Transport Reviews: A Transnational Transdisciplinary Journal

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ttrv20

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Published online: 04 Apr 2014.

Transport Reviews, 2014
http://dx.doi.org/10.1080/01441647.2014.903530

Routledge
Taylor & Francis Group

Review of GPS Travel Survey and GPS Data-Processing Methods

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(*Received 24 March 2013; revised 7 March 2014; accepted 9 March 2014*)

ABSTRACT *Global positioning system (GPS) devices have been utilised in travel surveys since the late 1990s. Because GPS devices are very accurate at recording time and positional characteristics of travel, they can correct the trip-misreporting issue resulting from self-reports of travel and improve the accuracy of travel data. Although the initial idea of using GPS surveys in transport data collection was just to replace paper-based travel diaries, GPS surveys currently are being applied in a number of transport fields. Several general reviews have been done about GPS surveys in the literature review sections in some papers, but a detailed systematic review from GPS data collection to the whole procedure of GPS data processing has not been undertaken. This paper comprehensively reviews the development of GPS surveys and their applications, and GPS data processing. Different from most reviews in GPS research, this paper provides a detailed and systematic comparison between different methods from trip identification to mode and purpose detection, introduces the methods that researchers and planners are currently using, and discusses the pros and cons of those methods. Based on this review, researchers can choose appropriate methods and endeavour to improve them.*

1. Introduction

Travel surveys are widely used around the world for transport planning. Traditionally, the face-to-face interview was the first approach used in travel surveys in the 1950s. Due to both safety and cost issues, other approaches, such as mail-out/mail-back and the telephone survey, gradually replaced face-to-face interviews by the 1970s in the USA, although face-to-face and other survey methods have continued in other countries around the world. In the late 1990s, global positioning system (GPS) technology started to be introduced in travel surveys and has been developed rapidly over the past decade. Because GPS devices are very accurate at recording time and positional characteristics of travel, GPS surveys can improve the accuracy and depth of travel survey data, and correct the trip-misreporting issue caused by respondents. Compared with GPS records, paper-based travel diaries under-report about 20–30% of trips (Bricka & Bhat, 2006; Stopher & Greaves, 2009; Stopher & Shen, 2011; Wolf,

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2000). However, as a new method, the GPS survey also has some shortcomings, such as unstable signal acquisition in certain areas and difficulties in GPS data processing.

The purpose of this study is to provide an overview of GPS surveys, compare different GPS data-processing methods to show the advantages and disadvantages for each of them, and understand the research directions that need to be pursued. In Section 2, the history of travel surveys from face-to-face interviews to GPS surveys is reviewed, showing the development of travel surveys. Section 3 discusses specifically GPS surveys in different countries. The initial idea of using GPS surveys in transport data collection was to replace paper-based travel diaries; GPS surveys currently are being applied in a number of transport fields. Some of these applications are introduced. The methods of processing GPS data are reviewed and compared in Section 4, and research gaps are suggested in the last section.

2. Traditional Travel Survey Methods

In the field of urban transport planning, the household travel survey started as a face-to-face interview in the 1950s, in which interviewers visited the participants' homes and asked questions about the household's travel information. The interviewers recorded the answers using paper and pencil. However, this method was considered to be unsafe in some areas in the USA and the labour and time costs for interviews were too high. Therefore, interviews were gradually replaced by the mail-out/mail-back survey, another method started in the 1960s (Wolf, 2000), in which households received some survey documents by mail and returned them after completing the survey. The main problem of a postal survey is the low response rate. In addition, the mail survey still needs labour to transfer the records from paper to computers.

In order to overcome the disadvantages of paper-and-pencil surveys, computer-assisted surveys were introduced in the 1980s. There are three main types of computer-assisted survey — the computer-assisted telephone interview (CATI), the computer-assisted personal interview and the computer-assisted self-interview (CASI) (Stopher, 2008). The web survey is one of the CASI methods. Respondents can fill in the travel information in a web interface. In the web survey, some information, such as travel modes and trip purposes, can be chosen from a list, while other information, such as start and end times for a trip and addresses of origins and destinations, must be typed in by the respondent. However, all of these methods face issues of non-response (Zimowski, Tourangeau, Ghadialy, & Pedlow, 1997) and misreporting (Wolf, 2000). Therefore, automated data collection methods were then considered.

3. GPS Travel Surveys

GPS technology has been used in travel surveys since the late 1990s (Wagner, 1997). Most GPS surveys were undertaken as supplementary surveys to measure the accuracy of traditional surveys. Due to issues of non-response and data inaccuracy in traditional survey methods, GPS technology provides the potential to replace the traditional travel survey and obtain more reliable and accurate data. Although GPS devices are very accurate at recording time and positional characteristics of travel, they cannot record travel mode, trip purpose or the number of occupants in a private vehicle — all important attributes in a traditional travel survey. Therefore, data-processing procedures become critical to the usefulness of GPS surveys, because there would be insufficient information for travel modelling purposes without the results of the processing.

For the past decade, GPS surveys have been undertaken in Australia, Austria, Canada, China, Demark, France, Israel, the Netherlands, Japan, Sweden, Switzerland, the UK and the USA (Beijing Municipal Committee of Transportation, 2012; Bohte & Maat, 2009; Itsubo & Hato, 2006; Kelly, Krenn, Titze, Stopher, & Foster, 2013; Kohla & Meschik, 2013; Krygsman & Nel, 2009; Marcha et al., 2008; Oliveira et al., 2006; Papinski, Scott, & Doherty, 2009; Rasmussen, Ingvardson, Halldórsdóttir, & Nielsen, 2013; Schönfelder, Axhausen, Antille, & Bierlaire, 2002; Schüssler & Axhausen, 2009; Stopher, Moutou, & Liu, 2013; Stopher & Wargelin, 2010) at least. Some countries have conducted a number of GPS studies, but Table 1 only shows some representative examples of GPS surveys in the world. From these surveys, researchers reported that GPS devices can correct the trip-misreporting issue caused by respondents and improve the accuracy of travel data (Bricka, Zmud, Wolf, & Freedman, 2009). The earliest GPS surveys required participants to enter additional trip information into a personal data assistant (PDA) when each trip started. However, this step increases the complexity and cost of the GPS survey (Bachu, Dudala, & Kothuri, 2001). After researchers improve the methods of processing GPS data, the PDAs have not been used.

With the entry of twenty-first century, prompted recall (PR) surveys have been conducted, in which respondents are assisted to recall their actual travel by receiving GPS-generated maps of where and when they travelled. PR surveys are used to validate the GPS data, because GPS devices are also subject to some problems such as difficulty in obtaining a signal in certain areas and devices being left at home, which means that GPS would miss data that need to be collected.

Bachu et al. (2001) undertook a proof-of-concept experiment with a PR survey. This survey was a face-to-face interview in which respondents reported their trip purposes and vehicle occupancy. Bachu et al. (2001) suggested that PR surveys could reduce burden on the respondent because it took only 15–20% of the time for completing a one-day diary, which results in a high response rate for PR surveys. They also found that even after three to four days, respondents still could recall their travel information in a PR survey.

