DOTTORATO IN AMBIENTE E TERRITORIO
XXV CICLO

TESI DI DOTTORATO

Observing travel behaviour from GPS data
A tool comparison survey in the Torino metropolitan area

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RINGRAZIAMENTI

Ringrazio chi mi ha seguito, supportato e sopportato in questi anni di dottorato. Ringrazio chi mi ha donato il suo tempo, ha condiviso con me la sua esperienza o ha semplicemente voluto scambiare quattro chiacchiere e strapparmi una risata nei momenti più impegnativi. Ringrazio chi c'è e chi non c'è più, chi è vicino e chi è lontano, perché avete tutti equamente contribuito a rendere significativa quest'avventura.

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INTRODUCTION

Travel surveys help researchers to paint a clear picture of specific aspects of travel behaviour. In the transport field, data quality is largely dictated by the data requirements of mathematical models, and by the rising complexity of individuals' travel behaviour.

Beginning with an illustration of the most common transport models, this thesis will first present an overview of traditional survey tools, in order to understand their structural biases and current developments in the transport survey field.

One of the recent solutions to common data collection problems is the implementation of passive data collection tools in household and personal travel surveys.

Passive data collection tools allow researchers to derive travel behaviour information from positional and navigational data, collected with devices that use location-aware technologies, such as GPS, GSM, and RFid. Passive data collection tools – in particular, GPS devices – have proven useful in household and personal travel surveys, and have shown themselves capable of providing researchers with high-quality travel data.

The objective of this research is to evaluate the use of GPS as a survey tool in household and personal travel surveys. Technological advances and decreasing costs have helped GPS to achieve wide use in the survey field. Furthermore, GPS-equipped devices allow surveyors to collect high-quality data on the time and position of individuals and vehicles – data that are more difficult to ascertain using traditional survey tools, such as self-administered questionnaires and telephonic interviews.

A research team at the Politecnico di Torino designed and carried out a multi-instrumental personal travel survey, in order to assess the context-specific problems of a GPS-based survey in the metropolitan area of Torino. Survey methods included both a paper-and-pencil travel diary, and locational data collected using GPS devices. The survey effort consisted of a 4-day pilot survey with a sample of 4 individuals, and a successive 14-day GPS survey with a sample of 8 individuals. Results from self-administered travel diaries and GPS-derived data provided surveyors with valuable data for assessing the quality and completeness of travel information, and for determining the data's ability to accurately describe respondents' travel behaviour.

This thesis consists of four chapters, discussing, in turn, the following elements:

- a description of the features of traditional household and personal travel surveys;
- identification of available passive data collection technologies, and analysis of their potential for implementation in travel surveys;
- a description of the state-of-the-art of the use of GPS devices in travel surveys;
- implementation of GPS technology in a GPS-based survey in the metropolitan area of Torino.

Chapter 1 will provide an overview of the various traditional travel survey methods used in the travel survey field, such as travel diaries and telephonic interviews. Current survey challenges will be discussed, including challenges in respondent recruitment and survey participation, as well as errors in data collection, such as rounding and incomplete reporting. Solutions for overcoming structural problems inherent in household and personal travel surveys will be discussed. The chapter will also describe expected survey outcomes and their uses in studies of travel demand.

Chapter 2 will provide an overview of available tracking technologies that can potentially be used in travel surveys, to provide surveyors with data on performed trips, travelled distance and trip duration. From the data collection point of view, positioning technologies fall into two categories – those in which users are aware of the tracking, and those in which they aren't. An overview of the applications of both approaches, and the respective advantages and drawbacks of their implementation in travel surveys, will be provided.

Chapter 3 will discuss the use of satellite positioning, or GPS, as a travel survey tool. GPS represents the most mature passive travel survey tool in the travel survey field. 30 years of experience, together with technological advancements in post-processing methods and in GPS devices themselves, has allowed surveyors to overcome many of the problems that plagued this survey tool in its earliest implementations. The successful use of GPS devices or GPS-equipped devices in large-scale travel surveys largely depends on the use of proper post-processing methods. The post-processing phase includes all the various steps necessary to derive complete travel behaviour information from raw GPS data. Despite their great potential, GPS receivers and GPS-based surveys present specific biases that researchers must consider and evaluate before the start of the survey. Signal loss, device mishandling, privacy issues and technology divide are some of the problems that surveyors have witnessed.

Chapter 4 will describe the survey planning, survey methodology, survey administration, and data analysis phases of a multi-instrumental (trip-diary and GPS devices) pilot survey, carried out by researchers in the metropolitan area of Torino, Italy. The pilot survey was carried out in order to highlight possible biases and setbacks, and to provide researchers with valuable information to design a full, GPS-based survey. This initial research led to the design and administration of a 2-week GPS travel survey, supplemented by a parallel 1-week traditional travel diary survey and a 1-week GPS functionality diary. Surveyors then compared data collected with GPS devices against data collected using traditional travel diaries.

The dissertation will conclude with discussion of the results of the Torino GPS survey and of supplementary passive data collection tests. The potential of passive travel surveys will be addressed, as will future developments in the field.

CHAPTER 1 - Household travel and activity surveys

'Surveying' can be defined as 'examining with reference to condition, situation or value' (Merriam-Webster, 2011). In the field of quantitative research, the word survey describes a method of gathering information about specific items in a population. A survey studies a target group, referred to as a sample, using different data-collection tools, to infer information about a larger population represented by the selected individuals. Sample sizes are determined based on the reliability of the derived information, which in turn depends upon the final outcomes desired. However, even a moderate sample size of 1500 can provide sufficient data to allow the inference of national attitudes and opinions. Surveys are used in a variety of scientific fields and are available in many different forms, allowing researchers to scientifically select tools and sample sizes based on their research needs (Ferber et. al., 1980).

The transport field has benefitted from the use of surveys since the 1950s, when urban transport planning in the US was in its early stages. (Stopher, 2009). Travel surveys allow researchers to collect personal travel behaviour information in order to describe actual travel trends, quantify travel demands, identify problems in transportation systems and study long-term trends and possible effects of planned intervention using forecasting models.

Many different types of travel surveys exist for use in a specific study area, differing in their purpose, application and recruitment mode. In general, the most commonly used surveys are these:

- household and personal travel and activity surveys: can be used to study travel behaviour, focusing on the relationships between activities and movements of people belonging to a household, or focusing specifically on personal trips and activities;
- vehicle intercept and external station surveys: surveys that address auto travellers entering or leaving a defined study area or crossing key screen lines, and share the common characteristic of requiring roadside recruitment;
- transit onboard surveys: designed to target passengers of public transportation services as they travel;
- commercial vehicle surveys: specifically designed to track commercial vehicle trips (taxis, trucks, etc.);
- workplace and establishment surveys: surveys that are carried out at places of employment;
- special trip generator surveys: designed to study travel to and from special trip generators, such as airports and hotels;
- visitor surveys: surveys that address the specific user category of tourists and visitors in general;
- parking surveys: surveys that are carried out in specific locations or parking lots within the study area.

(TSM, 2012; Richardson et al., 1995)

The universe of travel surveys is vast, and a wide range of issues must be considered in order to provide valuable information for policy makers. Travel surveys, and debates over their standardization, have been going strong for more than 40 years, thus demonstrating a strategic need for high-quality transportation data (NCHRP, 2008).

