns that the GPS survey would be undertaken by a biased subset of the population appears to have relatively little foundation, based on current work in Adelaide. The biases that are potentially present appear to be similar to the biases in conventional household travel surveys. Overall, there are no consistent data that suggest that the samples of households that will undertake a GPS survey are essentially different from the underlying population, nor that they differ markedly from those from conventional surveys.

4 Advantages of GPS

GPS measurement of travel has a number of advantages. The first of these relate to the precision of the GPS record. The second relate to the ability to collect multiple days of data, without unduly burdening the respondent.

4.1 Precision of the GPS record

This has been the basis of much of the past use of GPS in validating household travel surveys conducted by other methods. There is no selective reporting or remembering of trips carried out. Rather, the GPS device will record all trips, with the possible exception of some very short trips and trips that are made when a person intentionally or unintentionally leaves the GPS device at home. In the US, the use of GPS as a validation procedure has shown underreporting of travel by conventional CATI surveys of the order of 20 to 60 percent, while our work in Sydney showed underreporting against a continuous face-to-face interview survey of under 10 percent. All of these surveys also show that people do not make accurate estimates of times of departure and arrival, trip duration, or trip length. The GPS is able to provide very accurate information on the origin and destination locations of each trip, the time it starts and the time it ends, and the route taken. Information on route has never been available from household travel surveys conducted by conventional means.

The start and end time of each trip is recorded to within one second of its actual time. Trip duration is similarly accurate to within one second. The location of the origin and the destination is provided to within a few metres, offering the ability to geocode trip origins and destinations to within very precise geography. The trip distance is also known to within a few metres. The route is known precisely. An illustration of the type of data that it is possible to obtain from the GPS is provided in Figure 1, which presents the data for one person on one day.