Recently, PR surveys have been developed as web-based surveys (Giaimo, Anderson, Wargelin, & Stopher, 2010; Greaves, Fifer, Ellison, & Germanos, 2010). In these surveys, respondents usually receive a map of one day's travel based on a geographic information system (GIS) application. They are asked to add more information or correct the GPS records in terms of travel modes, trip purpose, and vehicle occupancy. Some PR surveys even allow respondents to modify their trip information (e.g. changing trip route, inserting trips) (Greaves et al., 2010).

In a very recent study, Bricka, Sen, Paleti, and Bhat (2012) suggested that the GPS survey is more suitable for the younger respondent, while traditional survey methods may be better for older respondents, because the younger respondents are more technology savvy. Another earlier research on the factors influencing response rates to GPS surveys by Hawkins and Stopher (2004) suggests that the acceptance/rejection rates of GPS surveys between the old and the young have no statistically significant differences. Different from Bricka et al.'s research, the method of recruitment of this survey in 2004 was a face-to-face interview. Even though the devices used in that survey were the old generation devices, it still

Table 1. GPS surveys conducted in the world

Location	Year	Survey purpose	Device	Sample size	Collection period	Technical details	Processing involved[a]
Four states in Australia	2007–13	Travel behaviour change monitoring	Dedicated GPS device, recording data every second	130 households	15 days (6 waves)	Random sampling; GPS-only survey	TI, MD
Ontario, Canada	2007	Route choice	Smartphone plus a GPS receiver	31 respondents	2 days	Snowball sampling; GPS survey with a pre-interview and a web-based PR survey	TI, PI
France	2007–08	Sub-sample of National Travel Surveys	Dedicated GPS device, recording data every 10 seconds	9% of the main survey	7 days	Random sampling; GPS survey with one-day travel diary	TI, MD, PI
Matsuyama, Japan	2004	Compare GPS records and travel diaries	GPS-equipped mobile phone, recording data every 30 seconds	31 respondents	5 days	Non-random sampling; paper-based diary and GPS survey with a web diary	TI
Jerusalem, Israel	2010	GPS-only household travel survey	Dedicated GPS device, recording data every second	3000 households	1 day	Random sampling; GPS-only with a PR survey	TI, MD, PI
Three cities in the Netherlands	2007	Residential selection	Dedicated GPS device, recording data every six seconds	1104 respondents	7 days	Random sampling; GPS-only survey with a web-based PR survey	TI, MD, PI
Western Cape, South Africa	2008	Assess the reliability of GPS survey	Dedicated GPS device, recording data every second	100 respondents	14 days	Random sampling; GPS survey with two-day travel diary	TI, MD, PI

Borlänge, Sweden	1999–2001	Traffic safety	In-vehicle GPS device, recording data every second	310 vehicles	15–243 days	Stratified sampling; in-vehicle GPS survey	TI, PI
Three cities in Switzerland	2008	Explore whether participants pass certain billboards	Dedicated GPS device	4882 respondents	Average 6.6 days	Random sampling; GPS-only survey	TI, MD, PI
UK	2011	Test the possibility of replacing travel diaries	Accelerometer-equipped GPS units, recording data every second	429 households	7 days	Random sampling; pilot survey (GPS only) for National Travel Surveys	TI, MD
Ohio, USA	2009–10	GPS-only household travel survey	Dedicated GPS device, recording data every second	2059 households	3 days	Random sampling; GPS-only survey with a web-based PR survey	TI, MD, PI
Graz and Tullnerfeld, Austria	2009–10	Test an integration of new technologies for a mobility survey	Dedicated GPS device	235 respondents	3 days	Random sampling for four groups (passive GPS-only, active GPS-only, GPS with diary, and diary-only; pilot GPS survey with PR)	TI, MD, PI
Beijing, China	2010	Sub-sample of Beijing Household Travel Surveys	Dedicated GPS device, recording data every five seconds	890 persons	1 day	Random sampling; GPS survey with one-day travel diary	TI, MD
Greater Copenhagen Area	2013	Part of the research on travel chain and sustainable mobility	Dedicated GPS device recording data every second	54 households	3–5 days	Random sampling from Danish National Travel Survey; GPS survey with one-day travel diary	TI, MD

[a]MD = mode detection, PI = purpose imputation.

reached the conclusion that there is no sufficient evidence showing the age of respondents could significantly influence the acceptance of a GPS survey. This suggests that different methods of recruitment also may change the response rate for different ages.

It is widely accepted that GPS surveys can report more accurate data. However, signal loss and signal noise are the two main issues that GPS units have. Signal problems occur for several reasons, such as a cold start or warm start, which usually occurs at the beginning of each day (i.e. cold start) or when the GPS device switches from 'sleep mode' to 'working mode' after a person stops for one or two hours (i.e. warm start), and travelling in urban canyons. Urban canyons are formed by roads cutting through blocks of tall buildings. They have impacts on GPS signal reception, and cause missing GPS data. Signal problems result in missing trips or parts of trips and generating spurious trips (a sequence of points generated by a stationary GPS device that have been incorrectly identified as a trip). For those studies that require data integrity and identification of mode for each trip, such as physical activity or energy expenditure for the travelling task, the travel information for missing GPS trips becomes critically important. Although a number of studies (Chen, Gong, Lawson, & Bialostozky, 2010; Gong, Chen, Bialostozky, & Lawson, 2012; Tsui, 2005) have discussed the reasons for signal problems, only a few studies suggest how to fix the problem or reduce the errors that missing data would cause. Chen et al. (2010) used GPS to record data all day long without the 'sleep mode' to solve the cold/warm start. This would increase the data-set size and reduce the working time of a device due to battery issues. The authors do not report the battery performance when they turned off the 'sleep mode'. Also, they adopted detailed GIS information to deal with the issue of travelling in urban canyons. Stopher, Greaves, and Shen (2013) added an additional step called 'map editing' to fix some data errors manually. Even though there are a few approaches to overcome signal problems, missing data and errors are still the main challenges for GPS studies.

3.1. *Smartphone-Based GPS Survey*

As Smartphones are becoming one of the necessities of daily life and a GPS module is usually built into Smartphones, Smartphone-based GPS surveys have been proposed to replace dedicated GPS devices (Gilani, 2005). Some research projects also use Smartphones to conduct surveys (Bierlaire, Chen, & Newman, 2013; Hudson, Duthie, Rathod, Larsen, & Meyer, 2012; Reddy et al., 2010; Xiao et al., 2012). Because Smartphones are now increasingly popular, using Smartphones to collect GPS data would reduce the costs. Also, most Smartphones have GPS and accelerometer sensors; both GPS and accelerometer data can be recorded by phones, and could be used to detect modes and purposes.

Although a Smartphone has less warm-up time to find the first position (Bierlaire et al., 2013), adoption of Smartphones as GPS devices in GPS surveys is limited by such issues as short battery life (compared with GPS devices), poor accuracy of positioning, and difficulties and high cost of transferring data from phones to data centres.

