WORKING PAPER
ITS-WP-03-02

Wearable GPS device as a data collection method for travel research

By

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February 2003

ISSN 1440-3501

INSTITUTE OF TRANSPORT STUDIES
The Australian Key Centre in Transport Management

The University of Sydney and Monash University
Established under the Australian Research Council's Key Centre Program.

NUMBER: Working Paper ITS-WP-03-02

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ABSTRACT: Global Positioning System (GPS) devices are emerging as a potential means to collect improved data on the spatial aspects of personal travel. This paper builds on earlier work by Stopher and others on the use of passive GPS devices, for which additional non-GPS data may be added through a subsequent prompted recall survey. This paper presents sets of rules which can be applied to the raw data acquired by wearable GPS devices to determine the modes of travel used and the trip ends. Experiments have been performed in which the devices were tested for a range of different situations, including collecting data on trains, buses, and ferries, collecting data in urban canyons and also with respect to the cold start phenomenon. The paper also describes the procedures undertaken to download and analyse the data.

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DATE: February 2003

1 Introduction

Household travel data are a critical component of the travel demand forecasting process. Data on the daily travel of people living in metropolitan areas are essential for developing models and policies, and for determining where transport problems are likely to occur in the future. However, people generally have difficulty in providing precise information about the geographic locations of the places to which they travel (aside from home, work, and school/university). Obtaining information about routes people use, the duration of their travel, and their time spent under congested conditions through questionnaires is an extremely burdensome and high cost activity, and is also notoriously inaccurate.

Data collection is improving all the time. Over the past 3 years, there has been growing interest in measuring human travel patterns using GPS or other similar semi-automatic devices. In most cases, individuals are recruited and asked to plug a GPS device into the car that the person usually drives. The GPS device then logs track points at a pre-specified interval, usually 1, 2 or 5 seconds. The device is capable of recording considerable quantities of data, which must subsequently be analysed so as to provide information useful to transport planners and others. There are generally two types of GPS device. The first of these are active devices, which usually consist of a GPS antenna attached to a Personal Data Assistant (PDA), where the PDA records the standard GPS data and additionally, the respondent is asked to enter data in response to certain questions at the commencement of each separate trip that is undertaken. In most of these versions it is necessary that the respondent activates the GPS device when beginning a vehicular trip, in order that the antenna and PDA are on, data are recorded, and the questions to be answered are displayed. The second type of device is a passive device which only consists of a GPS antenna connected to a data logger. There is no PDA attached to the antenna so it requires little or no intervention by the respondent (Stopher *et al.* 2002).

The primary problem with the active GPS device is that it represents a burden to the respondent. It requires diligence from the respondent in turning the device on for every trip and requires time to respond to the questions at the outset of travel. In many cases, respondents may be in too much of a hurry to go through this process, or may simply forget until well into the trip. In part, this defeats the purpose of the GPS device, which is not only to gain more precise geographic and temporal data than people are capable of providing, but also to record travel that they frequently forget to enter into a trip, activity or time-use diary.

The primary problem with the passive GPS is that it cannot provide additional data, such as the trip purpose, mode of travel, the identity of the person driving, the identity of other people accompanying the driver and the number of them, and any data on the costs of the travel. However, data of this type can be obtained through a retrospective prompted recall survey. This is a survey conducted within a few days after the GPS device has been retrieved. In such a survey the memory of the household members is prompted by providing maps and tabular displays of the data collected by the GPS device. The respondents are then requested to fill in missing information (Stopher *et al.* 2002). However, even though the respondents do not have to enter additional data they might still consider the passive device as a burden (Draijer *et al.* 2000). If the issue were only to produce a reasonable way to show a respondent a set of track points on a map, this would be relatively trivial, involving simply transferring the data collected to a GIS and printing the resulting map. However, this is not the issue. Rather, the data need to be transformed from a set of track points collected over some period of time – ranging from a couple of days to several weeks – to a set of, preferably, line records, wherein each line represents a trip from an origin to a destination, and where the origins and destinations each represent locations where the respondent undertook some non-travel activity. In addition, a tabular presentation is needed that indicates the day, location and time of the trip start and end where the length of the trip is in distance and time. This will make it easier for the respondent to recollect the purpose of the trips.

Within the class of passive GPS devices there are two types of devices currently being used: an in-vehicle device that is on whenever the ignition is on, and a wearable device that is on continuously. The in-vehicle devices have already been used extensively at Sydney's Institute of Transport Studies (ITS), but the wearable device has just become ready for use. It is the latter type of device with which this paper is concerned (Appendix 1).

2 Research design

2.1 Definition of the problem

One of the biggest challenges in conducting a GPS based survey is processing the raw GPS data and producing the materials necessary for the prompted recall interview a short period of time after the data are collected. At the time of the pilot (Stopher et al. 2002), ITS researchers had automated only part of the procedure used for processing data. As a result, more than five hours were needed to produce all necessary materials for the prompted recall interview. This places a considerable constraint on data collection capacity. Presently, ITS researchers have devised a good set of rules for determining the trips being recorded by the in-vehicle device. These rules have been implemented in processing software which considerably lowers the processing time of the raw data. However, there are still some problems associated with processing the trip data collected by the wearable passive GPS device. The first problem is how to determine the start and the end of a trip by looking at the data: what is actually happening with the data when a respondent ends his trip and starts engaging in some kind of non-travel activity? Also, in some cases the signal gets blocked resulting in no readings: when does this happen and is there a solution for it?

2.2 Aim

The aim of this research is to develop sets of rules to determine the different trips made and the modes of travel used by an individual using a wearable GPS logging device. This method should be programmable in the data processing software currently being developed at ITS

2.3 Research questions

Main question 1: How does the wearable GPS device determine its position and when does it fail to do so?

Sub question 1.1: How does the wearable GPS device determine its position?
Sub question 1.2: When does the wearable GPS device fail to collect useful data?
Sub question 1.3: What solutions are available for the failures of the wearable GPS device to collect data?

Main question 2: How can the mode(s) of travel be determined from the collected data?

Sub question 2.1: What are the relevant characteristics that distinguish one mode from another?
Sub question 2.2: How can these characteristics be recognised in the collected data?
Sub question 2.3: What rules are suitable for determining mode changes from the collected data?

Main question 3: How can the (corrected) raw data be processed to separate trips?

Sub question 3.1: How is a trip defined?
Sub question 3.2: What rules are suitable for determining trip ends from the collected data?

2.4 Research method

To find answers to the research questions, trips were made to acquire data suitable for analysis. In each case, data were collected with two loggers. One was set on a 1- second interval and the other on a 5-second interval. All other things were held equal, or, if this was not possible, differences were noted in the travel diaries (Appendix 2). Travel details such as the start and end time of the trip segments, origin and destination, mode, position in vehicle, way of wearing the devices and the type of vehicle in the case of travelling by train or ferry were needed to analyse the data using GIS software (Appendix 3). By comparing the data with the noted travel details, conclusions were drawn.