Household and personal travel surveys are the most often-used surveys for urban and regional travel studies. During the surveys, respondents (single individuals or household members) are contacted directly and asked to provide information on their trips or activities, as well as their demographics, behaviour and travel experiences. The key factor in household travel or personal travel surveys is data collection. Several methods have been developed to provide better data and guarantee the broadest possible participation among respondents.

Traditional survey methods fall into two broad categories, differing in the degree of involvement by respondents (Ampt et al., 1985):

- self-reporting, such as Computer-assisted Self Interview (CASI) or travel and activity diaries, in which respondents are responsible for recording data;
- personal interviews, in which data are collected by an interviewer, e.g. in Computer-assisted Telephonic Interview (CATI) or face-to-face interviews.

The choice of a survey method hinges upon costs, data needs, expected sample size and target population group, and the evolution of the survey method depends on respondents' behaviour towards surveys, technology development and travel demand forecast method data needs. Travel demand forecast methods consist of different families of mathematical models, adapted to their specific data needs.

1.1 Travel modelling

Transport models are simplified representations of the transportation systems they seek to interpret. Because the models are designed to estimate travel demand, which is a derived quantity, several variables should be considered in the estimation process. These include demographics (income, lifestyle, age, habits, preferences, etc.) and land use characteristics such as urban density, service availability, quality and availability of transport offer by mode (roads, public transport services), etc. (Ortuzar et al. 2011). Data from travel surveys and travel-related surveys (travel information included in census data) are used as inputs in travel forecast models. The results of the models are used in travel policies, planning and policy evaluation – and with limited resources available for infrastructure projects and transit systems, it is vital that both data collected, and models used, are accurate and efficient. Because models approximate actual behaviour, input data must represent actual travel trends.

Compared to the average travel trends in the era of the first travel surveys, travel patterns today are more spread out throughout the day, resulting in high day-to-day variability. This higher degree of variability, attributable largely to changes in lifestyle and working behaviour, can be detected only with more careful observation. While research once focused mainly on distinguishing weekend vs. workday patterns and measured representative times of the day (e.g. peak travel hours), recent trends show that behaviours are more complex, and it is now understood that it takes at least one week, or even several weeks of observation in order to detect repetitiveness in travel patterns (Axhausen et al., 2002; Bhat, C.R. et al., 2004; Krizek, 2003; Stopher et al., 2008a). Unfortunately, survey design constraints – limited time and financial resources, insufficient survey samples, burden on respondents, etc. – often lead researchers to use one-day, or two-to-three-day surveys (Schönfelder et al., 2002; Schlich and Axhausen, 2003). To ascertain meaningful results from these short-length surveys requires aggregation of the submissions of many survey respondents, resulting in the profile of an "aggregate user." Aggregation itself, however, yields statistical errors; the more variable the behaviour of a population, the larger the potential for such errors. (Axhausen et al., 2002).

From a statistical point of view, longer-duration surveys allow researchers to achieve reductions of standard deviation on the sample results, or alternatively, to achieve the same standard deviation of results with significantly smaller samples. By observing results from multi-day travel surveys and comparing them with the outcomes of shorter-duration surveys, it is possible to identify how benefits are generally more significant as the survey period lengthens (Stopher et al., 2008b).

The total variability of an observed value is in fact the sum of the variability between observation groups (differences among units) and within the same group (variability within the same unit across observations). Equation 1.1 describes the relationship of the components of the total variability, as measured by an analysis of variance.

$$TSS = SSB + SSW$$ **Equation 1.1**

Where:
TSS is the total sum of squares;
SSB is the sum of square between groups;
SSW is the sum of squares within groups.

Applying this relationship to the study of individuals' travel behaviour across different days, the total variability of a measured value can be defined as the sum of its interpersonal and intra-personal components, as reported in Equation 1.2.

$$Total\,Variability = InterPersonal + IntraPersonal$$ **Equation 1.2**

Inter-personal variability measures variation in the observed variable across different individuals, while the intra-personal component of overall variability refers to day-to-day variation within the behaviour of an individual. The relationship between these variabilities is illustrated in Equation 1.3. Studies suggest that the largest component of total variability of a measured travel behaviour is variability across days (Pas and Koppelman, 1984; Stopher et al., 2008; FHWA, 2011). Measuring this element properly is crucial for obtaining meaningful survey results.

$$Total\,Variability = Individual\_VAR + Daily\_VAR$$ **Equation 1.3**

Multi-day travel surveys are better than shorter-duration surveys at measuring intra-personal, day-to-day variability. Multi-day surveys thus yield a better estimation of the total variability of the observed variable, holding constant the same sample or the same estimated variability with a smaller sample.

Developments in model design and usage have made it necessary to collect different types of data and more in-depth data in general. The structure of the most commonly-used models has not changed significantly in the last 30 years (Stopher and Greaves, 2007), but analysis zones are becoming smaller and more focused, which in turn requires data to be more precise – for instance, location data is expected to be gathered at the street address level, and time data with minute precision. In addition to traditional models being used at levels of greater precision, new models (e.g. simulation, activity and tour-based models) are being used, and these require differently-structurally, quality-rich data, covering behaviours, activities, traffic volume and other variables. Beginning in the 1970s, modelling research started to shift its focus from the "what" to the "why" of travel behaviour, focusing on the processes by which people make travel choices, rather than the outcomes, e.g. trips (Golob, 2000).

The models most commonly referenced in literature include the following:

- Four-step
- Tour-based
- Activity-based
- Simulation

(TSM, 2012)

Transport research still relies heavily on traditional Four-step models, which require simpler, more basic data. However, there is a trend toward increasing the precision of collected data in order to provide results at a smaller geographic scale. Emerging models developed in the last 10 to 15 years – such as Activity-based, Tour-based and Simulation models – require higher-quality survey data, in addition to a more precise geographic dimension of data. This leads to a significant burden on respondents (Stopher and Greaves, 2007)

1.1.1 Four-step models

The traditional approach to the urban transportation planning system model consists of four steps:

1. Trip generation, used to determine the expected number of trips originating from each area, organized by purpose or intent of the trip. Information used in trip generation can include survey data, or estimations made using known land uses and socio-economic factors of a population.
2. Trip distribution, in which researchers match trip origins with trip destinations for each zone.
3. Mode slip, in which researchers allocate trips among available modes of transportation.
4. Route assignment, in which researchers name a "route" for each trip between a given pair of origins and destinations, using a particular mode of transport.

Data on completed trips, provided by respondents in trip diaries, are used for the calibration of four-step models. Trip-diaries are designed to measure trips between two activities, which consist of a continuous sequence of movements performed with one mode of transport, referred to as stages. Basic data needs also include the understanding of socio-economic characteristics and travel patterns of the surveyed population (Ortuzar et al. 2011; McNally, 2000).

A trip is a sequence of one or more moving segments performed with one transport mode, referred as stage. A trip is undertaken to switch from one activity to another (Axhausen, 1995). Figure 1 exemplifies the previous statements.