3.2. *GPS Survey Applications*

Because GPS surveys have significant advantages as described above, they have been applied in a number of transport fields. Bullock, Jiang, and Stopher (2005) used GPS technology to measure whether a bus service was running on time. According to their conclusion, it is also shown that GPS is a cost-effective method to collect data. In addition, analysis of highway travel time and travel speed was undertaken by Quiroga and Bullock (1998). They concluded that GPS speeds determined from the latitude–longitude information were preferable for computing segment speeds.

Due to the advantage of GPS to objectively report the spatial locations, research on walking and cycling has also used GPS to provide better understanding of pedestrians' and cyclists' behaviour. Menghini, Carrasco, Schüssler, and Axhausen (2010) specifically investigated cyclists' route choice by GPS data. They mentioned that, using GPS data, it is possible to estimate high-quality route choice models.

Route Choice, in fact, is one of the earliest fields to which GPS surveys were applied. Wolf, Hallmark, Oliveira, Guensler, and Sarasua (1999) applied GPS surveys for route choice data collection, just a couple of years after GPS was introduced in household travel data collection, to validate travel-demand models. GPS technology provides an opportunity to conduct revealed preference surveys for route choice research. The accuracy of trip identification (TI) and data integrity are often the most critical factors for route choice, because missing data could lead to inaccuracy of the results of route choice modelling. Papinski et al. (2009) recruited 31 individuals to carry GPS devices for their travel, and compared their planned routes and observed routes to understand the route choice decision-making process. In addition to the research on vehicles, route choice of cyclists has become a hot topic. GPS can be used to test the preference of cyclists regarding bike facilities (e.g. paths, lanes and boulevards). Generally, cyclists are more concerned with travel time and traffic volume, which are sometimes conflicting, because the shortest paths usually are arterial roads that have high traffic volumes (Broach, Dill, & Gliebe, 2012; Dill & Gliebe, 2008). Krizek et al. (2007) draw a similar conclusion, while they suggest that cyclists may not be deterred by intersections. Their conclusion also implies that land-use planning and transport policy for cycling could be adjusted according to the finding of route choice research.

Using GPS devices to assist an on-board survey is another GPS survey application (Oliveira & Casas, 2010). GPS was used to record the location of the participants and their arrival and departure times so that the boarding information, the routes of the trips, and transit trip times could be obtained more accurately.

GPS devices have also been applied in the health field to determine where physical activity happens (Rodriguez, Brown, & Troped, 2005). They combined GPS data with accelerometer data to observe the behaviour of transport-related physical activities. Krenn, Titze, Oja, Jones, and Ogilvie (2011) reviewed several GPS applications in physical activity to determine the capability of GPS in research on the relationship between physical activity and the environment, and they concluded that GPS is a promising tool to obtain more reliable data. Mackett, Brown, Gong, Kitazawa, and Paskins (2006) conducted a survey using GPS and a diary especially for children to analyse their activities. University of California, San Diego, has also endeavoured to develop a Personal Activity and Location Measurement System (http://ucsd-palms-project.wikispaces.com/) to estimate Physical Activity Energy Expenditure by combining accelerometer data, heart rate monitor data, and GPS data.

Stopher, Zhang, Zhang, and Halling (2009) applied GPS travel surveys to evaluate travel behaviour change initiatives. They asked respondents over 14 to carry

GPS devices for a week or 15 days for three waves (from 2005 to 2007). The evaluation was undertaken of a TravelSmart intervention in South Australia, which is an important element of the national programme to reduce greenhouse gas emissions from cars. They also used GPS for this purpose in Canberra, and have recently completed a long-term evaluation over four states in Australia (Stopher, Moutou et al., 2013).

4. GPS Data Processing

The typical GPS data processing can be divided into two principal steps. The first step is to transfer data from GPS devices to computers and create output files that could be used for statistical analysis. The second step is to identify trips and other information (e.g. travel modes and trip purposes). GPS devices can record the travel time and the coordinates of locations every second, which can therefore report speed, start time and end time, and routes of the trips (Wolf, 2000); however, most GPS devices cannot automatically identify trip ends or report travel modes and trip purposes, although an in-vehicle device with no internal power supply can detect trip ends through the turning on and off of the ignition. Figure 1 shows a common procedure to process GPS data.

Most research needs to process millions of data points, so looking for a potential to reduce data points becomes important. Although the latest computers have increased their capability, several days are still needed to process millions of data points from TI to mode and purpose detection. In practice, one second as the interval to record data is typically used, while three seconds, five seconds, or even longer intervals are also applied in some research. Reducing the number of data points by increasing the time interval of recording data can reduce the processing time and further reduce the data-processing cost. (Note

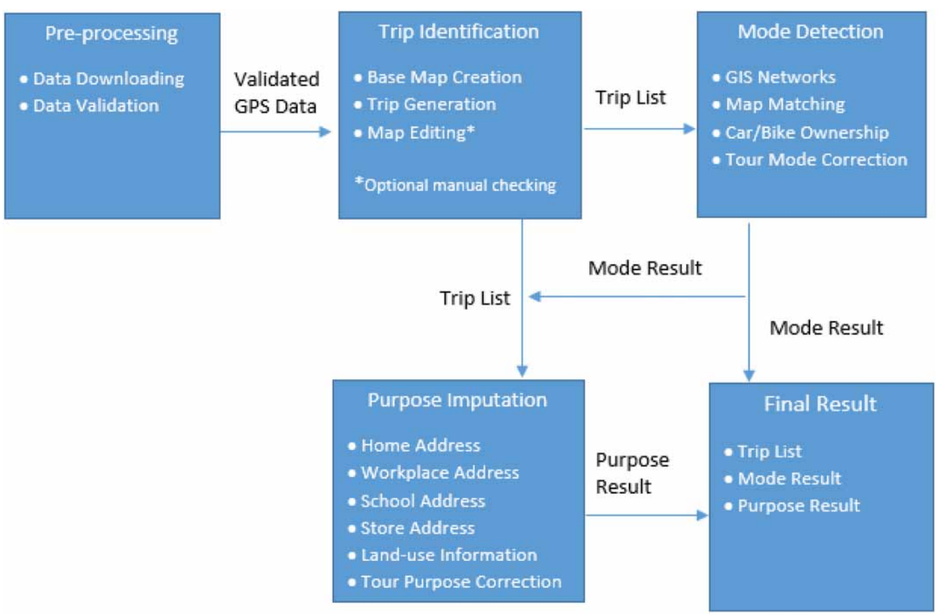

Figure 1. Process to analyse GPS data.

that using three-second interval data would reduce the size of data sets by two-thirds and five-second data by 80%). Also, with the increasing use of smartphones in travel data collection, increasing the data recording interval could improve the performance of other devices (e.g. smartphones) to collect data. For instance, smartphones will have a longer battery life if a longer interval for recording data is applied. Shen and Stopher (2013b) conducted an in-depth test for different options of data recording interval to see what influences each option would have on the final processing results. They concluded that five-second data still can provide reliable results in TI. They did not report the results of mode and purpose detection.