3 Position determination and failure

3.1 Signal reception and processing

Global Positioning System satellites transmit signals to equipment on the ground. GPS receivers passively receive satellite signals; they do not transmit. GPS receivers require an unobstructed view of the sky, so they are used only outdoors and they often do not perform well within forested areas or near tall buildings. GPS operations depend on a very accurate time reference, which is provided by atomic clocks at the U.S. Naval Observatory. Each GPS satellite has atomic clocks on board and transmits data that indicates its location and the current time. All GPS satellites synchronize operations so that these repeating signals are transmitted at the same instant. The GPS receiver picks up two kinds of coded information from the satellites. One type of information, called “almanac” data, contains the approximate positions of the satellites. These data are continuously transmitted and stored in the memory of the GPS receiver, so it knows the orbits of the satellites and where each satellite is supposed to be. The almanac data is periodically updated with new information as the satellites move around. Any satellite can travel slightly out of orbit, so ground monitor stations keep track of the satellite orbits, altitude, location, and speed. The ground stations send the orbital data to the master control station, which in turn sends corrected data up to the satellites. This corrected and exact position data is called the “ephemeris” data, which is valid for about four to six hours, and is transmitted to the GPS receiver.

The distance to a given GPS satellite equals the velocity of the transmitted signal multiplied by the time it takes the signal to reach the receiver. The velocity is the speed of a radio wave – 300,000 km/s (the speed of light), less any delay as the signal moves through the Earth's atmosphere. The satellites transmit coded signals. The transmitted code is called "pseudo-random code" because it looks like a noise signal. When a satellite is generating the pseudo-random code, the GPS receiver is generating the same code and tries to match up to the satellite's code. The receiver then compares the two codes to determine how much it needs to delay (or shift) its code to match the satellite code. This delay time (shift) is multiplied by the speed of light to get the distance.

By estimating how far away a satellite is, the receiver also "knows" it is located somewhere on the surface of an imaginary sphere centred at the satellite. It then determines the sizes of several spheres, one for each satellite. The receiver is located where these spheres intersect. When the receiver estimates the distance to at least four GPS satellites, it can calculate its position in three dimensions. This is because there have to be four spheres to have an intersection at only one common point (Garmin 2000).

There are at least 24 operational GPS satellites at all times. The satellites, operated by the U.S. Air Force, orbit over a period of 12 hours. The accuracy of a position determined with GPS depends on the type of receiver. Most hand-held GPS units have about 5-20 metre accuracy

3.2 GPS signal errors

There are several known sources of GPS signal errors. The following factors can degrade the GPS signal and thus affect accuracy (Garmin 2000):

- **Ionospheric and tropospheric delays**: This occurs when the signals from the satellite are delayed in their journey to the receiver by travelling through an area of charged particles, the ionosphere, above the earth and through our atmosphere. The GPS system uses a built-in model that calculates an average amount of delay to partially correct for this type of error.
- **Clock errors**: The satellites and receivers both need very good clocks to do their job. A receiver's built-in clock is not as accurate as the atomic clocks onboard the GPS satellites. Therefore, it may have very slight timing errors. The smallest error can throw off the "range measurement" from the receiver to the satellite by many 10's, 100's or even 1000's of meters. For example a 10 nanosecond (0.00000001 sec) error would cause a 3-metre error in the range.
- **Orbital errors**: The positions of the satellites obtained from the signal information are really a prediction of where the satellite should be at a given moment, and can differ slightly from the actual position.
- **Satellite geometry/shading**: This refers to the relative position of the satellites at any given time. Ideal satellite geometry exists when the satellites are located at wide angles relative to each other. Poor geometry results when the satellites are located in a line or in a tight grouping.
- **Intentional degradation of the satellite signal**: Selective Availability (SA) is an intentional degradation of the signal once imposed by the U.S. Department of Defence. SA was intended to prevent military adversaries from using the highly accurate GPS signals. The government turned off SA in May 2000, which significantly improved the accuracy of civilian GPS receivers.
- **Receiver Noise:** This is a function of how well a GPS receiver can measure the signal coming from the satellite. Some are better at it than others.

- **Signal multipath:** This occurs when the GPS signal is reflected off objects such as tall buildings or large rock surfaces before it reaches the receiver. This increases the travel time of the signal, thereby causing errors.
- **Number of satellites visible**: The more satellites a GPS receiver can "see," the better the accuracy. Buildings, terrain, electronic interference, or sometimes even dense foliage can block signal reception, causing position errors or possibly no position reading at all. GPS units typically will not work indoors, underwater or underground.

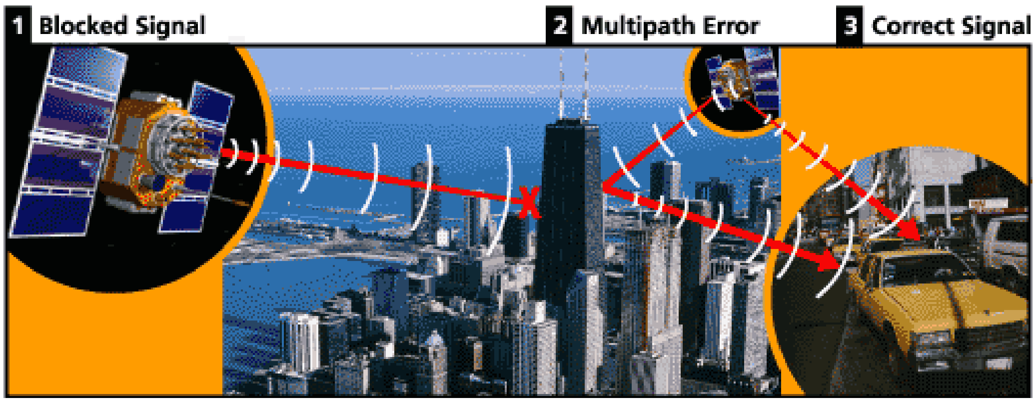

Figure 3.1: Blocked Signal and Multipath Error

In this research, interest was particularly about the type of errors caused by the number of satellites visible or by signal multipath. Data were gathered to sort out when the signal reception was blocked or reflected thereby causing position errors or resulting in no reading at all. This was done for the following three different modes: train, bus, and ferry; also, for walking in the city centre of Sydney and with respect to the cold start phenomenon. The loggers always were set to both record position and speed, and also to record all valid points. However, for every set of trips, data were gathered with one logger on 1-second interval logging and one logger on 5-second interval logging. In the following paragraphs conclusions are presented regarding the blocking or reflection of the signal. This is done for the above described cases:

Train: The different types of trains in Sydney can be divided into two general groups. The first group contains all the trains of the Tangara type. The second group, called “Normal”, contains all the trains other than Tangara (C sets, K sets or Millenniums). The Tangara type has large windows which go overhead on the upper deck. The “normal” trains have smaller windows which only give a view to the side.