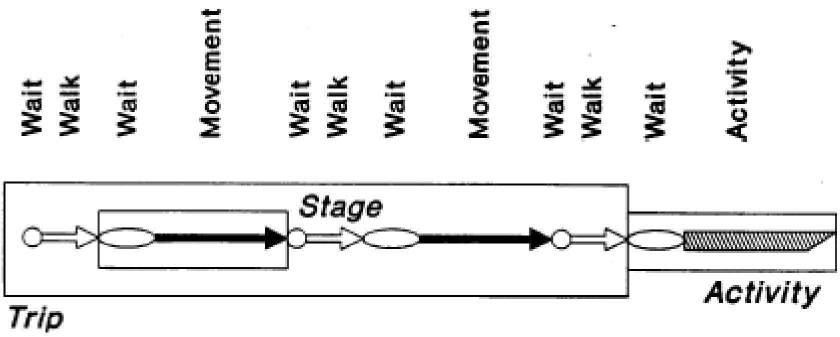


Figure 1 – Elements of the movement/activity chain (Axhausen, 1995)

1.1.2 Tour-based models

Tour-based models study travel demand at the trip level, but also consider each trip as part of a higher level 'tour,' that is a particular sequence or chain of trips. Considering trips as parts of more complex 'tours' allows researchers to understand the associations between reported trips – an element that can be lost when trips are considered only individually (Krizek, 2003).

The typical tour used for travel survey purposes is the home-to-home tour, which covers all activities and trips completed between when the respondent first leaves his home for the day and when he returns at the end of the day. In order for researchers to better evaluate relationships between trips within a tour, demographic characteristics of the traveler should be taken into account (NCHRP, 2010).

Information on individual trips and activities feeds the tour-based model. Researchers must thoroughly study the individual trips and activities that make up a tour, and must accurately reconstruct trip chains, in order to understand the underlying behavioural relationships between individual trips. (NCHRP, 2010).

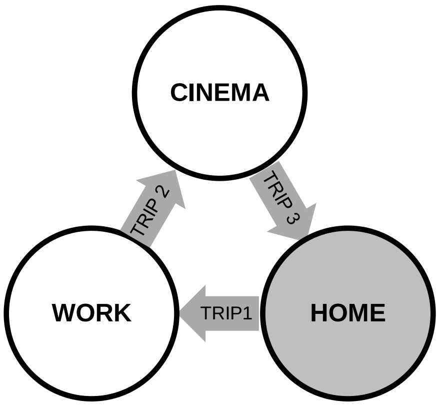


Figure 2 – Example of Home-to-Home tour

The model in Figure 2 demonstrates a simple home-to-home tour, in which the respondent made one trip from home to work, then a subsequent trip from work to the cinema, before returning home from the cinema. Considering the three trips together allows researchers to study the relationships between them, and possibly the behavioural reasons the trips were made.

1.1.3 Activity-based models

Activity-based models are based on the study of travel as a derived demand, i.e., the assumption that the motivation for a person's travelling is to pursue activities that are distributed in space. This modeling approach studies the interactions between activities, both in home and out-of-home, and travel behaviour. Activity-based models shift their focus from the observation of trips to the study of sequences of daily and weekly activities. The activity-based model generates a picture of a population's activity patterns, which researchers can use to estimate respondents' travel needs (Axhausen, 2000; Bhat et al. 2003).

Inputs for activity-based models include time-use survey outcomes, analysis, and estimation. Time-use questionnaires are the most commonly-used tool for gathering data on activities performed by individuals during the survey period. Information collected through these surveys allows researchers to check for data integrity and missing information, once activity chains and trip histories have been reconstructed. Activity-based surveys are data-intensive and therefore result in a higher burden on respondents.

Activity diaries allow researchers to reconstruct respondents' activity chains throughout the day in order to determine constraints and commitments that influence their personal behaviour, thereby influencing their travel needs (Ortuzar et al., 2011). Figure 3 shows an example of a daily activity schedule framework.

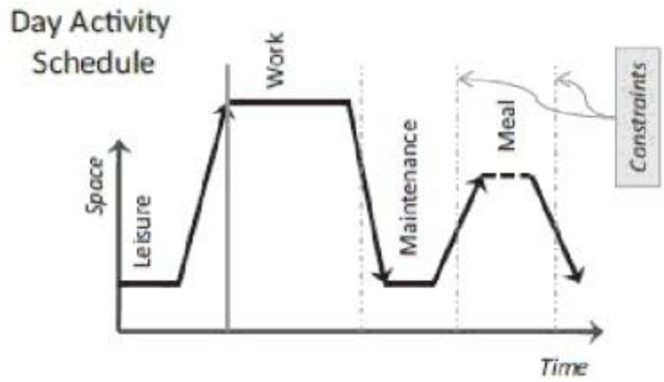


Figure 3 – Activities and travel throughout the day (Ortuzar et al., 2011)

1.1.4 Demand simulation models

Demand simulation models are designed to estimate the behaviours and needs of individual transport users rather than aggregate groups. Such tools model household and individual behaviour within a micro-simulation. Demand simulation models can be used alongside other types of models, as they rely upon information also used in conventional travel, economic and land use models. While originally developed for small scale projects, demand simulation models are now being used increasingly for area-wide analysis (NCHRP, 2010).

1.2 Travel survey process

All types of travel surveys are performed according to a common procedure composed of the following four stages, as illustrated in Figure 4:

- Survey planning: Researchers, often in cooperation with policy makers and agencies, evaluate desired survey outcomes and available resources.
- Survey design: Researchers choose a survey method, design a survey instrument, select participant recruitment methods and prepare for eventual data analysis.
- Survey field implementation: Researchers recruit participants, administer the survey and collect responses.
- Data preparation and analysis: Collected data – in the case of travel surveys, data could include socioeconomic and demographic information, as well as information on trips, activities, preferences and habits – is made ready for use by the surveyor or other researchers, through data cleaning and coding.

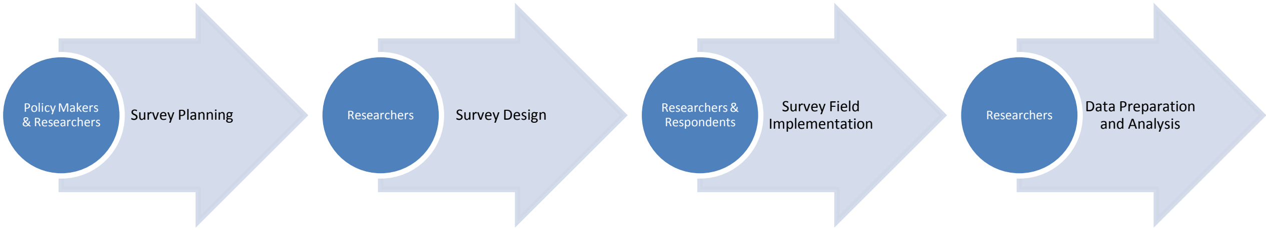


Figure 4 – Travel survey stages and subjects involved

Each of the four survey stages poses specific structural challenges.

1.2.1 Survey planning stage

The planning stage involves a careful review of existing data sources, with the goal of collecting background information on the context in which the survey will be administered. This preliminary review helps researchers to study the population for recruitment and sampling methods, to locate data that could substitute or be integrated with survey results (i.e., existing travel datasets), and to look for existing data that could be used to validate final survey outcomes (TRB, 2012).

In addition to context-related characteristics, two major challenges facing surveyors in the planning stage are the need for better data and forecast results, and the increasing cost of resources. The availability of financial resources determines researchers' ability to hire human resources, as well as their choice of survey method, the length of the survey, and the possible sizes and recruitment methods of the survey sample (Richardson et. al 1995).