4.1. *Trip/Segment Identification*

TI or segment identification (SI) would be the first challenge for all researchers. The travel-demand model needs information about each trip, and the following data processing (i.e. mode detection and trip purpose detection) is currently based on the results of TI. In this step, the concept *trip* refers to a one-mode trip, which is also known as a *segment*. There are also two common concepts, trip chains and tours, which are usually used by researchers. Trip chains means a journey between 'significant' locations (e.g. home, workplace, etc.). It can show how people link their segments in journeys. Tour means a round trip from one place back to the same place. For instance, a home-based tour is a tour from home back to home.

Currently, most researchers use rule-based algorithms to undertake the TI/SI processing. The early work of Wolf (2000) assumed that the dwell time between activities would be a main criterion for TI/SI. She suggested that 120 seconds of dwell time would be a reasonable time because the traffic signal cycle should always be less than 120 seconds according to the Highway Capacity Manual, and the signal light stops should not be regarded as trip ends. This rule has been widely accepted. Although other researchers provided some supplementary rules (e.g. Schüssler & Axhausen, 2009 set point density as another criterion; Stopher, FitzGerald, & Zhang, 2008 adopted a rule of the latitude and longitude change), the 120-second rule is still being used in practice. However, the 120-second rule actually lacks empirical and/or theoretical research to support. Also some activities, such as pick-up/drop-off, may have a shorter duration. Therefore, it is reasonable to argue that the number of trips may be underestimated due to the excessive dwell time. Shen and Stopher (2013b) tested different thresholds of dwell time from 15 seconds to 120 seconds, and concluded that 60 seconds would be a better option for the threshold. Biljecki (2010) applied a two-step method to segment the travel. The first step is to segment *journeys* (between two meaningful locations), and then segment journeys to single-mode segments before detecting transport modes. He applied 12 seconds as a dwell time, which is much less than 120 s (but also lacks empirical research to support), which generated excessive segments. As a result, some segments are merged after mode detection if the adjacent trips have the same mode classification results. This method may identify stops with short duration when people change mode, but it might also generate too many segments to merge, which will increase the processing time. Also, it could mistakenly merge two segments which have the same mode results but there actually is a real stop between them.

In the TI/SI procedure, besides identifying short stops, there are mainly two difficulties that need to be dealt with: signal loss and signal noise (Biljecki, 2010; Tsui, 2005). Based on the 120-second rule, Tsui (2005) analysed the cases of signal loss. Specifically, if the duration of signal loss is longer than 120 seconds and shorter than 600 seconds, and the travel distance is less than 50 metres, there should be a short duration activity occurring in the time of signal loss; if the distance travelled during this time is more than 500 m, even if the signal loss time is longer than 120 seconds, it is possibly an underground trip without a stop. Most of TI/SI methods take the number of satellites and the horizontal dilution of precision into account to exclude signal noise. In general, this will delete only a few noisy data points. Spurious trips still exist in most research results.

All these methods use specific approaches for TI/SI, and the results of this step are used further for mode and purpose detection. In this case, mode and purpose detection would rely greatly on the accuracy of TI/SI. Unfortunately, the results of TI/SI still have a great number of problems (e.g. spurious trips, missing trips, etc.).

4.2. *Travel Mode Detection*

Travel mode detection is the next data-processing step. Similar to TI/SI, mode detection is usually based on rules. It is widely accepted that the main criteria for mode detection are travel speed, acceleration/deceleration, and the information from the GIS database (Bohte & Maat, 2009; Gilani, 2005; Stopher et al., 2008). Specifically, speed can distinguish most walk trips because they are made at speeds below 6 km/h and car trips, which are above 40 km/h, while acceleration/deceleration can be used to differentiate bike trips from walk trips and public transport trips from car trips (Stopher et al., 2008). Public transport can also be easily detected by public transport timetables, and public transport routes and stops based on GIS databases. However, one still cannot be fully confident of the results because these deterministic methods struggle with the ambiguity of two similar modes, such as bicycle and bus. Stopher et al. (2008) also suggested that household information could be used for the detection. For example, if the household does not own bicycles or cars, the mode they probably use would be public transport. This rule would be especially useful when it is difficult to distinguish bicycle trips, bus trips, or car trips only by speed. However, it cannot help to identify modes when respondents are passengers rather than drivers because people from other households could drive a respondent who does not own a car to a place. Comparing to data collected by a PR survey, Stopher et al. (2008) report that 95% of modes are correctly detected by their deterministic method.

By adopting GIS databases, map matching is another challenge especially for the situation where the quality of GPS data is poor. White, Bernstein, and Kornhauser (2000) discuss some simple map-matching algorithms to match inaccurate locational data with an inaccurate map/network. However, the match is usually somewhat uncertain. Bierlaire et al. (2013) used a more sophisticated probabilistic method based on a structural model and a measurement mode to match the GPS points and transport networks. They calculated the log-likelihood for all the possible routes, and the real path is assumed to be that with the highest log-likelihood. The probabilistic approach not only provides more accurate map matching results, but reduces the influences of GPS data errors.

Some researchers have adopted a probabilistic method to detect mode. Schüssler and Axhausen (2009) proposed a fuzzy-logic approach for mode detection. They set three fuzzy variables – the median of the speed distribution and the 95th percentiles of the speed and acceleration distributions. For the median speed, there were four membership functions (i.e. very low, low, medium, and high); and for the latter two variables, three membership functions were set (i.e. low, medium, and high). Based on the membership functions, each mode is given a probability. They did not report their accuracy of detection because there is no ground truth for them to compare against. The paper does not report the accuracy of detection, but the authors compared the trip distance and distribution for each mode between their results and the Swiss Microcensus on Travel Behaviour 2005 to evaluate the performance of their system in mode detection. They concluded that mode detection yields realistic results.

Although researchers are becoming interested in accelerometers, and accelerometers have been proved helpful to identify trips and stops underground when the GPS signal is lost, it is still arguable whether accelerometer data should necessarily be used in mode detection. First of all, an accelerometer also has similar problems to GPS devices in distinguishing modes with similar accelerometer readings (e.g. trains and buses) (Stenneth, Wolfson, Yu, & Xu, 2011). Also, accelerometer data are very sensitive to the location where people put the device/hold the device, especially for cycling due to movements of the cyclist's body (e.g. the accelerometer data would be very different if the respondents fasten the devices on their arms or on their legs when they are cycling).