When the wearables were used on the upper deck of a Tangara the results were generally good. On the lower deck of a Tangara the results were generally bad, however next to the window there was a slight chance on having good results. This is the same with the normal trains where the results were all bad on all positions on all decks. Sometimes positions near the window gave some good results (Appendix 4). Because there were good results on the upper deck of the Tangara, it is unlikely that the overhead wiring is causing troubles. So, bad results are due to the type of train and the position in the train. No significant differences were found with respect to losing the signal between the 1-second and the 5-second interval logging setting.

Bus: Buses are not divided into different types because buses do not differ markedly. On the whole the results of the use of the wearables in the bus were good. On all positions in the bus the wearable gave good results. However the tests were done in an area without interference from tall buildings. Bad results were acquired when testing in buses in areas with more interference from buildings (Appendix 5). So the conclusion is that bus travel itself is no problem for receiving a signal but, when the signal is lost, it is generally due to the surroundings. For example, in narrow streets with high buildings on the sides it is unlikely to get decent results. No significant differences were found with respect to losing the signal between the 1-second and the 5-second interval logging setting.

City centre: In general the test trips showed the wearables produce bad results in the city centre. The bad results are because of the so called "urban canyon effect". The urban canyon is caused by the high buildings in the city centre. The satellite transmissions are bounced around by these buildings (like sound echoes in a canyon). When a wearable picks up a bounced transmission it will calculate a wrong position because the transmission is also 'in the wrong position'. Because of this, results of the wearable become very scattered (Appendix 6). This can also happen in other areas with high buildings close together. Again no significant differences were found with respect to losing the signal between the 1-second and the 5-second interval logging setting.

Cold start: The GPS unit stores data about where the satellites are located at any given time. This data is called the almanac. Sometimes when the GPS unit is not turned on for a length of time the almanac can get outdated or "cold". When a wearable is turned on for the first use of a day or loses signal for 4 to 6 hours, a cold start will take place. It will take the GPS receiver longer to acquire satellites then. The findings are that such a cold start may take up to 28 minutes depending on the surroundings and the speed of travel. While staying at a fixed location the cold start took less than 1 minute but when the receiver was moving with walking speed it generally took 3 to 15 minutes to acquire a signal. During the cold start no data will be recorded (Appendix 7).

Since 15 (or even 28) minutes is quite a long time, problems can occur. The first or more trip segments or even the whole first trip might not be recorded. This gives very inaccurate data of travel behaviour. Even cold starts which last only a couple of minutes can be very problematic. With respect to the 1-second and 5-second interval logging setting no verifiable differences were found.

3.3 Solutions

For the failures due to the blocking of the signal by train or ferry roofs and due to the cold start, there are no simple technical solutions at hand. This is because the receiver simply cannot "see" the satellites. However, in the next two chapters, an attempt has been made to find solutions for these problems by presenting rules which can infer what was occurring when the signal was lost.

For the position errors caused by high buildings (urban canyon effect) a technical solution might be available. It is called Differential GPS (DGPS). However DGPS will add bulk, weight and additional power requirements to the wearable. So, DGPS may not be feasible for the wearable GPS devices at this time. DGPS works by placing a GPS receiver, called a reference station, at a known location. Since the reference station knows its exact location, it can determine the errors in the satellite signals. It does this by measuring the ranges to each satellite using the signals received and comparing these measured ranges to the actual ranges calculated from its known position. The difference between the measured and calculated range for each satellite in view becomes a "differential correction". The differential corrections for each tracked satellite are formatted into a correction message and transmitted to DGPS receivers. These differential corrections are then applied to the GPS receiver's calculations, removing many of the common errors and improving accuracy (Garmin 2000).

In the future GSM technology may have improved enough to be feasible for accurate position determination. An advantage of GSM is that it is able to determine its position wherever a mobile phone can pick up a signal. This means GSM would also work in for example buildings, trains, tunnels and urban cannons.

4 Data processing: Travel modes

4.1 Mode characteristics

It is impossible to come up with a way to determine the mode(s) of travel used by a respondent before looking into the different modes of travel. The modes relevant to this research with characteristics are presented in table 4.1. Travel by bicycle was left out of this research because it is not a very important mode of travel in Sydney.

Characteristics / Mode	Fixed route?	Fixed stops?[1]	Unwanted stops?	Max. speed (km/h)	Av. Speed (km/h)	Own infrastructure?
Walk	No	No	Rare	7 (15)[2]	4	No
Train	Yes	Yes	Rare	110	60	Yes
Ferry	Yes	Yes	Rare	25 (45)[3]	20 (30)[3]	Yes
Bus	Yes	Yes	Often	100	30	No
Car	No	No	Often	120	40	No

Table 4.1: Mode characteristics

[1] This means the mode is likely to stop at fixed locations (e.g., a train will stop at train stations, but a pedestrian can stop at a random place).
[2] Max speed of a running pedestrian.
[3] Applies to the Jetcat ferry type.

4.2 Mode change determination

Before the raw data could be used to determine the mode changes, it had to be cleaned first. On average 28% of the data was thrown away after cleaning. In the most unfavourable case, this amount rose to 77% (Appendix 3).

To determine a mode change the assumption was used that every trip segment, which always consist of only one mode, ends with a speed of zero. If one was getting off a bus, train, ferry or car the vehicle should stop first before getting off. All data was cut in segments between the points with a speed of zero. Data was also cut if the VALID-field gave a V (Appendix 8). After the data was cut in different segments every segment was reviewed separately. For each segment the following rules were drafted and used to determine the mode of travel.

- If all points in a certain segment have a speed below 7 km then the mode of travel in that segment is walking.
- If all points in a segment are on a railway track or the points at the beginning and/or at the end of a segment are on a train station then the mode of travel is train.
- If all points in a segment are on the water or the points at the beginning and/or at the end of a segment are on a wharf then the mode of travel is the ferry.
- If all points in a segment are on the same bus route and there are points in the segment with speed between 7 km and 80 km then the mode of travel is bus.
- If the mode of a segment is not walk, train, ferry or bus and there are points in the segment with a speed between 7 and 80 then the mode of travel is car.

After the mode of a segment was determined there needs to be a review to determine if there was a trip end between two segments. If there was no trip end between segments, segments were merged together. For example two walking segments without a trip end between the segments were merged to one large walking segment. This rule also applied to the other modes.

Problems occur if cars drive along bus routes. For example a car drives along a certain road which is not a bus route. Its stops at an intersection (the speed is now 0 so a new segment starts). The car makes a turn and continues on a road which is also a bus route. After a while the car stops (start of a new segment) at another intersection and turns off the bus route road. The segment which is on the road with the bus route will be marked as a bus segment (figure 4.1).