1.2.2 Survey design

After considering the survey context and limitations in time and resources, researchers must next determine the sample size, method of sample selection, and level of detail/expected quality of collected data. The following are factors researchers must take into account when designing a survey:

- survey organization;
- survey procedures design;
- choice of recruitment procedures.

Survey organization

The organization phase deals specifically with resource management. Researchers must properly recruit staff, purchase survey materials, acquire desired additional travel data, contact consultants for help, verify field-workers' expertise, etc., according to available funds and human resources.

Survey procedures design

Once a survey method has been selected, the survey must be designed; questions must be selected, length of survey determined, survey period scheduled, etc. In this phase, researchers must consider several factors affecting the degree of respondent participation.

Construction of survey data collection tools

Survey instruments are used to gather the information necessary for meaningful analysis. Survey tools should be able to record socioeconomic and demographic information, as well as information on trips, activities, preferences or habits, according to the researchers' needs.

Surveys should be written in understandable language with all terminology clearly defined (e.g. include definition of what constitutes a ‘trip’ – see Figure 1). Questions must be designed to clearly seek the degree of accuracy in responses that researchers expect or desire in the outcomes. Questions should be written in consideration of respondents’ privacy, religion and traditions. Literacy and language barriers of sample populations must also be taken into account.

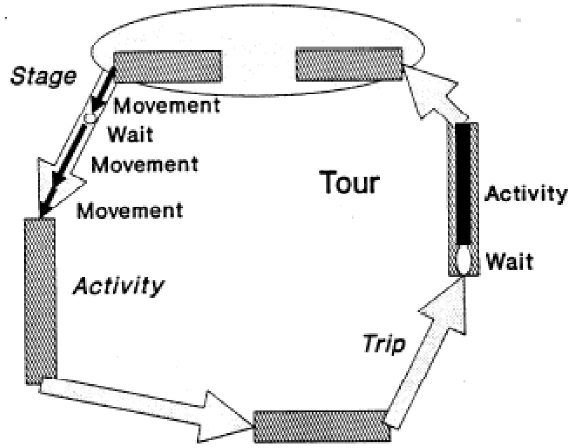


Figure 5 – Schema of basic travel survey units (activity, stage, trip, tour) (Axhausen, 1995)

Definition of survey length and survey period

Determination of survey length depends on both researchers’ needs and the burden placed on respondents. A proper survey length is one that allows researchers to detect all variability and patterns of the analyzed phenomenon, i.e. all movement patterns of daily life, while not causing respondents to experience fatigue and eventual drop-off. Achieving the proper survey length is, thus, a delicate balance. For all the previously mentioned reasons, survey lengths largely vary across travel survey experiences, from a single day to a multi-week survey. Table 2 reports examples of survey lengths adopted in past travel surveys.

SURVEY	YEAR	DURATION
Jerusalem, ISR	2010	1 day
California, USA	2001	1 weekday or 2 weekend days
Puget Sound, USA	1999	2 days
Atlanta, USA	2000	5 days
National Travel Survey, UK	2011	1 week
Colorado, USA	2011	2 weeks
Uppsala, Sweden	1971	35 days

Table 1 – Examples of travel survey duration

Equally important is the selection of an appropriate survey period, as travel survey outcomes depend on the specific time of the day or days of the weeks travel behaviour is observed. Researchers might seek to study respondents’ movements specifically on work days or weekend days, holiday periods, or before and after infrastructural changes or life transitions (Flamm and Kaufmann, 2007). Consideration of the desired period of study could also directly affect researchers' choice of overall survey length.

Choice of recruitment procedures

One of the most important phases prior to field implementation is respondent recruitment. Surveyors must select a representative sample of sufficient size, with both size and degree of representation varying according to the focus of the research. To apply research results in a broader, more universal context requires a larger, more varied survey sample; to apply results to a more specific population, e.g. university students or car-users, requires a smaller, more targeted survey sample (Richardson et. al 1995).

Samples are obtained through the recruitment of participants, a process that can be carried out using various contacts (e.g. mail-in form, telephone contact, door-to-door contact) and following one of several possible sampling methods (e.g random sampling, systematic sampling, stratified, etc.). Sample quality is crucial, as it allows researchers to better estimate variability. Recruitment methods vary in their ability to reach the target population, and in their capacity to obtain samples of sufficient size and representativeness. Specific population segments, such as low-income, immigrants, households without landlines, etc., are particularly difficult to sample, due to challenges in reaching and recruiting them (TRB, 1996; NCHRP, 2008).

1.2.3 Field implementation

In addition to survey method and design, final research outcomes depend largely upon the quality and completeness of participants' responses. Even a perfectly-designed, perfectly-executed household travel survey can yield poor-quality data if responses are inadequate. Factors affecting respondents' degree of participation and the quality of reported data include the following:

- lower participation rates: in recent years, researchers have documented a general drop in survey participation rates, due to various social factors (e.g. overexposure to marketing surveys). Overall participation rates are typically no higher than 60% of recruitment in North American surveys (Stopher and Greaves, 2007);
- refusal and drop-out: researchers face a percentage of participation refusal (or non-response to the participation invitation). This refusal ratio is partially unavoidable, as researchers can always expect to lose a portion of contacted recipients. However, it is also structural for certain survey tools and for certain population groups. If the survey uses panels (e.g. German Mobility Panel) with the objective of limiting refusal from one observation to the other, a drop-out ratio is also expected (Stopher and Greaves, 2007);
- burden: travel surveys are becoming more data–intensive, and respondents are asked to report their daily movements or activities with an increasing level of detail. This leads to underreporting, especially for larger households (NCHRP, 2006); which, due to their higher number of household members, need to spend more time on interviews or questionnaires.
- fatigue: generally, multi-day surveys cause a drop in response rates due to survey fatigue and demotivation (Golob and Meurs, 1986). This structural bias inherent in longer surveys leads to a progressive tendency to underreport trips and to falsely report non-trip days (Golob, 1986; Schlich and Axhausen, 2003);
- item non-response: item non-response occurs when a piece of information requested of respondents is not reported, either for a complex or sensitive reason or because the respondent

forgot to answer. This error is more evident for survey methods that lack a data quality check during the data collection process – typically, self-administered survey tools. Item non-response is a difficult problem to address and directly affects survey results;

- memory: some survey methods, both interview and self-administered, ask respondents to report their trips from an earlier day. Such questions are subject to a memory effect bias. This phenomenon affects primarily short, non-commuting trips. Survey designers must try to correct for memory effect bias by providing memory joggers and instructing participants to note a trip as soon as possible after it has been completed (Stopher, 1992);
- rounding: respondents tend to report time-related information with a rounding of 5 to 15 minutes. This phenomenon affects information on the duration of trips and activities, and it has a greater impact on shorter events;
- trip chain complexity: the rising complexity of trip chains is related to changes in travel and activity patterns (Bhat et al., 2004). This phenomenon results in a higher burden on survey respondents, who must remember and record increasingly complex and non-habitual trips. This effect can be considered a joint effect of memory and rounding issues, and it often leads to item non-response.

1.2.4 Data preparation and analysis

In the data preparation and analysis stage, raw data collected during the survey implementation phase are aggregated, translated into codes, transformed into geo-locations, etc., in order to build a set of data that can be used for model development and presentation of results. Researchers must also check the data for completeness and consistency among responses (logical check), using manual and automated procedures. After checking the data, datasets can be prepared for analysis by treating non-responses (imputation or discarding) and weighting the results (to overcome oversampling or undersampling of population groups) (TSM, 2012).