Biljecki (2010) designed a more sophisticated fuzzy expert system to classify more modes. He mentioned several indicators that might influence the output, such as speed, proximity to a network (e.g. railway, bus network, roads, etc.), water surfaces (for the detection of ferry), potential transition points (e.g. parking lots, bus stops or train stations), acceleration, stop rate, heading change rate, elevation, journey distance, and journey duration. However, due to the lack of data and low performance of some indicators, he only chose mean speed, mean moving speed, nearly maximum speed (i.e. 95th percentile), proximity to the nearest networks, and the location of a segment with respect to a water surface as the inputs. He developed a fuzzy expert system that achieved 91.6% accuracy for ten modes determined by a PR survey and the author's own experiments. Certainty factors are applied in his fuzzy system to measure the confidence of drawing a conclusion from the evidence. He also suggested that it still had much room for improvement, such as adding more inputs and removing noisy samples, e.g. a gap between two trips or a missing trip.

Due to the limitations of setting rules/algorithms for software, researchers have tried to apply new technologies in the transport area. Artificial intelligence, a learning system, has become possible to use in GPS data processing.

Gonzalez et al. (2010) applied neural networks (NNs) to deduce travel modes. They used mobile phones to record GPS data. As they mentioned, the advantage of using NNs is that they can explore the information from data that is missed by humans or other analysis algorithms. NNs need inputs and outputs to learn. In their research, the inputs they chose were acceleration, speed, estimated horizontal accuracy uncertainty, the percentage of location fixes that refer to the cellular signal coverage area instead of the GPS-calculated position of the phone, the standard deviation of distances between stop locations, and the average dwell time. The NN learnt the small differences between car, bus, and walking trips based on the input attributes. After the training process, the NN was used to automatically determine the modes for new trips. Because NNs perform better with more training data points, they trained the system 500 times and got a result with around 90% accuracy for detection of all modes determined from the data that people input. There are three main limitations of their research. First, the number of inputs for the NNs might be insufficient. More inputs could possibly increase the accuracy of the NNs. Second, the sample size or the amount of GPS data for the training is still not large enough. These problems influenced their results and also limited their system to determining only three different modes. Third, the data they used are mobile phone data rather than dedicated GPS data, which have the problems of short battery life (compared with GPS devices), lack of multitasking, poor accuracy of positioning, and difficulties and high-cost of transferring data from phones to data centres. It should be noted that their accuracy of results are still not as high as those obtained with rule-based methods.

Tsui (2005) combined a fuzzy-logic system with NNs for mode detection. Her work was mainly based on the fuzzy system, while the values of parameters for membership functions of the fuzzy sets are determined by existing NN software, NEFCLASS-J, developed by the Technical University of Braunschweig. It can be improved by developing a dedicated NN system for GPS data processing. Her work identified modes correctly 94% of the time. However, the accuracy of the detection is calculated by comparing the GPS results with volunteers' travel diary results, which is not ground truth.

Similar to the above probabilistic methods, another method currently used in mode detection is Bayesian belief networks (BBNs). Feng and Timmermans (2012) adopted a BBN to detect modes based on both GPS data and accelerometer data. Due to the problem of recording speed (they were struggling with this manufacturing problem for their devices), they had to calculate average speed to define the real speed based on latitude and longitude information of each point. This decreases the accuracy of detection, because speed is one of the most important factors in the detection system. Moreover, the data are not rich enough (only 80 000 points) for detecting more than five modes. These records are not continuous segments in a whole day, which also simplifies the procedure. From their results, the model is excellent in most of the modes but train, and it also has some difficulties to identify a stop. It also cannot be concluded that this method is better at detecting modes than other methods.

Another current method to detect transport modes is Discriminant function analysis (DFA). Troped et al. (2008) conducted a survey requiring respondents to take GPS devices and accelerometers when they walk, run, cycle, in-line skate, or drive. Participants were asked to perform prescribed activities. In their analysis, they tested nine classification variables that could influence mode detection: means, medians, and inter-quartile ranges for accelerometer counts and steps, and GPS speed (calculated by using Doppler measurement). Modes were determined from the combinations of the nine variables. They do not provide more details of this method for the whole GPS data processing. From their results, the accuracy of mode detection using their approach is around 90%.

Reddy et al. (2010) conducted an experiment to ask 16 volunteers to carry six phones positioned on different places (e.g. positioned on the arm, waist, etc.) for 15 minutes for each mode. GIS information was not used in their research. They used a decision tree followed by a discrete Hidden Markov Model to

Table 2. Summary of different approaches for mode detection

Author/s	Method	Attributes	Accuracy	Ground truth
Stopher et al. (2008)	Rule-based algorithm	Speed, GIS, car/bike ownership	95%	PR survey
Schüssler and Axhausen (2009)	Fuzzy-logic system	Speed, acceleration	n/a	n/a
Biljecki (2010)	Fuzzy expert system	Speed, proximity to the nearest networks	91.6%	PR survey
Gonzalez et al. (2010)	NNs	Speed, acceleration, data quality, travel distance, average dwell time	90%	User input in mobile phones
Tsui (2005)	Fuzzy system plus existing NNs	Speed, acceleration, data quality	94%	Travel diaries
Feng and Timmermans (2012)	BBNs	Speed, GIS, car/bike ownership, data quality	96%	Travel diaries
Troped et al. (2008)	DFA	Speed, accelerometer counts and steps	90%	n/a
Reddy et al. (2010)	Decision tree and discrete hidden Markov model	Speed, acceleration	93.6%	Experiment (i.e. mode known)

detect modes and achieve 93.6% accuracy overall. Because it was based on an experiment, the quality of GPS data was better. Unfortunately, they did not test the method on a whole-day survey in which signal problems would usually influence the quality of data and further reduce the accuracy of detection.

Table 2 summaries different approaches applied for mode detection,according to the detection accuracy of these methods used currently. Overall, none of the complex methods appears to have achieved a higher accuracy than the simple rule-based procedures.

4.3. *Trip Purpose Imputation*

The next stage in processing GPS data is trip purpose imputation. There are only a few papers that have looked into the area of trip purpose imputation. The traditional process of trip purpose imputation is based on either land-use information (Wolf, Guensler, & Bachman, 2001; Wolf, Schönfelder, Samaga, & Axhausen, 2004) or a combination of land-use and personal information (e.g. home address, possession of vehicles) (Bohte & Maat, 2009; Stopher et al. 2008).

Wolf et al. (2001) suggested that GIS land-use data can be used to detect trip purpose. Based on a vehicle-only survey, they identified ten categories, i.e. return home, shop, go to work, go to school, pick up/drop off, change mode, social/recreation, personal business, eat, and unknown. Based on the addresses of different locations, they provided three possible purposes for each location. The previous purpose and arrival time were used to further identify the exact purpose from those three possible purposes. According to a CATI-based recall survey, although they only reported ten wrong purposes (out of a total of 151 trips), 39 trips (26%) are unknown trips and they failed to detect ten pickup/drop-off trips due to problems of TI.

Stopher et al. (2008) introduced personal information into the purpose imputation to improve the accuracy of the detection, especially for return home trips and work trips. Respondents provided the addresses of home, workplace, or school, and the address of the two most frequently used grocery stores. Based on these types of data, they detected purpose correctly over 60% of the time determined by a web-based PR survey.