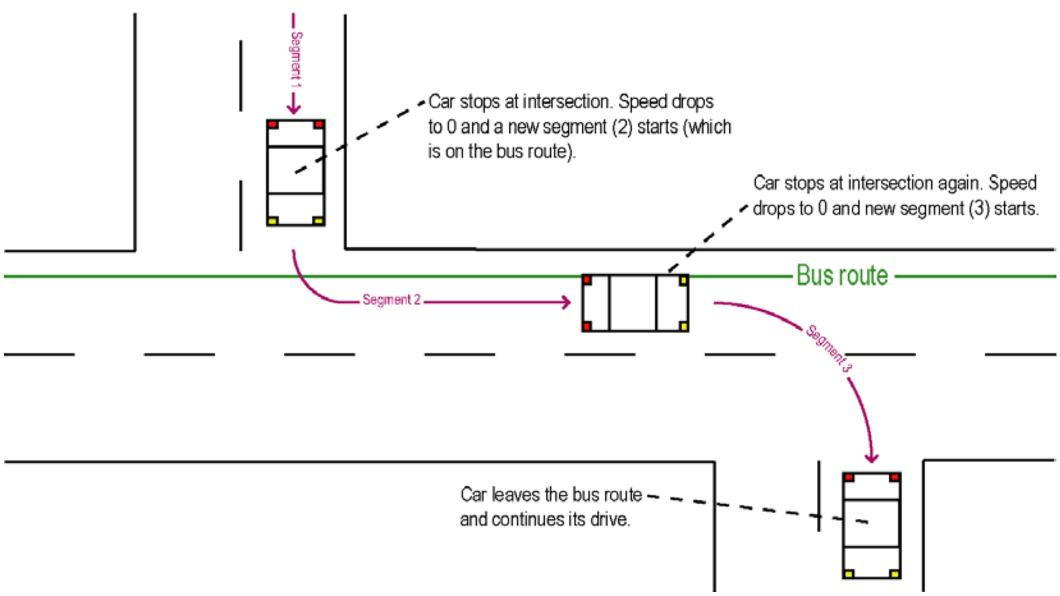

Figure 4.1: Car driving along a bus route for a while.

A solution for this problem is as follows. If there are one or more bus segments after, before or between one or more car segments, then all segments will be marked as car segments, because a respondent can never switch immediately from a car to a bus (or vice versa) without walking.

Another problem occurs with determining whether or not data points are on a railway track. The results of the wearable are always a bit scattered or shifted. This means a boundary has to be drawn around the railway track. If all the points are within this boundary they are on the railway track. The same applies to points on bus and ferry routes.

5 Data processing: trip ends

5.1 Trip definition

The target of this research, as stated before in section 2.2, was to find an accurate way to determine the different *trips* made and the modes of travel used by an individual using a wearable GPS logging device. So it is important to clearly state what was meant by a trip in this research. In this paper a trip is defined as follows:

A *trip* is a one-way movement from a point of origin where an activity (other than travel) is being conducted to a point of destination where another activity is being conducted.

A trip can be made up of different *trip segments* which consist of movement on a single mode. Serving a passenger is conceived as a non travel activity. So changing travel mode is not an end of a trip and serving a passenger is. In figure 5.1 two trips are being displayed. The first one consists of one walking segment to the shop. The second trip consists of three segments. This trip starts at the shop with a walking segment to the car followed by a car segment and ending with a walking segment to the office.

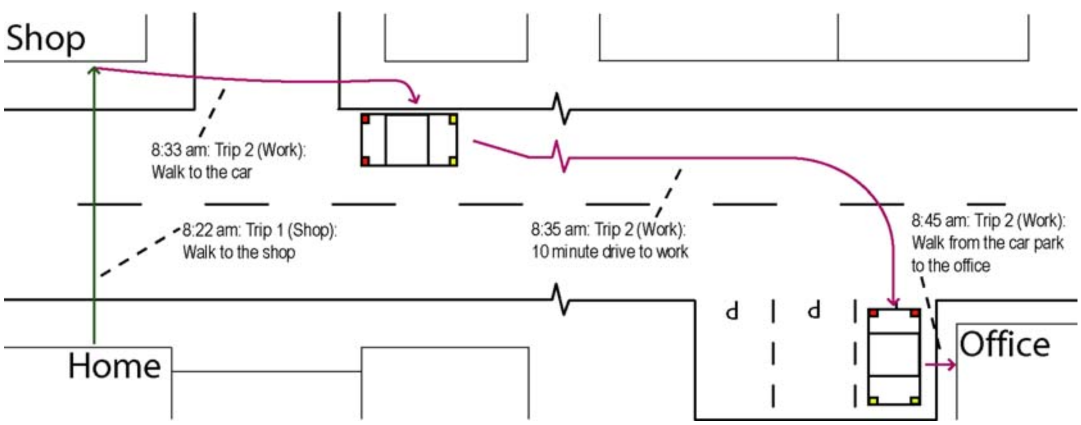

Figure 5.1: Trips and segments

5.2 Trip end determination

The last chapter explained how the raw data can be divided into different trip segments. As stated before the target of this research was not only to find an accurate method to determine modes of travel used by an individual using a wearable GPS logging device, but also to indicate the different trip ends. While constructing trip end rules, some assumptions were made. The first is that the minimal time needed for an activity is 60 seconds. This could be the case if one buys a drink at a convenience store. The second assumption made is that the minimal walking speed equals 2 km/h. For the fact that a respondent is more likely to be at home at 3 a.m. than at 12 a.m. the last assumption is that a day starts and ends at 3 a.m. Considering these assumptions a trip end was flagged in the following cases:

- The last recorded data point on a day is considered a trip end. This is because of the fact that often after engaging in some activity no data were recorded on the way back home. It might very well be that the last recorded data point was in fact not a stop. In that case the respondent should be able to remember that during the prompted recall interview.

- In addition to the above rule, an additional trip is assumed from the last recorded data point to the home of the respondent. So every day the last trip end is assumed to be at the home of the respondent.

- In a similar manner, it is assumed that, every day, the first trip starts at the home of the respondent. This reduces the negative effect of the cold start.

- If the heading between two segments (last 30 seconds and first 30 seconds) with the same mode changes by 180 degrees. This might be the case if someone posts a letter and returns home; or if someone driving a car serves a passenger and returns the same way.

- If between two segments the signal is lost for more than 60 seconds and reappears at the same position (+/- 15m). This might be the case if someone walks into a shop, buys something and walks out of the shop again.

- If between two segments the signal is lost for more than 600 sec and reappears elsewhere, then the average speed between the last point before the signal disappeared and the first point when the signal reappears should be calculated. If the average speed is less than 2 km/h a trip end is flagged at the last point before the signal was lost. This situation might be the case when an activity takes place in a specific area and not at a specific location. One could think of a large Mall with different places of entering and exiting. The distance between the place of entering and exiting could be as large as 300 meters. So the 600 seconds consist of 300 metres divided by a speed of 2km/h. This gives 9 minutes. This outcome plus 1 minute minimal activity time give 600 seconds. A problem might surface when a respondent has to wait a long time for changing modes. In this case a very short distance might be travelled in a relatively long period of time, thus resulting in a very low average speed. In this case a trip end is flagged where it shouldn't be. However it is easy for a respondent to correct a non made trip end during the prompted recall interview.