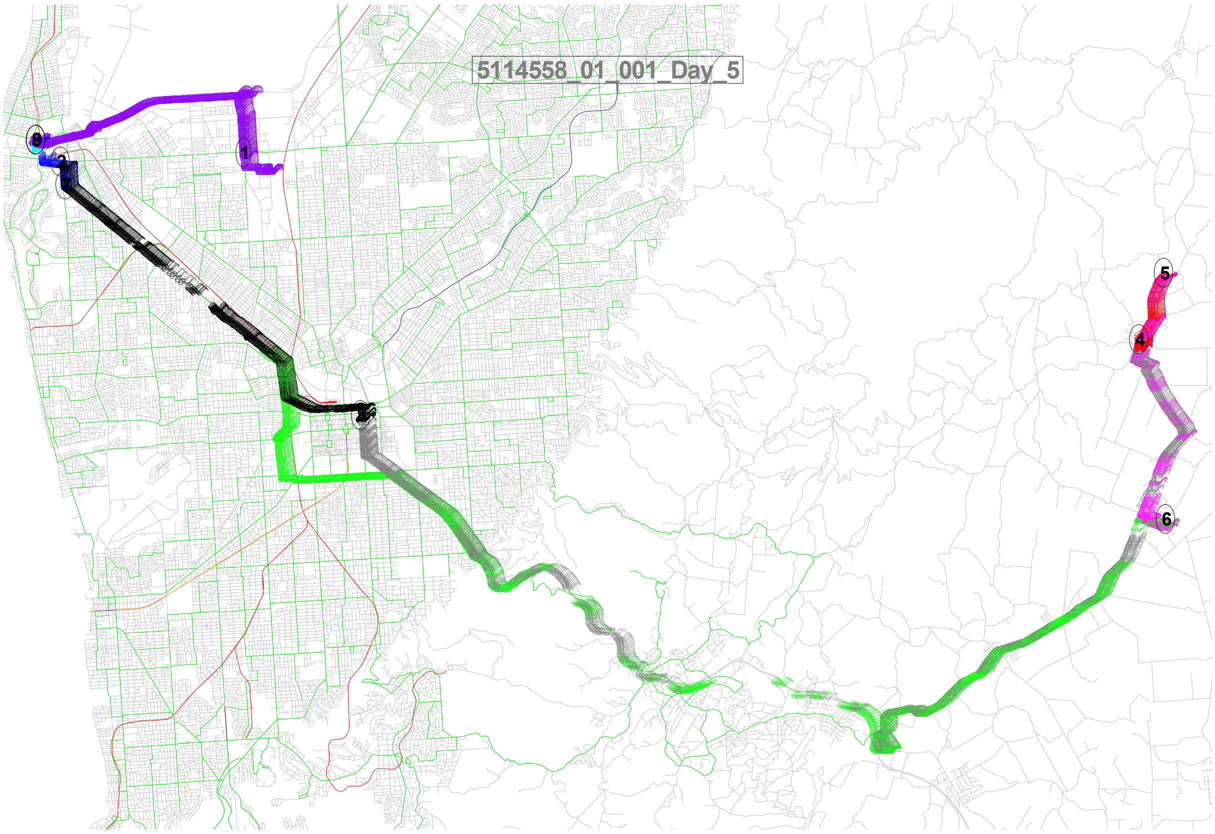

Figure 1: Trips for one person for one day

From Figure 1 and the trip list that was developed from our software, we are able to determine that this person started out their day at the eastern end of trip 1 at 6:19 a.m. in the morning, and travelled to the next location arriving there just before 6:31 a.m. The trip took 11 minutes and 32 seconds, and covered a distance of 10.759 kilometres at an average speed of 55.9 km/h. The person remained at this location until 2:13 p.m., for a total elapsed time of 7 hours and 42 minutes. Leaving at that time, the person travelled for 26 minutes and 15 seconds to a location in downtown Adelaide, a distance of 15.142 kilometres and at an average speed of 34.6 km/h. He or she stayed at this location until 3:20 p.m. (a period of almost 41 minutes), and then travelled to the east a distance of 41.547 kilometres at an average speed of 56.4 km/h. The person remained at this location for only 7 minutes, before travelling further to the north a distance of 3.839 kilometres at a speed of 26.8 km/h, arriving there at 4:19 p.m. She or he then travelled again after remaining here for 45 minutes to a point 10.045 kilometres back to the south, arriving at 5:21 p.m. and remaining there for 1 hour and 17 minutes. Speed of travel was 37.7 km/h. The person now began the trip back towards home, leaving at 6:38 p.m. and arriving at 7:23 p.m., having travelled 41.938 kilometres in 44 minutes and 41 seconds, at an average speed of 56.3 km/h. We have a break in the record at this point, lasting for 9 minutes and covering 8.654 kilometres, but this is picked up again after the breaks and shows the person arriving at their next destination at 7:37 p.m., having travelled a further 2.365 kilometres at a speed of 31.9 km/h. Again, the person made a stop here, that lasted for 2 hours and 5 minutes, and then set off to return home, arriving there at 9:55 p.m., after travelling a further 11.178 kilometres at an average speed of 51.9 km/h for 12 minutes and 55 seconds. This is the end of this person's day.

Within the data that we have summarised here, we have actual locations of each of the stops made by this person, and can also determine the second-by-second speed of travel. It is fairly evident, just from the speeds shown, that all this travel was undertaken by car. We also have a record for a second person in the same household and can determine that this person did not make any trips at the same time or location as person 1. There is a wealth of information provided that is much more complete than can be gained from traditional survey methods, yet all that the respondent must do is to carry a small device that is about the size and weight of a mobile telephone.

4.2 Multi-day data

A second aspect of the advantages of GPS data collection is that we can obtain accurate data for a number of days. In experiments that ITLS has recently undertaken, we have asked people to carry GPS devices with them for as little as three days (Stopher *et al.*, 2006c) and as much as 28 days (Stopher *et al.*, 2006d). While we have found a drop off in completion of the 28-day task, completion of the three-day and seven-day task have been very good. For the 28-day survey, after determining which days of no travel were genuine no-travel days and which were days when the GPS was not taken with the individual, we found that only 24 people out of a total of 107 people had actually completed the full 28 days. We found that 167 out of 283 had completed the full seven days in the one-week data. Therefore, it appears that about a 60 percent completion rate is achievable with the seven-day task, while this drops to less than 25 percent for the 28-day task. In the seven day data, the remaining persons still provided a substantial amount of data, with often 3 or 4 days of complete data. In the 28-day survey, we were able to get 15 days of data from 65 people (or about 60 percent) and 10 days from 67 people. However, for our analyses we removed two people (from different households) who had unusually high trip rates.