Bohte and Maat (2009) also applied a rule-based system to detect trip purpose, mainly based on the GIS land-use data and the addresses of home and work place. They suggested that for a non-home or non-work location, if a trip ends within a radius of 50 metres from that location, it can be regarded as a destination. For a home or work location, the threshold is changed to 100 metres. Because home and work addresses are known and frequently visited, a wider radius still would be reliable. The accuracy of their trip purpose detection is 43%. They also used a web-based PR survey to test the accuracy of their detection method.

Except for the influences from TI/SI, the main challenge for those methods is to classify purposes in mixed-use locations such as shopping centres. Bricka et al. (2012) also found that processing algorithms using primary working place only to determine a work trip may under-report work trips. A new perspective of trip purpose imputation is that tour-based trip purpose sequences can be used to correct the initial results. According to previous findings (O'Fallon & Sullivan, 2004; Zhang, Stopher, & Jiang, 2010), there are several possible trip purpose sequences for a tour. A simple sequence would be home–work–home, referring to a tour from home to the work place and then from work to home. This tour-based information can validate the purpose imputation. For example, Zhang et al. (2010) suggested that a complex work, education, and shopping tour (e.g. home–work–education–shopping–home) in people's daily travel occurs very rarely, so that any such instances should be re-examined carefully, to see if evidence is strong in suggesting such a tour. In Shen and Stopher's (2013a) recent research, they undertook an empirical analysis of the National Household Travel Survey in the USA (2009) and a GPS survey in the Greater Cincinnati region, and concluded that using activity duration, the time when activities occur and tour-based information can improve the purpose imputation accuracy by approximately 8% compared to the results if none of those attributes are used.

A decision tree is another method used in purpose imputation (Griffin & Huang, 2005). Trip stop length and the time of trip ends are the two attributes to detect purpose. Their work can only detect some 'go to work' trips and 'go to school' trips. But for most other purposes, stop time and arrival time alone are not sufficient.

McGowen and McNally (2007) adopted two methods to impute trip purpose — discriminant analysis and classification trees. Their final results for both methods are similar, 72% and 74% accuracy. A very detailed GIS map was used in their research, including all the locations for points of interest. Thus, they reported more accurate results than other research for shopping and social recreational activities. However, for most research, such detailed GIS mapping is difficult to obtain and it would increase the budget of a GPS survey.

To sum up, there are only a few methods that have been used in trip purpose imputation, and the results of this research are unconvincing from lack of accuracy. Table 3 summarises the different approaches for purpose imputation.

The last issue for both mode and purpose detection is 'ground truth'. The most popular recent method to obtain ground truth is conducting PR surveys, in which

Table 3. Summary of different approaches for purpose imputation

Author/s	Method	Attributes	Accuracy	Ground truth
Wolf et al. (2001)	Rule-based algorithm	GIS land-use data	60.9%	Travel diaries
Stopher et al. (2008)	Rule-based algorithm	GIS land-use data, home and workplace/school addresses, address of the two most frequently used grocery stores	Over 60%	PR survey
Bohte and Maat (2009)	Rule-based algorithm	GIS land-use data, home and workplace/school addresses	43%	PR survey
Shen and Stopher (2013a)	Rule-based algorithm	Tour-based information and the time that activities occur	68%	PR survey
Griffin and Huang (2005)	Decision trees	Trip stop length and the time of trip ends	90% (work and education)	n/a
McGowen and McNally (2007)	Discriminant analysis and classification trees	Detailed GIS land-use map	72% and 74%	Travel diaries

respondents are assisted to recall their actual travel by receiving GPS-generated maps of where and when they travelled. However, PR results are still far from the 'ground truth' due again to self-report errors, similar to those in conventional surveys. Most current research uses PR results or PR-combined travel diaries as ground truth to calculate the accuracy of mode and purpose detection, or train learning systems. Therefore, the results and conclusions from those research projects must be considered to be questionable. Shen and Stopher (2013c) introduced the SenseCam, a passive digital camera, to capture images automatically. SenseCam contains a number of different electronic sensors. Certain changes in sensor readings can be used to automatically trigger a photograph to be taken. Overall, it can capture images approximately every 20 seconds throughout the day. The images can help to obtain the ground truth of travel information.

5. Conclusion and Research Gaps

GPS surveys are increasingly applied for travel data collection. To obtain more accurate travel data, a number of methods of processing GPS data have been developed during the past decade. This paper has systematically reviewed the approaches to identifying trip ends, detecting travel modes, and inferring trip purposes. This review discussed both advantages and disadvantages for different approaches. Although researchers try to use different methods to obtain accurate results, there are several research gaps in all the steps of GPS data processing.

TI/SI processing is usually undertaken before mode and purpose detection. Therefore, the accuracy of mode and purpose detection is likely to be highly influenced by the accuracy of TI. The errors caused by this step also reduce the accuracy of mode and purpose detection. Furthermore, signal noise and signal loss are still challenging the quality of GPS data. For travel mode and purpose detection, deterministic methods are struggling with the ambiguity of similar modes, such as bicycle and bus. Probabilistic methods are also subject to either long training procedures or a lack of required 'ground truth' data. Also, all the methods only focus on a single trip (segment) to determine its mode. Yet little has been done on the analysis of a tour-based *mode chain* for people's travel. In the process of purpose imputation, a single point is usually used to represent a place, which would be a problem for the case where the area of that place is large (e.g. airport, university, shopping centre with parking, etc.). Instead, a polygon could be used to represent a place.

There are several potential directions for travel data collection in the future, which can deal with the current problems of GPS surveys. Bolbol, Cheng, and Paracha (2010) have proposed Geoweb 2.0, crowdsourcing and user-generated content as a possible way to collect data, and enable travellers to upload their trips directly onto the web to see them. Using passive digital cameras is also a new approach to collect travel data. Travel information, especially for mode and purpose, can be shown visually by images (Shen & Stopher, 2013c).

Although GPS surveys may still have some issues currently, admittedly GPS devices can record more accurate travel information than self-reported diaries, and GPS surveys have become more reliable and cheaper nowadays for data collection. With the development of new technology, more new devices could be introduced in travel data collection, along with GPS units, to collect more accurate data.

References

Bachu, P., Dudala, T., & Kothuri, S. M. (2001). Prompted recall in global positioning system survey: Proof-of-concept study. *Transportation Research Record*, (1768), 106–113.

Beijing Municipal Committee of Transportation. (2012, July). *The fourth Beijing comprehensive transportation survey report*. Beijing Transport Research Centre, Beijing Municipal Committee of Transportation.

Bierlaire, M., Chen, J., & Newman, J. (2013). A probabilistic map matching method for Smartphone GPS data. *Transportation Research Part C*, *26*, 78–98.

Biljecki, F. (2010). *Automatic segmentation and classification of movement trajectories for transportation modes* (Dissertation, MSc in Geomatrics). Delft University of Technology, TU Delft.

Bohte, W., & Maat, K. (2009). Deriving and validating trip purposes and travel modes for multi-day GPS-based travel surveys: A large-scale application in the Netherlands. *Transportation Research Part C*, *17*, 285–297.