The following trip end rule is an optional one. The use of it depends on the definition of what is considered as a trip or an activity. If shopping in an open mall or market is considered as one activity this rule is very useful. For example:

- If from a point X in a walking segment for Y minutes all points were walking segment points (don't have to be the same walking segment) and all these points were within a fixed area of Z by Z meters with X as centroid then a trip end is flagged on all these points' average coordinate. The time of this stop would also be the average time of all these points. After having assigned a trip end, no further attention should be paid to those points within the Y minutes time frame. What is meant is that this rule can't be applied again on point X+1. The first point worth considering for this rule would be point W which is the first point after Y minutes point X was recorded.

- Another optional rule has been drafted because of a specific problem encountered. To make the problem clear the specific trip is summarized hereunder: This day the train was taken from Central to Bondi Junction. From Bondi Junction the bus was taken to see a doctor on Bondi Road. After seeing the doctor the trip went the same way back to Central. What happened here is that after having a signal on Central (A) the next recorded signal (B) was on Bondi Road on the way back. Thus, missing all the data on the way to see the doctor. To still detect a trip end here, and in similar cases, this optional rule was developed. The distance and speed requirements have to be reviewed.

- If the distance between a point A and the next point B is more than 2 km and the average between these points is less than 20 km/h a trip end is flagged.

With using all these rules it was possible to detect all the trip ends made during the tests.

6 Conclusions

6.1 Findings

The outcome of this research consists of two sets of rules. One set is for determining the different trips made by a HTS respondent wearing a wearable GPS device. The other set is for determining the various modes of travel used while making those trips. The findings are that when also using the optional rules as stated in chapter 5 all trips and mode changes made while gathering the data could be identified. However to make those optional rules generally applicable they still need some fine tuning.

Although the developed rules worked well there were quite a few problems while testing the devices. Often many trip segments could not be recorded due to a blocked signal reception. This resulted in position errors or possibly no position reading at all which in turn made the data useless. This occurred frequently during window shopping, travelling in the city centre or travelling by train, but also sometimes with no clear cause.

The worst problems encountered are related to the cold start phenomenon. These cold starts took sometimes 15 up to 28 minutes depending on the surroundings and the speed of the travel. Because, during the cold start, no data will be recorded this is considered a very severe problem. The first or more trip segments or even the whole first trip might be left unrecorded. No verifiable cause or solution has yet been found for this problem.

In many cases the GPS devices recorded useful data. However, if a good explanation and solution for the very long cold start times is not found, the use of passive GPS devices in household travel surveys may be doubted.

6.2 Recommendations

From experiments, it appears that one megabyte of storage is sufficient to record approximately 180,000 track points. If position is recorded every second, this would permit approximately 50 hours of travel to be recorded (Stopher *et al.* 2002). This is more than sufficient for respondents who will use the wearable GPS devices for one week. Especially when one assumes that most individuals spend about 1.5 hours per day in travel. Also, the newest release of the loggers has a storage capacity of 4 megabytes. Because of this, it is recommended to always set the loggers on a 1-second interval logging. Even though no verifiable differences in data quality were discovered between the 1-second and 5-second interval setting it will not harm the research effort to the set logger on a 1-second interval logging. Also the 1-second interval setting is believed to have a better chance of detecting data points with a speed of 0. Because of the importance of finding those points to detect different trip segments the 1-second setting is considered the most suitable.

Additional research has to be done regarding the urban canyon effect for example in the city centre of Sydney. A direction for this research might be to divide the city centre into a number of areas and see if a rule relating to the time staying in such an area can be developed to determine trip ends. So, if the scattered points are within such an area for a specific time a trip end may be assumed to have taken place.

It would be worthwhile to acquire additional data from car segments and to do extra tests on the validity of the rules presented in this paper. Also, data should be gathered to see what happens if a driver drops off or picks up a passenger at different locations.

The wearable GPS devices might also have potentials in analysing route choices, travel times, congestion and speed profiles. This would be an interesting point for further research.

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Stopher, P., Bullock, P. and Jiang, Q. (2002) *GPS, GIS and Personal Travel Surveys: An Exercise in Visualisation*, Institute of Transport Studies, Sydney.

8 Appendix 1: The wearable GPS Device

The actual GPS device used in this research is the wearable GeoStats GeoLogger™. It consists of a simple GPS receiver (located on the shoulder strap), a data logger (located in the front of the carry bag), which is powered by an internal 9V battery and a battery pack (clip and battery located inside the bag) to power the GPS unit. The data available from these devices is the standard output data from a GPS antenna, consisting of:

- Latitude and longitude in degrees and decimal degrees, with E,W,N,S designation
- Altitude in meters above sea level
- Heading in degrees from North
- UTC Time

- UTC Date
- Speed in kph
- HDOP (Horizontal dispersion of precision)
- Satellites in view

The logger also has different logging options:

- Record position only or record position and speed
- Record at either 1-second or 5-second intervals
- Record all valid points or record only valid points with speed greater than 1 mph
- Record altitude or not

Figure A1.1: The Wearable GeoStats GeoLogger™.

9 Appendix 2: Travel diary example

Wearable GPS Travel Data Collecting Project

By: Robert de Jong and Wytse Mensonides
Date: 23 December 2002

ITS

Travel Diary - Travel Details

Download name: R_020103_020103_Parramatta.csv
Interval: ~~1~~ / 5 sec

Date: 02 - 01 - 2003 (dd-mm-yyyy)
Name: Robert de Jong
Trip description: Parramatta
Logger/GPS number: 1 / 2 **Page:** 1 / 1

Start time / End Time	Origin / Destination	Mode? (Bus, train, ferry, etc)	Position in vehicle? NW = Near Window, AW = Away Window, STA = Standing, SIT = Sitting, F/B = Front/Back, U/L = Upper/Lower	Wear? R=Regular, B=Bandolier, L = Left, R = Right	Route?	Type of Vehicle?
9:35	ITS	Walk	~~NW/AW STA/SIT F/B U/L~~	**R** / ~~B~~		
9:40	MacDonaldtown			~~L~~ / **R**		
9:55	MacDonaldtown	Train	~~NW~~/**AW** ~~STA~~/**SIT** ~~FB~~ ~~U~~/**L**	**R** / ~~B~~	Purple	Normal
10:12	Strathfield			~~L~~ / **R**		
10:39	Strathfield	Train	~~NW~~/**AW** ~~STA~~/**SIT** ~~FB~~ **U**/~~L~~	**R** / ~~B~~	Yellow	Normal
10:48	Olympic Park			~~L~~ / **R**		
11:09	Olympic Park	Train	~~NW~~/**AW** ~~STA~~/**SIT** ~~FB~~ **U**/~~L~~	**R** / ~~B~~	Yellow	Normal
11:15	Lidcombe			~~L~~ / **R**		
11:39	Lidcombe	Train	~~NW~~/**AW** ~~STA~~/**SIT** ~~FB~~ ~~U~~/**L**	**R** / ~~B~~	Yellow	Tangara
11:49	Parramatta			~~L~~ / **R**		
11:49	Parramatta	Walk	~~NW/AW STA/SIT F/B U/L~~	**R** / ~~B~~		
11:56	Parramatta Mall			~~L~~ / **R**		
12:59	Parramatta Mall	Walk	~~NW/AW STA/SIT F/B U/L~~	**R** / ~~B~~		
13:17	Parramatta Wharf			~~L~~ / **R**		
14:37	Parramatta Wharf	Ferry	During the trip shifted to	**R** / ~~B~~		RiverCat
15:30	Circular Quay		different positions.	~~L~~ / **R**		
15:34	Circular Quay	Bus	~~NW~~/**AW** ~~STA~~/**SIT** **F**/~~B~~ ~~U/L~~	**R** / ~~B~~	423	
15:54	Broadway			~~L~~ / **R**		
15:54	Broadway	Walk	~~NW/AW STA/SIT F/B U/L~~	**R** / ~~B~~		
16:05	City Road			~~L~~ / **R**		
16:12	City Road	Bus	~~NW~~/**AW** **STA**/~~SIT~~ ~~F~~/**B** ~~UL~~	**R** / ~~B~~	422	
16:17	King Street			~~L~~ / **R**		
16:18	King Street	Walk	~~NW/AW STA/SIT F/B U/L~~	**R** / ~~B~~		
16:26	ITS			~~L~~ / **R**		
			NW/AW STA/SIT F/B U/L	R / B		
				L / R		
			NW/AW STA/SIT F/B U/L	R / B		
				L / R		
			NW/AW STA/SIT F/B U/L	R / B		
				L / R		
			NW/AW STA/SIT F/B U/L	R / B		
				L / R		
			NW/AW STA/SIT F/B U/L	R / B		
				L / R		
			NW/AW STA/SIT F/B U/L	R / B		
				L / R		