1.3 Survey methods

The choice of a survey method is one of the key factors in obtaining the desired survey outcomes. Researchers should select survey methods according to their target population and data needs.

Each potential survey method has its advantages (e.g. low costs, ease of reaching the survey population, possibility for data quality control, low burden on respondents) and disadvantages/structural biases (e.g. technology divides, privacy concerns, high burden on respondents).

Survey methods are variously adapted for use within specific contexts and with different levels of resource availability. Common survey methods fall into two categories: personal interview surveys, and self-reporting surveys. Personal interview survey methods include personally-administered (face-to-face) interviews and telephone interviews. Self-reporting survey methods include self-administered surveys distributed by intercept methods, self-administered surveys administered to groups, self-administered mail surveys and self-administered Internet surveys.

Selection of a travel survey method depends on researchers’ assessments made during the survey planning phase. Methods differ by cost, control over data quality, and burden placed on respondents.

Surveyors often use one main survey method, supported by other survey methods, to maximize the utility of the survey. For example, researchers might use a self-administered questionnaire with a prompted-recall interview in case of the need for additional information (TSM, 2012).

The characteristics of each survey method are described in the following paragraphs (TRB, 1996; Richardson et al. 1995). Table 2 shows a schematic comparison of the most commonly-used survey methods ordered by degree of surveyor supervision on respondent data collection.

	RESOURCE NEEDS	DATA QUALITY	BURDEN ON RESPONDENTS
Personally-Administered Interviews (CAPI)	XXXXX	XXXXX	XXXXX
Telephone Interviews (CATI)	XXXX	XXX	XXX
Self-Administered Surveys Distributed to Groups	XXX	X	XX
Self-Administered Surveys Distributed by Intercept Methods	XXXX	XXX	XXXX
Computer Assisted Self-Interviewing and Web Surveys (CASI and CAWI)	X	XX	X
Mail Surveys	X	X	X

Table 2 – Overview of survey method families and characteristics

Personal interviews

Personal interviews require direct interaction between the interviewer and the respondent. The interviewer supervises the entire data collection process and is able to both assist the survey participant and ask for correction of missing or inconsistent information. The main distinction within this category is communication strategy, which can be either in person or by phone.

Personally-administered interviews

Personally-administered interviews require trained interviewers to ask respondents survey questions using a face-to-face interview. This type of interview can differ by the location of the contact – at home, in a specific location other than home (workplace or public place), or during travel (in vehicle, roadside). While this method provides the highest-quality data of all the interview types and allows interviewers to supervise and guide the entire data collection process (CAPI), it poses a high burden on respondents and is the most expensive survey tool, due to the consistently rising costs of fieldwork.

Telephone interviews

Telephone surveys are more cost-effective than resource-intensive personal administered interviews. The interviewer contacts respondents by telephone and is able to check for data integrity (CATI). Travel surveys using telephonic interviews are typically limited to in-home surveys. The inconsistent availability of landlines across demographic groups creates a structural sampling bias, and the burden on respondents is high, though lower than with face-to-face interviews.

Self-administered interviews

Self-administered interviews place the responsibility for data collection on the respondent. In self-administered interviews, the interviewer explains the survey to the respondent or designs a data integrity procedure, but respondents are in charge of recording the demographic, travel or activity data themselves, on the selected medium.

Self-administered surveys distributed by intercept methods

Using intercept methods, respondents fill in a questionnaire unassisted and return it to the surveyors once completed, usually by mail. Surveyors contact respondents directly, as in personally-administered interviews, and are able to explain the survey and reply to specific questions when they deliver the survey tool. While this method allows researchers to succeed in reaching selected survey respondents and places a low burden on respondents, data integrity is not assured.

Self-administered surveys distributed to groups

To address an underrepresented population group, researchers can gather specific groups of respondents and ask them to complete a self-administered survey under researcher supervision. This survey method combines the advantages of personal interview surveys with the advantages of personally-distributed self-administered surveys, and it is suitable for use with small groups.

Mail surveys

A mail survey consists of mailing self-administered surveys to households, using an address database, and waiting for replies. While observed response rates are among the lowest of all survey methods and data quality checks are not possible, the advantages of mail surveys include their low cost, low burden on respondents, limited resource requirements and ability to effectively reach the targeted population.

Web surveys

An online survey consists of an online questionnaire, which respondents fill-in and submit. Data completeness and quality are achieved through computer-aided data integrity checks, which are required in addition to the basic prevention of item non-responses. Implementation costs and resource needs for this survey method are very low; however, completion of a web survey depends on the availability of computers and internet connections, which results in a strong technological bias.

1.3.1 Survey methods in household travel surveys

The first generation of household and personal travel surveys collected trip information using face-to-face home interviews. These surveys, which first came into use for transportation planning applications in major urban areas of the US during the 1950s and 1960s, focused solely on travel patterns (Arentze et al., 2001; Stopher, 2009) This method of data collection was very expensive from the start, and low participation rates were reported. On the sampling side, the number of recruited respondents dropped progressively from 1-3 % of the studied population during the first household travel survey experiences, to less than 1 % of the studied population in recent applications (Stopher, Greaves, 2007). By the end of the 1970s, increasing costs and problems with interviewers' safety led to the use of different survey methods, especially in North America (Stopher and Metcalf, 1996). Over time the home interview survey was gradually replaced by a telephone or mail recruitment, followed by a mail survey using self-administered travel diaries. Self-administered diary surveys were first used in Upssala, Sweden in 1971 (Brög et al., 1983) and were first developed as standardized travel survey tools in Germany (KONTIV, designed by Socialdata) in 1976 (Stopher et al., 2008b). Self-administered travel diaries were introduced in US travel surveys in the early 1980s after the KONTIV scheme had proven its applicability in different cultural contexts and across language barriers. (Brög et al., 1983).

The switch from face-to-face surveys to this lower-burden travel diary didn't solve all the research problems, however. The use of a diary to collect information on personal and household trips allowed researchers to carry out longer surveys, but the tool carried with it some biases, such as low response rates, underreporting of short trips, and fatigue throughout the duration of the survey (Golob and Meurs, 1986).

Beginning in the 1980s, telephonic interviews were used for both respondent recruitment and data retrieval. These interviews were often assisted by computer (CATI) in order to help tighten data accuracy. Computer assistance was also implemented in face-to-face interviews (CAPI) as well as self-administered survey tools (CASI), such as Internet surveys. The 1980s also saw researchers beginning to incorporate activity information, as well as trip information, into travel diaries (Stopher, 1992). Gradually, incorporation of activity information into travel diaries increased, eventually yielding travel diaries comprised solely of activity information (activity-based diaries). Currently, travel diaries vary in design across the continuum between pure trip-based and pure activity-based, usually combining the two techniques in order to best meet project needs (Arentze et al., 2001).