Bolbol, A., Cheng, T., & Paracha, A. (2010, August). *GEOTRAVELDIARY: Towards Online automatic travel behaviour detection*. WebMGS: 1st International Workshop on Pervasive Web Mapping, Geoprocessing and Services, Politecnico di Milano, Como, Italy.

Bricka, S., & Bhat, C. (2006). Comparative analysis of global positioning system-based and travel survey-based data. *Transportation Research Record*, (1972), 9–20.

Bricka, S., Sen, S., Paleti, R., & Bhat, C. R. (2012). An analysis of the factors influencing differences in survey-reported and GPS-recorded trips. *Transportation Research Part C*, *21*, 67–88.

Bricka, S., Zmud, J., Wolf, J., & Freedman, J. (2009). Household travel surveys with GPS: An experiment. *Transportation Research Record*, (2105), 51–56.

Broach, J., Dill, J., & Gliebe, J. (2012). Where do cyclists ride? A route choice model developed with revealed preference GPS data. *Transportation Research Part A: Policy and Practice*, *46*(10), 1730–1740.

Bullock, P., Jiang, Q., & Stopher, P. (2005). Using GPS technology to measure on-time running of scheduled bus services. *Journal of Public Transportation*, *8*(1), 21–40.

Chen, C., Gong, H., Lawson, C., & Bialostozky, E. (2010). Evaluating the feasibility of a passive travel survey collection in a complex urban environment. *Transportation Research Part A*, *44*(10), 830–840.

Dill, J., & Gliebe, J. (2008). *Understanding and measuring bicycling behavior: A focus on travel time and route choice*. Final report. Oregon Transportation Research and Education Consortium. Retrieved from http://trid.trb.org/view.aspx?id=884287

Feng, T., & Timmermans, H .J. P. (2012, July 15–20). *Recognition of transport mode using GPS and accelerometer data*. Proceedings of the 13th international conference of the International Association for Travel Behaviour Research (IATBR), Toronto, Canada.

Giaimo, G., Anderson, R., Wargelin, L., & Stopher, P. (2010). Will it work? Pilot results from the first large-scale GPS-based household travel survey in the United States. *Transportation Research Record*, (2176), 26–34.

Gilani, H. (2005). *Automatically determining route and mode of transport using a GPS enabled phone* (Dissertation, the degree of Master of Science in Computer Science). University of South Florida.

Gong, H., Chen, C., Bialostozky, E., & Lawson, C. (2012). A GPS/GIS method for travel mode detection in New York city. *Computers, Environment and Urban Systems*, *36*(2), 131–139.

Gonzalez, P., Weinstein, J., Barbeau, S., Labrador, M., Winters, P., Georggi, N., & Perez, R. (2010). Automating mode detection for travel behaviour analysis by using global positioning systems-enabled mobile phones and neural networks. *IET Intelligent Transport Systems*, *4*(1), 37–49.

Greaves, S., Fifer, S., Ellison, R., & Germanos, G. (2010). Development of a global positioning system web-based prompted recall solution for longitudinal travel surveys. *Transportation Research Record*, (2183), 69–77.

Griffin, T., & Huang, Y. (2005, November 9–11). *A decision tree classification model to automate trip purpose derivation*. Proceedings of the ISCA 18th international conference on computer applications in industry and engineering, Sheraton Moana Surfrider, Honolulu, HI, pp. 44–49.

Hawkins, R., & Stopher, P. (2004, September 29–1 October). *Collecting data with GPS: Those who reject, and those who receive*. 27th Australasian Transport Research Forum, Adelaide.

Hudson, J. G., Duthie, J. C., Rathod, Y. K., Larsen, K. A., & Meyer, J. L. (2012). *Using smartphones to collect bicycle travel data in Texas*. Final report (Report No. UTCM 11-35-69). Retrieved from http://ntl.bts.gov/lib/45000/45700/45731/Hudson_11-35-69.pdf

Itsubo, S., & Hato, E. (2006, January). *A study of the effectiveness of a household travel survey using GPS-equipped cell phones and a WEB diary through a comparative study with a paper based travel survey.* Presented in Transportation Research Board (TRB) 85th annual meeting, Washington, DC.

Kelly, P., Krenn, P., Titze, S., Stopher, P., & Foster, C. (2013). Quantifying the difference between self-reported and global positioning systems-measured journey durations: A systematic review. *Transport Reviews: A Transnational Transdisciplinary Journal*, *33*(4), 443–459.

Kohla, B., & Meschik, M. (2013). Comparing trip diaries with GPS tracking: An Austrian study. In J. Zmud & xM. Lee-Gosselin (Eds.), *Transport survey methods: Best practice for decision making* (pp. 306–320). Bingley: Emerald Group Publishing Limited.

Krenn, P., Titze, S., Oja, P., Jones, A., & Ogilvie, D. (2011, November). Use of global positioning systems to study physical activity and the environment: A systematic review. *American Journal of Preventive Medicine*, *41*(5), 508–515.

Krizek, K. J., El-Geneidy, A., & Thompson, K. (2007). A detailed analysis of how an urban trail system affects cyclists' travel. *Transportation*, *34*(5), 611–624.

Krygsman, S., & Nel, J. (2009, July). *The use of global positioning devices in travel surveys—a developing country application*. 28th annual Southern African transport conference 2009 proceedings, Pretoria, South Africa.

Mackett, R., Brown, B., Gong, Y., Kitazawa, K., & Paskins, J. (2006). Children's independent movement in the local environment. *Built Environment*, *33*(4), 454–468.

Marcha, P., Roux, S., Yuan, S., Hubert, J.-P., Armoogum, J., Madre, J-L., & Lee-Gosselin, M. (2008, May 25–31). *A study of non-response in the GPS sub-sample of the French national travel survey 2007–08*. In P. Bonnel & J.-L. Madre (Eds.), The 8th international conference on survey methods in transport.

McGowen, P., & McNally, M. (2007, January). *Evaluating the potential to predict activity types from GPS and GIS data*. Proceedings of the 86th annual meeting of the Transportation Research Board.

Menghini, G., Carrasco, N., Schüssler, N., & Axhausen, K. W. (2010). Route choice of cyclists in Zurich. *Transportation Research Part A: Policy and Practice*, *44*(9), 754–765.

O'Fallon, C., & Sullivan, C. (2004, September). *Trip chaining: Understanding how New Zealanders link their travel*. Research report to Transfund New Zealand.

Oliveira, M., & Casas, J. (2010). Improving data quality, accuracy, and response in on-board surveys: Application of innovative technologies. *Transportation Research Record*, (2183), 41–48.

Oliveira, M., Vovsha, P., Wolf, J. L., Birotker, Y., Givon, D., & Paasche, J. (2006, January 23–27). *GPS-assisted prompted recall household travel survey to support development of advanced travel model in Jerusalem, Israel*. Presented at the 90th annual meeting of the Transportation Research Board, Washington, DC.