Figure A2.1: Travel diary example

10 Appendix 3: Data Manipulation

Manipulation

Certain items of the data require manipulation to make them useful and usable for GIS representation. First, the record must be re-ordered so that it can be recognized by the GIS software as a geographic file. The software being used for this is Caliper Corporation's TransCAD® software. This requires that each line of the file is uniquely numbered with an ID number, and that the first column after the ID is the longitude and the second is the latitude. Further, longitude and latitude are to be expressed in millionths of a degree, with negative values indicating south or west, and positive values indicating north or east. The compass quadrant is therefore removed, and replaced by the appropriate positive or negative sign for the latitude and longitude. Next, the UTC date and time are converted to local date and time. At the same time, these records are converted so that they are recognized by the database procedures to be times and dates, so that calculations involving times and dates can be performed. Some additional computations are needed in order to enable better visualization of the results. First, the elapsed time and distance are desired between successive track points. These are used to determine trip lengths in time and distance in subsequent steps. For the purposes of better communication, it is also desirable to add the day of the week to the date and time. Additionally, acceleration or deceleration between successive points may be desired, and are calculated from the speed data.

Cleaning

After manipulation the data have to be cleaned to remove bad data. Data are considered bad when the records have a reading of three or less satellites or when they have an HDOP (Horizontal dispersion of precision) of more than five. A reading of less than three satellites is not good because the receiver needs to estimate the distance to at least four GPS satellites to be able to calculate its position in three dimensions. A high HDOP value means that the visible satellites were in line. This results in unreliable data because the underlying triangulation process doesn't function properly then. Experience at ITS with analysing the GPS data had learned that HDOP readings higher than five should be considered as not reliable. Because the V in the VALID field is used for the determination of the mode of travel, a V must be shifted to the next record with enough satellites and a HDOP lower then five. The cleaned data is suitable for analysis and mapping in a GIS file.

11 Appendix 4: Train Results

To find out whether or not the satellites' signals are blocked by the overhead wiring, by the train itself or not at all, several experimental trips were undertaken. The different possible positions in the trains were numbered to see if there was a difference in the quality of the signal on those positions (figure A4.1).

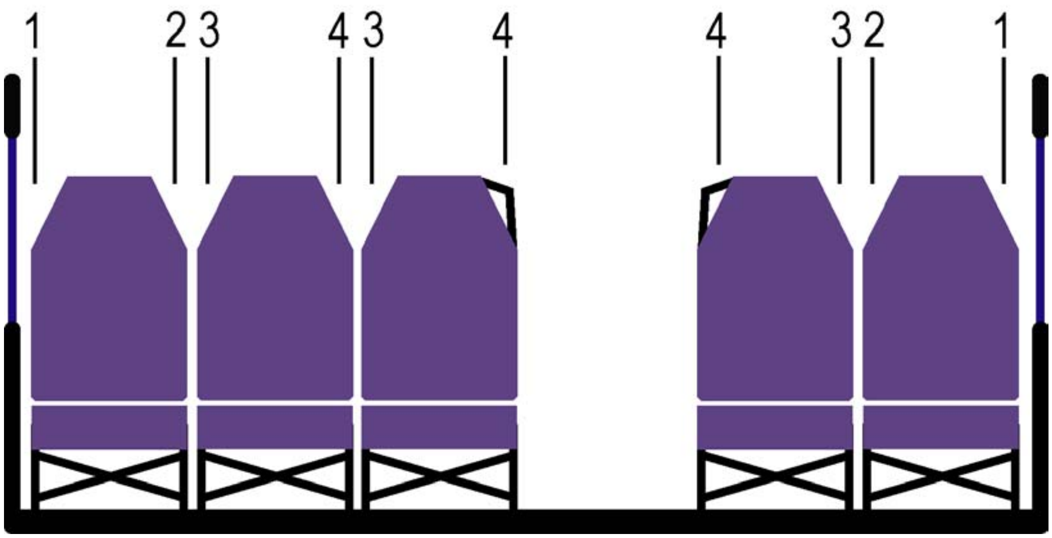

Figure A4.1: Positions on train

All the experimental train trips were made on the Sydney CityRail section between Redfern station and Ashfield station. This section has generally a good view, so there was little chance of the signals being blocked by the surrounding area. Here, the results for both the Tangara and Normal train types are represented. Data were recorded on all 4 possible positions on the lower level as well as on the upper level. Distinction was made between the loggers' 1-second and 5-second interval setting.

Figure A4.2: Normal Train

Type of train: Normal; Level: upper							
1 sec logging				5 sec logging			
Pos 1	G	B	B	Pos 1	B	B	B
Pos 2	B	B	B	Pos 2	B	B	B
Pos 3	B	B	B	Pos 2	B	B	B
Pos 4	B	B	B	Pos 4	B	B	B

Table A4.1: Results Normal upper level

Type of train: Normal; Level: lower							
1 sec logging				5 sec logging			
Pos 1	B	B	B	Pos 1	G	B	B
Pos 2	B	B	B	Pos 2	B	B	B
Pos 3	B	B	B	Pos 2	B	B	B
Pos 4	B	B	B	Pos 4	B	B	B

Table A4.2: Results Normal lower level

From the above tables the conclusion can be drawn that for the normal trains results were bad (**B**) on all positions on all decks. Sometimes positions near the window gave some good results (*G*). There was also no difference between the 1-second and 5-second logging setting.