The first generation of household travel surveys collected basic information on how people traveled (number of trips, destination, and mode of transport), whereas new modeling requirements demand additional behavioural information on respondents' travel choices, attitudes and activities, both in-home and out. This demand for higher-quality data has led to the request for additional information, related to the following aspects:

- vehicle features and usage data, which provide valuable information for environmental analysis;
- non-motorized travel, which was not considered in earlier travel surveys but is becoming increasingly important in recent travel surveys. In particular, walking and biking are now included in mode-choice models;
- activities, using activity-based travel diaries. These diaries help researchers to develop activity-based models, which are used to evaluate the correlations between activities that require travel and those that do not;
- time-of-day of travel, which is an important consideration in peak and off-peak travel modelling;
- opinion and attitude, to study respondents' overall attitudes toward a specific subject of interest, or the degree to which respondents agree to statements provided by the researcher;
- stated response/preference. Historically, travel surveys have recorded actual respondent behaviour, or respondents' "revealed preferences." Some recent travel survey efforts have also sought to predict the effects of new policies and travel options for which little revealed preference data are available. These efforts usually rely on exercises that ask respondents to make hypothetical decisions involving multiple attributes or parameters.

(TSM, 2012; Richardson et al., 1995)

1.4 Household travel survey challenges

Although current transport models are generally based on the same concepts as models designed 30 years ago, traffic analysis zones are shrinking, and therefore, derived data must be more precise. Newer models – including simulation models, activity models and tour-based models – require an even higher level of data quality. A current trend in transport demand modeling has been the shift from outcome models to process models – models based on the processes that people use to make decisions, rather than on the choices, or travel outcomes, that they eventually select. (Stopher and Greaves, 2007).

Data collection still focuses heavily on outcomes, but increasing researcher interest in process data has resulted in an increasing burden on the respondent. Effects on responses are similar to those that researchers witness in longer-duration surveys: no response, biases, and unreported or underreported trips.

Researchers must pursue low-burden travel survey tools that still guarantee high-quality data and allow for longer survey periods – a compromise that is difficult to reach. Due to rounding and memory effect, lower-burden travel diaries cannot guarantee the data accuracy that they were designed to capture. Conversely, the data integrity check used with higher-burden interviews often leads to underreporting, especially for short trips and very active, large households (Bricka et al., 2012). Both sets of problems have significant effects upon final survey outcomes, as illustrated in Figure 6.

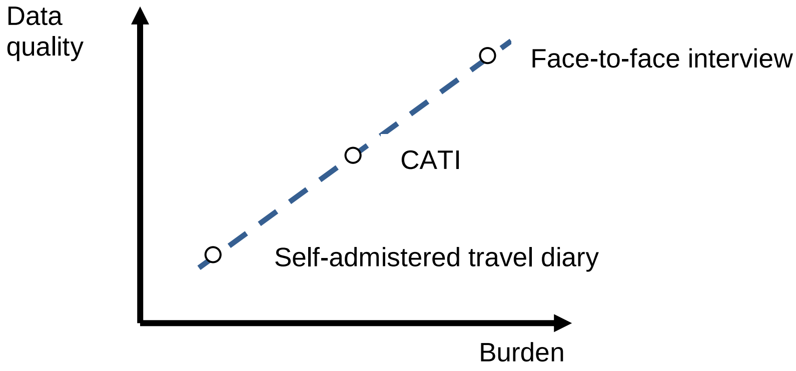


Figure 6 – Relationship between survey tools data quality and burden on respondents

Considering the increasing complexity of travel patterns, it has become necessary to design longer-duration surveys in order to identify daily and weekly travel trends (Schlich and Axhausen, 2003). These longer surveys, however, can lead to survey fatigue and a reduction in the quality of the data obtained throughout the length of the survey.

1.4.1 Sources of survey errors

A survey can be considered successful if the expected sample size is met or exceeded, data quality is as desired, and budgetary limits are not exceeded. These aspects are evaluated and defined during the survey planning stage according to resource limits and researchers' needs.

Accuracy in survey outcomes is affected by two sources of errors – sampling and non-sampling. Sampling errors are related to recruitment methods, while non-sampling errors are related to survey tool design and implementation. Common sampling errors include the following:

- respondent contact: traditional recruitment methods cannot guarantee that a representative sample of potential respondents is contacted for recruitment;
- survey acceptability: In cases where response rates to survey recruitment efforts are low – e.g., when few of the people contacted to participate in a survey actually agree to participate – biases can occur.

Common non-sampling errors include the following:

- item non-response: participants fail to answer one or more survey questions due to burden, fatigue, incorrect survey design, etc.;
- rounding and memory bias: reported data do not match expected results because of respondents' tendency to round times and to forget to report certain short or non-habitual trips.

Sampling and non-sampling errors are further discussed below.

Sampling errors

The magnitude of sampling error can be estimated based on recruitment goals and desired level of accuracy in survey outcomes. Sampling errors can be caused both by problems in reaching a targeted population, and by problems in getting respondents to agree to participate ("survey acceptability"). Both varieties of sampling errors can lead to over- and underrepresentation of certain groups within the targeted population. The effect is that actual survey respondents – among those contacted and asked to participate in a survey, those who actually participate – might be more similar, and have fewer socioeconomic differences, than the remainder of the population, who declined to participate.

Respondent Contact

Recruitment methods vary in their execution costs and ability to reach all groups of a targeted population.

One of the latest recruitment-related issues affects the traditional telephonic method of random digit dialing (RDD) sampling, in which potential respondents are chosen through random selection of landline phone numbers and contacted for recruitment purposes on landline phones. Cell phone usage has grown exponentially in recent decades, whereas many households have moved away from landline phones, and some are using cell phones exclusively. In 2010, the US Department of Health and Human Services estimated that 29,3% of adults in the US lived in a household without a landline phone. Considering that the majority of cell phone numbers are unlisted and therefore unavailable to researchers, it is becoming increasingly difficult to contact large sections of the population through RDD (NCHRP, 2008).

Other recruitment methods include direct (face-to-face) contact and mail requests, which offer more chances for contact with potential respondents. However, the higher costs of face-to-face recruitment and the lower response rates of mail requests are recognized as the main drawbacks of these recruitment methods.

Participation

Problems with survey participation have been documented in all fields that utilize surveys. Recruitment of willing survey participants can be difficult in general, while specific demographic and social groups – such as the elderly or those with lower levels of education – can be particularly hard to recruit. Lower survey participation rates and higher underreporting rates can also be observed in large households or highly-mobile individuals, due to the greater amount of time required to enter the greater amount of travel information that these respondent groups provide. (NCHRP, 2006; Groves, 2006).

Common approaches to tackle the participation problem in the travel survey fields are the use of longitudinal surveys and the use of incentives, as discussed as follows.

Longitudinal surveys: travel surveys are traditionally cross-sectional, meaning that data are collected across a sample over one specific time period. If the same population is to be sampled again, a new sampling phase is required, which incurs further costs and recruitment challenges.

To address this issue, researchers have begun using longitudinal studies – such as panels, the longitudinal study method most commonly-used in transport research – for multi-day surveys (Stopher and Greaves, 2007). A longitudinal study consists of repeated observation of the same set of variables within the same sample, over long periods of time.

Longitudinal studies, such as panels, are not a survey tool but a sampling methodology. When working with a study panel, surveyors select the survey sample at the start of the study and define the sampling rules for future observation. Researchers might choose to replace participants who drop out, or to continue surveying the remaining sample without replacement. Panels can be used to study the behaviour of particular subgroups of the population, and they are often carried out in conjunction with cross-sectional surveys taken from separate, non-overlapping samples. Traditionally, panels have seen wide use in the fields of medicine, health and economics, but their use in the transport field has been limited.