While there are some statistical issues to be resolved on this point, if one can count each person day as a separate observation for modelling and analysis purposes, then the GPS survey is capable of providing large data sets, from a relatively small number of households. In the 200 household panel, which contains 283 persons who were eligible to carry GPS devices, we estimate that we have 1,367 person days of data, for an average of 4.83 days per person, or 6.73 days per household (there were actually 203 households in wave 1 of the panel). From our work on the 28-day data, we believe that it is optimal to ask people to carry GPS devices for 10 to 14 days. Our expectation is that this will produce an average of between 8 and 9 person days of data from each person in the sample, because people will usually not travel for 10 to 20 percent of the time. This will include providing data on both weekday and weekend travel, a luxury that is not now possible with most traditional surveys. The advantages of multi-day data are yet to be explored in detail. However, Stopher *et al.* (2006d) have provided some initial exploration of the information provided by the 28-day panel that we have been running in South Australia.

4.3 Costs

Perhaps it is a little surprising to put costs under the advantages, rather than the disadvantages of GPS surveys. However, we believe that it is demonstrable that, on a per person-day of data basis, GPS surveys are less expensive than traditional survey methods. While GPS devices are expensive to purchase initially, it is clear that any one survey should not be burdened with covering the full cost of the devices. At ITLS, we have developed a daily device cost that is less than $3. We are also able to use software to do more and more of the checking and correcting of the records provided by the GPS. Recruitment costs for a GPS survey are similar to those for any one-day or two-day conventional survey, especially because we have found that response rates to recruitment are very comparable to response rates for more traditional surveys. The costs of undertaking the survey are the recruitment costs, the costs of sending the devices to each household by courier and collecting them again from the household, and then the processing costs for the data retrieved. Our software requires little more than 20 minutes of person time per device for downloading, processing, and storing the data. The time-consuming part at the moment is that we still undertake a manual check of maps such as that shown in Figure 1. This is a slow process that currently requires about 2½ minutes per day of data. Assuming a sample of 400 persons undertaking a GPS survey for 14 days, this will produce about 3,500 person days of travel in our estimation. Manual checking of this will take almost 150 hours of labour. The per household costs of the GPS survey are quite high. However, pro-rated to the person days of data, they are low in comparison to any other survey method, including a postal survey, and produce data that are far more accurate.

4.4 Prompted recall surveys

One option that has not been discussed at this point in this paper is that, for the data that are possibly required but not collectable by means of the GPS device, a prompted recall survey can be conducted. This is a survey in which respondents are sent maps and tabular presentations of the GPS data within a few days of completion of the GPS task, and are then asked to provide the additional information required about each trip through one of several alternative means – a postal survey, an Internet survey, or a telephone interview, for example. We have found that this is a productive method for collecting additional details about the travel, although it adds significantly to the cost of the survey. A more detailed discussion of this option can be found in Stopher *et al.* (2004).

5 Conclusions

While GPS is not yet a foolproof method of collecting all travel that people do (and possibly never will be), this paper shows that there are some profound advantages in collecting data with GPS that overcome numerous problems in more traditional methods of collecting household and person travel data. The advantages of a GPS-based method are as follows:

- It is a passive method of data collection that requires very little from the respondent other than carrying the device with them for the period requested;
- It records data very accurately about routes used, distance travelled, time taken, and when and where the trip takes place;
- It provides a means to obtain travel data over a number of days, with very little additional burden for respondents as the length of the survey is increased;
- Devices will record distances for all modes of travel, and permit the analyst to infer the mode of travel. Hence, VKT and PKT can be estimated much more accurately than from diaries, and also walking and bicycling travel can be captured; and
- The data can potentially serve a number of additional uses such as providing travel speed by time-of-day and route, inputs for fuel consumption and emissions estimates, and measures of physical activity and health.

The GPS also has disadvantages:

- Initial versions of the device were vehicle-based and later adapted to be person-based. They were somewhat awkward to carry. Newest technology has resolved this problem and provided a small and lightweight device.

- Signal loss or serious signal degradation can occur in various circumstances including indoors, tunnels, urban canyons, heavy tree canopies, and in certain modes of transport such as trains and buses, although the newest technology has largely overcome these problems.
- Devices may take time to acquire position, such that some trips are lost altogether, and the beginning of other trips may not be recorded. This can be fixed in part through software repair routines.
- Devices can easily be left at home and not carried by the respondent or the respondent can forget to charge them.
- Processing requirements can be extensive.
- It is still perceived (incorrectly, we argue) as a more expensive method for conducting a survey than a diary-based survey.

Overall, we believe that there is much that can be gained by moving traditional travel surveys to a passive GPS survey, in which multiple days of data are collected. Ideally, it seems that the survey should request respondents to carry their GPS devices with them for 10 to 15 days. A wealth of weekday and weekend day data will result from such applications, with current and projected software being able to provide rich data for analysis and modelling.

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