Figure A4.3: Tangara Train

Type of train: Tangara; Level: upper					
1 sec logging			5 sec logging		
Pos 1	G	G	Pos 1	G	G
Pos 2	G	G	Pos 2	G	G
Pos 3	G	G	Pos 2	G	G
Pos 4	G	G	Pos 4	G	B

Table A4.3: Results Tangara upper level

Type of train: Tangara; Level: lower					
1 sec logging			5 sec logging		
Pos 1	G	B	Pos 1	B	B
Pos 2	B	B	Pos 2	B	B
Pos 3	B	B	Pos 2	B	B
Pos 4	B	B	Pos 4	B	B

Table A4.4: Results Tangara lower level

From the above tables the conclusion can be drawn that when the wearables were used on the upper deck of a Tangara the results were generally good. On the lower deck of a Tangara the results were generally bad but next to the window there was a slight chance on having good results. It might be the case that the 1-second setting gives better results but with this amount of results no significant differences can be seen with respect to losing the signal between the 1-second and the 5-second interval logging setting.

Because there were good results on the upper deck of the Tangara it's unlikely that the overhead wiring is causing troubles. So, bad results are due to the type of train and the position in the train.

12 Appendix 5: Bus results

To find out whether or not the satellites' signals are blocked by the bus itself or not all several experimental trips were undertaken. The different possible positions in the buses were numbered to see if there was a difference in the quality of the signal in those positions (figure A5.1)

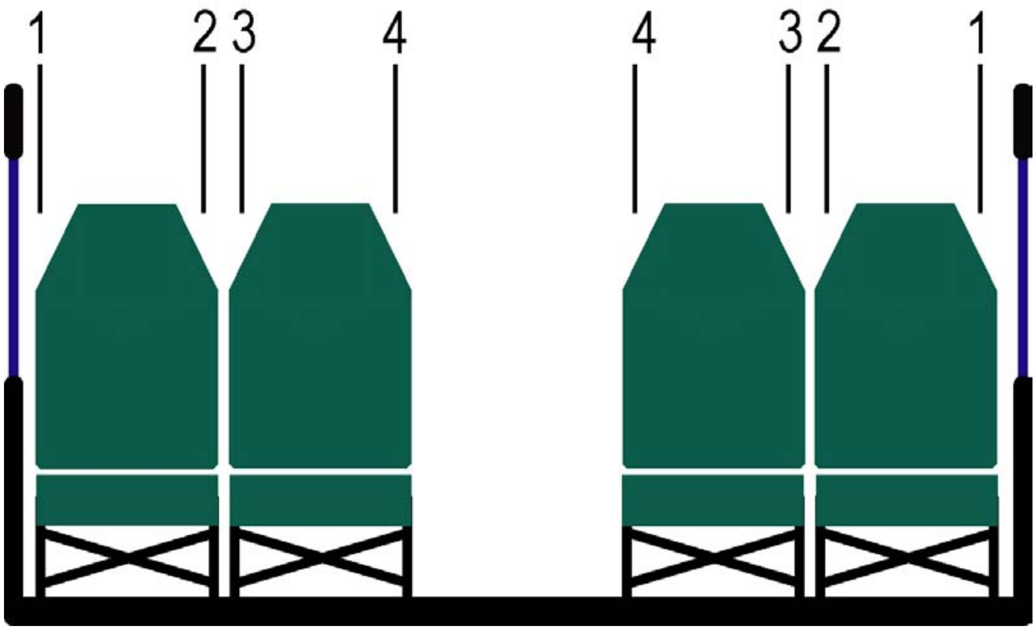

Figure A5.1: Positions on bus

The experimental bus trips were made on King Street and City Road which are located in Sydney's Newtown suburb. These streets have generally a good view, so, there was little chance of the signals to be blocked by the surrounding area. Here, the results for the bus are represented. Data were recorded on all 4 possible positions and also while standing in the bus. Distinction was made between the loggers' 1-second and 5-second interval setting.

Bus							
1 sec logging				5 sec logging			
Pos 1	G	G	G	Pos 1	G	G	G
Pos 2	G	G	G	Pos 2	G	G	G
Pos 3	G	G	G	Pos 3	G	G	G
Pos 4	G	G	G	Pos 4	G	G	G
Standing	G	G	G	Standing	G	G	G

Table A5.1: Results bus on King Street and City Road

From the above tables the conclusion can be drawn that on all positions in the bus the wearable gave good (*G*) results. No significant differences were found with respect to losing the signal between the 1-second and the 5-second interval logging setting. However the tests were done in an area with a good view. Bad results (**B**) were acquired when testing in buses in areas with less view (Table A5.2). The strange thing that happened here is the 5-second interval logging gave better results than the 1-second interval logging setting. So the conclusion is that taking a bus itself is no problem for receiving a signal, but when then the signal is lost it is generally due to the surroundings. For example, in narrow streets with high buildings on the sides it is unlikely to get decent results.

Bus							
1 sec logging				5 sec logging			
Pos 1	B	B	B	Pos 1	G	G	B
Pos 2	B	B	B	Pos 2	G	G	B
Pos 3	B	B		Pos 3	G	G	
Pos 4	G	B		Pos 4	G	G	