Noted examples of the use of longitudinal surveys in the transport field include the following:

- Puget Sound Transportation Panel, 1989-2002
- Dutch Transport Panel, 1984-1989
- German Mobility Panel, 1994-present

Longitudinal travel studies allow researchers to observe changes in participants' responses or behaviours, increase respondent participation and add additional questions as the study progresses. The possibility of adding new questions allows researchers to study the dynamics of change, thereby enhancing the quality of resultant data. Between-sample variance is eliminated, because the sample stays the same throughout the duration of the study. Sampling and recruitment requirements are substantially lower in a longitudinal study than in a cross-sectional survey. Additionally, panel participants become de-facto trained respondents, they provide more complete data and are more willing to participate than cross-sectional survey participants (Stopher, 2009).

Incentives: researchers occasionally offer monetary or non-monetary incentives to participants. This approach has proven effective in contributing to higher recruitment rates and lower unit non-response, especially in the case of monetary incentives (Singer et al., 1999). Incentives vary in type, and can include cash, vouchers, discounts, merchandise, lottery tickets, etc.

The recruitment benefits gained by offering incentives are not consistent across social groups. A targeted incentive policy should be used in order to focus on those groups whose participation will be most affected by the offering— usually, the population groups which refuse to participate in or complete a survey (NCHRP, 2008). Researchers should note that the use of incentives may not be always necessary in order to obtain a desired sample from a targeted population; furthermore, and larger incentives do not necessarily result in better data (Minser et al., 2012). However, the possibility of paid panels could be explored in future surveys (Stopher and Greaves, 2008).

Non-sampling errors

Unlike with sampling errors, there is no simple and direct method for estimating the impact of non-sampling errors on survey outcomes. Several current studies are examining the varying magnitudes of non-sampling errors associated with different types of survey tools (Zmud and Wolf, 2003; NuStats, 2003; Bricka and Bhat, 2006).

Item non-response

Missing data entries, i.e. forgotten or non-reported trips or omitted trip information, can be remedied through data imputation, or by removing the entry if no reparative action can be taken. Though data imputation can reduce the impact of item non-response, its use should be limited, so that survey results are not biased by the data imputation itself (TSM, 2012).

In addition, data quality checks can overcome item non-response issues by warning researchers or respondents if missing data entries occur during the survey process. This approach can be easily implemented in computer-aided surveys (CATI, CAPI, internet-based) but cannot be included in paper and pencil survey tools (Stopher, 2009).

When properly targeted, incentives have been shown to reduce item non-response and increase participation rates (Tooley, 1996; Minser et al., 2012).

One common cause of item non-response is survey fatigue – the general tendency of respondents to report information less completely as the survey goes on. Item non-response due to survey fatigue has been demonstrated in several multi-day studies (Golob and Meurs, 1986; Murakami et al., 1999; Wolf and Lee, 2009).

Rounding and memory bias

The effects of rounding and memory biases – e.g., misreporting times, distances, addresses or missing trips – are occasionally present in all surveys which require respondents to log their past trips and activities. Certain situations – e.g., shorter trips or trip-based diaries – exhibit higher instances of rounding and memory bias. (Arentze, 2001). In general, respondents tend to round their reported travel times in increments of 5 minutes and distances in kilometer increments (Axhausen et al., 2003; Schüssler and Axhausen, 2009), and they tend to forget to report shorter, incidental trips (Bricka and Bhat, 2006). This rounding bias largely affects accuracy in the reporting of shorter trips.

1.4.2 Facing challenges in travel surveys

Table 3 reports a summary of the challenges researchers face during the travel survey process. Both travel forecast needs and the demand for travel survey data remain high, despite the rising cost of surveys and reductions in resources available to researchers. New generations of forecast models require higher quality data, without which, surveys often achieve unreliable outcomes. (TRB, 1996).

Travel survey stage	Challenges
Planning and design	- Resource constraints - Lower sample size - Collection tool biases
Implementation	- Lower participation rate - Underreporting
Data analysis	- Unmatched data accuracy standards - Missing data

Table 3 – Travel survey challenges by survey stage

Researchers face the challenge of meeting the demand for higher-quality data while simultaneously keeping research costs in check. Measures such as data integrity checks and incentives, currently being implemented in travel survey processes, have helped to reduce underreporting. New approaches must be considered in order to balance researchers' needs for greater data with respondents' need for a lower-burden method of study.

CHAPTER 2 - New opportunities - Passive travel surveys

Some of the drawbacks of traditional travel surveys are structural to the surveys themselves, while others derive from the choice of survey method or choice of survey tools used for data collection. To overcome structural problems related to traditional survey methods, new approaches should be considered.

One of the latest developments in data collection methodologies is the Passive Travel Survey. In passive travel surveys, trip information is derived not solely from respondents, but also from positional data, collected automatically with tools that use location-aware technologies, such as NAVSTAR Global Positioning System (GPS). Researchers can derive travel behaviour from this positional data, which reduces the burden on participants while improving the quality of the gathered information. Having a complete picture of respondents' travel information helps researchers intuit reasons for underreporting, and helps them to identify suitable correction factors to be applied to the main surveys. Several studies using location-aware technology have demonstrated the feasibility of this method. (Wolf et al., 2006; Bricka et al., 2009; Ahas et al., 2011)

Various research studies make use of tracking technology. These can be grouped into a new 'family' of surveys – identified as Passive Travel Surveys. Table 4 reports the updated version of the currently available families of survey tools.

SURVEY TYPE	SURVEY NAME
Personal	Personally Administered Interviews (CAPI) Telephone Interviews (CATI)
Self-Administered	Self-Administered Surveys Distributed to Groups Self-Administered Surveys Distributed by Intercept Methods Computer Assisted Self-Interviewing and Web Surveys (CASI and CAWI) Mail Surveys
Passive	Data Collection with Tracking Technologies

Table 4 – Families of survey tools

The structure of a passive travel survey and the expected quality level of the data depend largely upon the tracking technology used. The choice of a specific tracking technology also affects other survey parameters, such as survey costs, degree of user interaction, survey acceptance, sampling biases, data collection continuity and survey area.

2.1 Tracking technologies

Various tracking technologies are available for use in travel surveys, each of which carries its own advantages and disadvantages, particularly in the fields of data accuracy, continuity, and issues related to user privacy. Currently available tracking technologies with potential for application in travel surveys include the use of satellite-based positioning such as GPS, data from cellular network services using Global System for Mobile Communications standards (GSM), wireless enabled devices with Bluetooth, radio-frequency identification systems such as RFID, video tracking, etc. (Wolf et al., 2006).

Each available technology is addressed below, with overviews of the type of devices used, their output, accuracy and continuity, and of the use of each technology to date.

Global Navigation Satellite Systems (GNSS)

A Global Navigation Satellite System is a satellite-based system, designed to provide users with geo-spatial position information with global coverage. As of 2012, there are two fully-functioning GNSS, GPS and GLONASS, and two under development.

In the last 30 years, travel surveys have benefitted from the use of GPS technology. There is no evidence of the use of other GNSS in travel surveys, neither the recently restored Russian Navigation System GLONASS nor the two navigation systems under development - the European system GALILEO and the Chinese COMPASS.

GPS is currently the most commonly-used positioning technology. Its accuracy and reliance are improving rapidly, guaranteeing an accuracy of approximately 10 to 20 meters, based on trilateration of satellite signals. Technological developments in GPS devices, such as heightened receiver sensitivity and the ability to manage more satellites simultaneously, are increasing the devices' data reliability and accuracy (NCO, 2012).