Papinski, D., Scott, D., & Doherty, S. (2009). Exploring the route choice decision-making process: A comparison of planned and observed routes obtained using person-based GPS. *Transportation Research Part F*, *12*, 347–358.

Quiroga, C., & Bullock, D. (1998). Travel time studies with global positioning and geographic information systems: An integrated methodology. *Transport Research Part C*, *6*(1–2), 101–127.

Rasmussen, T., Ingvardson, J. B., Halldórsdóttir, K., & Nielsen, O. A. (2013). *Using wearable GPS devices in travel surveys: A case study in the Greater Copenhagen area*. Transport conference at Aalborg University. ISSN 1603–9696. Retrieved from http://www.trafikdage.dk/papers_2013/188_ThomasKjaerRasmussen.pdf

Reddy, S., Mun, M., Burke, J., Estrin, D., Hansen, M., & Srivastava, M. (2010). Using mobile phones to determine transportation modes. *ACM Transactions on Sensor Networks*, *6*(2), Article 13, 27 pages.

Rodriguez, D., Brown, A. L., & Troped, P. J. (2005). Portable global positioning units to complement accelerometry-based physical activity monitors. *Medicine & Science in Sports & Exercise*, *37*(11 Suppl), S572–S581.

Schönfelder, S., Axhausen, K. W., Antille, N., & Bierlaire, M. (2002). Exploring the potentials of automatically collected GPS data for travel behaviour analysis. A Swedish data source. In J. Möltgen & A. Wytzisk (Eds.), *GITechnologien für Verkehr und Logistik, IfGIprints*, 13, pp. 155–179. Münster, Germany: Institut für Geoinformatik, Universität Münster.

Schüssler, N., & Axhausen, K. (2009). Processing raw data from global positioning systems without additional information. *Transportation Research Record: Journal of the Transportation Research Board*, (2105), 28–36.

Shen, L., & Stopher, P. (2013a). A process for trip purpose imputation from Global Positioning System data. *Transportation Research Part C: Emerging Technologies*, *36*, 261–267.

Shen, L., & Stopher, P. (2013b, October 4, 2013). *Should we change the rules for trip identification for GPS travel records*. Proceedings of the 36th Australasian Transport Research Forum ATRF 2013 — "Transport and the New World City", Brisbane, Australia.

Shen, L., & Stopher, P. (2013c, May 9). *Using SenseCam to pursue 'ground truth' for GPS travel surveys*. Presented at 14th TRB National Transportation Planning Applications conference, Columbus, OH.

Stenneth, L., Wolfson, O., Yu, P., & Xu, B. (2011, November 1–4). *Transportation mode detection using mobile phones and GIS information*. Proceedings of 19th ACM SIGSPATIAL International Symposium on Advances in Geographic Information Systems, ACM-GIS 2011, Chicago, IL.

Stopher, P. (2008). The travel survey toolkit: Where to from here? In J. Madre, P. Bonnel, J. Zmud, & M. Lee-Gosselin (Eds.), *Transport survey methods: Keeping up with a changing world* (pp. 15–46). Bingley: Emerald Group Publishing Limited.

Stopher, P., FitzGerald, C., & Zhang, J. (2008). Search for a global positioning system device to measure person travel. *Transportation Research Part C*, *16*, 350–369.

Stopher, P., & Greaves, S. (2009, October 1). *Missing and inaccurate information from travel surveys — pilot results*, 32nd Australasian Transport Research Forum ATRF 2009, Auckland, New Zealand.

Stopher, P., Greaves, S., & Shen, L. (2013, October 4). *Comparing two processing routines for GPS traces — lessons learnt*. Proceedings of the 36th Australasian Transport Research Forum ATRF 2013 — "Transport and the New World City", Brisbane, Australia.

Stopher, P., Moutou, C., & Liu, W. (2013). *Sustainability of voluntary travel behaviour change initiatives: A 5-year study* (Working Paper ITLS-WP-13–12).

Stopher, P., & Shen, L. (2011). In-depth comparison of global positioning system and diary records. *Transportation Research Record: Journal of the Transportation Research Board*, (2246), 32–37.

Stopher, P., & Wargelin, L. (2010, July 11–15). *Conducting a household travel survey with GPS: Reports on a pilot study*. 12th World Conference on Transport Research (WCTR)2010, Lisbon, Portugal.

Stopher, P., Zhang, J., Zhang, Y., & Halling, B. (2009, October 1). *Results of an evaluation of TravelSmart in South Australia*. 32nd Australasian Transport Research Forum ATRF 2009, Auckland, New Zealand.

Troped, P. J., Oliveira, M. S., Matthews, C. E., Cromley, E. K., Melly, S. J., & Craig, B. A. (2008, May). Prediction of activity mode with global positioning system and accelerometer data. *Medicine & Science in Sports & Exercise*, *40*(5), 972–978.

Tsui, S. Y. A. (2005). *An enhanced system for link and mode identifications for GPS-based personal travel surveys* (Dissertation, Graduate Department of Civil Engineering). University of Toronto.

U.S. Department of Transportation, Federal Highway Administration. (2009). *National Household Travel Survey 2009*. Retrieved from http://nhts.ornl.gov

Wagner, D. (1997). *Lexington area travel data collection test; global positioning systems for personal travel surveys*. Final report to Office of Highway Information Management, Office of Technology Application and US Federal Highway Administration.

White, C., Bernstein, D., & Kornhauser, A. (2000). Some map matching algorithms for personal navigation assistants. *Transportation Research Part C*, *8*, 91–108.

Wolf, J. (2000). *Using GPS data loggers to replace travel diaries in the collection of travel data* (Dissertation). Georgia Institute of Technology, School of Civil and Environmental Engineering, Atlanta, GA.

Wolf, J., Guensler, S., & Bachman, W. (2001). Elimination of the travel diary: An experiment to derive trip purpose from GPS travel data. *Transportation Research Record*, (1768), Paper No. 01-3255, 125–134.

Wolf, J., Hallmark, S., Oliveira, M., Guensler, R., & Sarasua, W. (1999). Accuracy issues with route choice data collection by using global positioning system. *Transportation Research Record*, (1660), 66–74.

Wolf, J., Schönfelder, S., Samaga, U., & Axhausen, K. W. (2004, January). *80 weeks of GPS-traces: Approaches to enriching trip information*. Presented at the 83rd annual meeting of the Transportation Research Board, Washington, DC.

Xiao, Y., Low, D., Bandara, T., Pathak, P., Lim, H. B., Goyal, D., … Ben-Akiva, M. (2012, January 14–17). *Transportation activity analysis using smartphones*. Consumer Communications and Networking Conference (CCNC), IEEE, pp. 60–61.

Zhang, Y., Stopher, P., & Jiang, Q. (2010, September). *Developing tour-based data from multi-day GPS data*. Australasian Transport Research Forum (ATRF), 33rd, Canberra, ACT, Australia.

Zimowski, M., Tourangeau, R., Ghadialy, R., & Pedlow, S. (1997). *Non-response in household travel surveys*. A report prepared for the Federal Highway Administration.