Table A5.2: Results bus with less view

13 Appendix 6: Sydney City Centre results

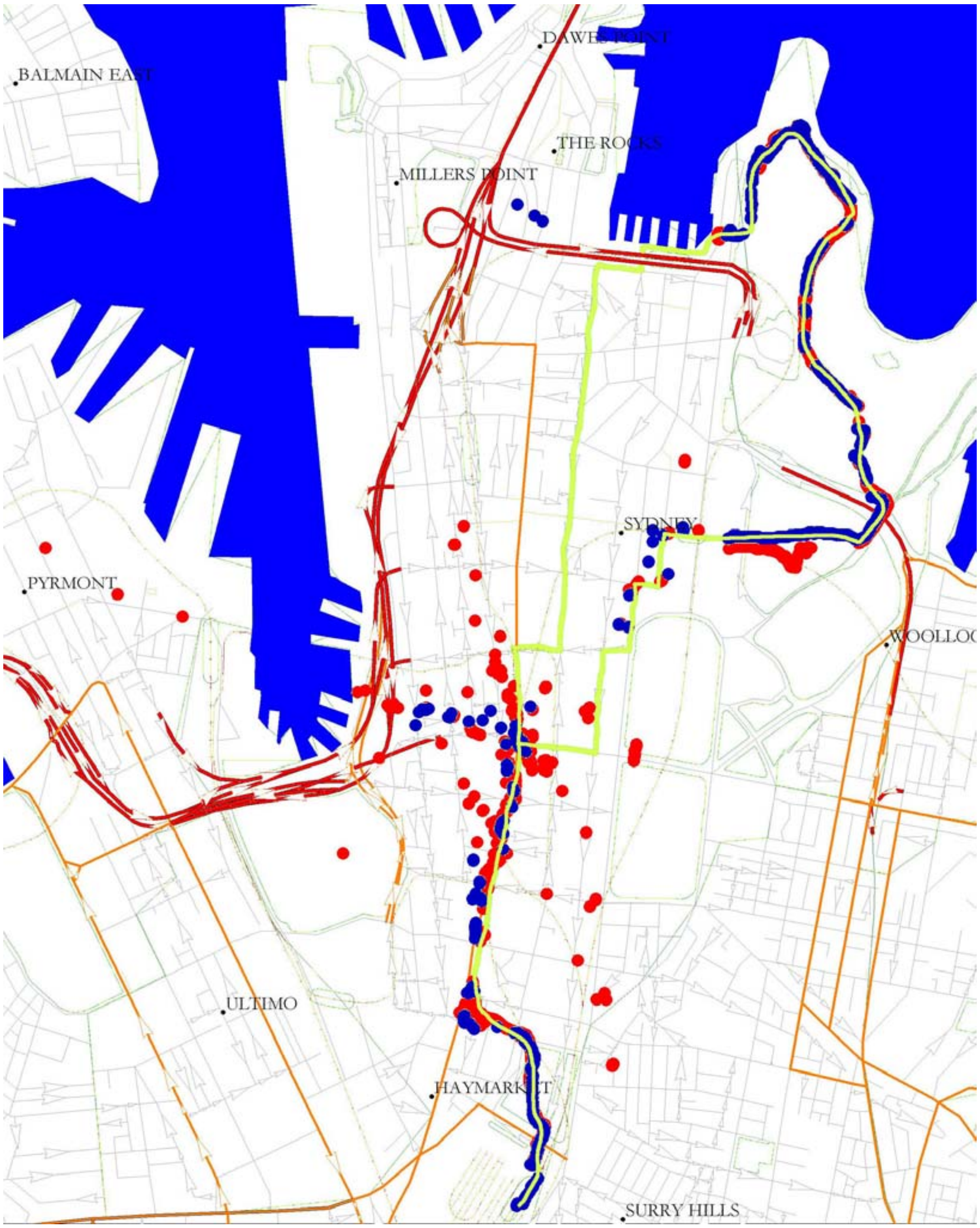

Figure A6.1: Results of a trip to the city centre of Sydney

Results of the wearable can be very scattered. Figure A6.1 shows a trip to the city centre of Sydney. The red and blue dots are the results of two people, walking along the light green route, using the wearable to log their location.

The results in the upper right corner and at the bottom are pretty good (parks without high buildings). In the centre of the figure, results become very scattered (even points in Pyrmont!). Also a great part of the trip is missing.

14 Appendix 7: Cold start results

Figure A7.1: Example of cold start

Figure A7.1 shows a walking trip trough a suburb (Newtown) of Sydney. The buildings in this suburb are a maximum of three stories high, streets are wide and there are some parks. Red dots are the results of a person using a wearable (started with cold start). The green line represents the points that are missing because of the cold start.

15 Appendix 8: Example segments

ID	LONGITUD	LATITUDE	VALID	HDOP	SATELLIT	LOC_TIME	SPEED	DISTANCE	
1	151.0671	-33.8471	V	0.0	4	105457	0.0	6.4	
2	151.0668	-33.8471	A	1.9	4	105512	6.0	8.2	Segment 1 The mode of travel in this segment is walking, because points have a speed below 7 km/h.
3	151.0668	-33.8472	A	1.9	4	105517	5.5	7.7	
4	151.0667	-33.8472	A	1.9	4	105522	5.1	6.4	
5	151.0666	-33.8472	A	1.9	4	105527	4.7	5.9	
6	151.0666	-33.8472	A	1.9	4	105532	4.5	6.5	
7	151.0665	-33.8472	A	1.9	4	105537	4.5	6.4	
8	151.0664	-33.8472	A	1.9	4	105543	4.3	7.3	
9	151.0663	-33.8472	A	1.9	4	105548	4.5	6.4	
10	151.0663	-33.8471	A	3.0	4	105552	0.0	9.2	
11	151.0662	-33.8471	A	3.0	4	105558	0.0	4.5	
12	151.0661	-33.8472	A	2.4	4	105607	0.0	13.9	
13	151.0660	-33.8472	A	2.7	4	105612	0.0	7.7	
14	151.0659	-33.8472	A	2.0	4	105617	0.0	3.8	
18	151.0656	-33.8472	A	2.7	5	105637	0.0	6.5	
19	151.0656	-33.8473	A	2.7	5	105642	0.0	5.1	
20	151.0107	-33.8139	V	1.8	4	105741	0.0	0.1	
21	151.0107	-33.8139	A	1.8	4	105746	0.0	2.3	
22	151.0107	-33.8139	A	1.8	4	105751	1.6	1.6	Segment 2 See: Segment 1
23	151.0107	-33.8139	A	1.8	4	105756	3.7	5.9	
24	151.0108	-33.8140	A	1.8	4	105801	5.5	10.6	
25	151.0110	-33.8143	A	1.8	4	105801	0.0	13.5	
26	151.0111	-33.8144	A	1.8	4	105806	0.0	14.0	
27	151.0123	-33.8152	A	1.8	4	105811	11.4	64.9	Segment 3 The mode of travel in this segment is **train**, because all points are on the railway track and there is at least one point with a speed between 7 and 80 km/h. Also the points start at a railway station.
28	151.0138	-33.8157	A	2.0	4	105816	12.1	17.3	
29	151.0140	-33.8158	A	1.8	4	105821	12.4	17.2	
30	151.0142	-33.8158	A	1.9	4	105826	12.6	19.4	
31	151.0146	-33.8160	A	1.8	4	105831	13.7	22.1	
32	151.0148	-33.8160	A	1.8	4	105836	14.5	21.2	
33	151.0150	-33.8161	A	1.8	4	105841	15.1	22.1	
34	151.0153	-33.8161	A	2.2	5	105846	19.3	23.3	
35	151.0155	-33.8161	A	2.0	5	105851	23.4	23.2	
37	151.0160	-33.8161	A	2.0	5	105856	27.1	25.0	
38	151.0165	-33.8161	A	1.7	5	105901	27.6	18.6	
39	151.0168	-33.8161	A	1.8	5	105906	28.6	23.3	
40	151.0170	-33.8161	A	1.7	6	105911	29.9	23.2	
41	151.0173	-33.8161	V	1.8	5	110312	57.4	35.1	Segment 4 The mode of travel in this segment is train, because all points are on the railway track and there is at least one point with a speed between 7 and 80 km/h.
42	151.0176	-33.8161	A	2.0	5	110317	57.4	35.1	
43	151.0178	-33.8160	A	1.8	5	110322	57.5	35.4	
44	151.0181	-33.8160	A	1.8	5	110327	57.5	35.4	
45	151.0183	-33.8159	A	1.8	5	110332	57.5	35.4	
46	151.0195	-33.8155	A	1.8	4	110337	57.5	35.4	
47	151.0198	-33.8154	A	1.8	4	110342	57.5	24.9	

Table A8.1: Example of a set cleaned data divided in different segments.