Data collection continuity and accuracy depends on the ability of the GPS device to receive information from satellites. Common collection problems occur when the device is unable to rely on a suitable number of satellite signals, or when signals are degraded. Both issues are more significant in dense urban areas.

Possible methods for further improving accuracy, reliability and availability of GPS data include augmentation, the use of supplementary information in the calculation process. The most common augmentation methods are the Ground-based Augmentation System (GBAS) and the Satellite Based Augmentation System (SBAS).

Despite having the lowest degree of accuracy among the currently manufactured GPS receivers and devices, commercially-available non-augmented GPS devices achieve a level of accuracy that is acceptable for use in travel surveys (El Esawey et al., 2006). GPS-based augmented devices can mitigate, but are not able to successfully overcome, the common problems related to GPS technology.

Global System for Mobile Communications (GSM)

The GSM positioning system calculates location using signal strengths and known antenna positions of mobile phone service infrastructures. Signal reception from one transmitter is sufficient for deriving a location, even indoors and in urban canyons. Unlike in the use of a GPS, geo-localization using a GSM is unaffected by data collection gaps, but accuracy varies significantly according to antenna density. Position accuracy depends on the number of antennas in the area, the strength of their transmitted signal and the adopted positioning method. Possible positioning methods include:

- network based, in which information is collected passively from the network operator based on the data recorded by antennae;
- handset-based, in which information is recorded by a handset itself, using information from the GSM infrastructure to calculate a position (Drane et al., 1998).

Accuracy can reach 10-50 meters using handset-based positioning and can be as accurate as 75-125 meters with the use of network-based methods. These estimation values are most valid in dense urban areas, degrading consistently in suburban and rural areas and, where errors of up to several kilometers can result. The potential for such errors reduces this technology’s reliability for use in travel surveys (3GPP, 2012).

The drawbacks to using GSM as a travel survey tool include its difficulty in providing precise and continuous respondent locations, and the difficulty of deriving trip information (means of transport, distance, time) from GSM-obtained data (Ahas et al., 2011; Asakura and Hato, 2004).

Wi-Fi

As with GSM, it is possible to use signals and positions from Wi-Fi hotspots to identify a receiver’s location. This method has been tested in indoor environments with an accuracy of 2 to 4 meters, but calibration is necessary to detect the different Wi-Fi access points and their exact positions. For travel survey purposes, with proper calibration, it is possible to reach an accuracy of 13 to 20 meters in dense urban areas, degrading to 40 meters in suburban neighborhoods. Calibration typically consists of searching for the exact position of Wi-Fi networks using a moving vehicle equipped with a GPS device and a Wi-Fi signal receiver (wardriving). As in GSM positioning, results using Wi-Fi are dependent upon the availability and density of access points in the area. To guarantee the highest levels of accuracy, it is necessary to periodically repeat the calibration process. Wi-Fi appears to be a suitable tool for use in travel surveys, due to both the accuracy of the technology and the availability of signals in dense urban areas, both outdoors and indoors. Furthermore, 'time to first position fix' issues do not arise with the use of Wi-Fi. However, accuracy degrades beyond travel survey acceptability standards and coverage is not guaranteed in rural areas (Cheng et al., 2005, Chiou et al., 2009).

Radio Frequency Identification

Radio Frequency Identification (RFID) technology consists of the identification of unique items using radio waves. Identification requires a reader that communicates with an RFID tag holding digital information, which acts as a transponder. Tags can be active or passive. Active tags are battery-powered transponders, capable of transmitting information to the RFID reader through a radio signal. They can be activated by the reader's signal or transmitted at given time intervals. Passive tags, by contrast, receive radio waves from the reader and send information back to the reader. They lack an autonomous power source, and instead derive power from the radio signal from the transmitter. Active tags have a range of up to 100 meters, while the range of passive tags varies from direct contact to a maximum of approximately 2 meters (Weis, 2003).

RFID is able to determine when tags cross a reference point (a reader with a known position). In the transport and logistics fields, this technology is applied in transport fare cards, electronic tooling, baggage tracking in airports, goods monitoring, etc.

RFID can also be used to design a real-time locating system for indoor environments and confined areas using the principles of triangulation. When three or more readers detect an RFID tag, the system estimates the tags' position according to the readers' spatial location (Hahnel et al., 2004). The monitoring area extension depends on the coverage of the reference points (position and signal range).

Bluetooth

Bluetooth is a wireless technology standard designed for data exchange between many different types of devices. Bluetooth applications include automotive devices, consumer electronics, devices for health and wellness, mobile telephony, computers and peripherals, sports and fitness devices, and smart home applications (Bluetooth®, 2012).

A Bluetooth signal can reach up to 100 meters. Coverage depends upon the number and positioning of receivers, determined by surveyors according to location-tracking needs. The use of Bluetooth-enabled devices for tracking has dual advantages: first, such devices are easily available and are in widespread use; second, signals from these devices are simple to identify, as each device has a unique ID.

Positioning methods can utilize either single-sensor monitoring or more accurate triangulation. Single-sensor monitoring is used to evaluate the number, approximate position and dwell-time of locatable Bluetooth-enabled devices that stay within the sensor coverage area (Camacho et al., 2010; Rutherford et al., 2011; Malinovskiy et al., 2001). Positional accuracy can be below one meter and generally lower than 10 meters using triangulation, within signal coverage, depending on the number of available reference points (Genco, 2005).

Inertial navigation system

It is possible to detect the characteristic of movement using motion sensors, such as accelerometers paired with gyroscopes to measure rotation. Such sensors – components of an 'internal navigation system' – are used to determine changes in position, speed and acceleration, without using external references. These systems are often used in vehicle navigation, in cars, ships, aircrafts, submarines and spacecraft. The use of motion and rotation sensors as navigation aids is limited by high implementation costs. Cheaper and less accurate motion sensors are currently used for dead reckoning, which is used to cover gaps in the service of other positioning systems, such as GPS (Quddus and Zheng, 2011).

The use of wearable motion sensors such as accelerometers or low-cost pedometers as activity monitors for survey participants allows researchers to detect motion and estimate trip distance for on-foot movements. Car or truck odometers have also been used as low-cost vehicle distance-recording tools in several past travel survey experiences (Wolf et al., 2006).

Hybrid Positioning Systems

Combined, or hybrid, use of multiple positioning technologies can provide better overall results and can overcome the drawbacks of using each positioning system individually. For example, integrating the more precise location data of GPS in clear sky conditions with the less precise, but continuous, data in dense urban areas provided by GSM and Wi-Fi, is a reliable method for reducing problems in data collection.

The use of accelerometers and motion sensors to collect data through dead reckoning is another solution already in use in the transport field, as a way to overcome signal loss issues.

The use of combined, or hybrid, positioning technologies, with GPS as the primary component, is promising. AGPS devices with motion sensors and Smartphones equipped with multiple positioning systems (AGPS, WiFi, GSM, motion sensors) are currently available commercially. Thanks to technological developments and the decreasing costs of both GPS receivers and data transfers, the use of combined positioning systems can be adapted for use in travel surveys (Wolf, 2004; Wolf and Lee, 2008; Gong et al., 2012).

2.2 Use of location-aware technologies as household travel survey tools

Since the mid 1990s, the travel survey field has benefitted from the use of various location-aware technologies to collect accurate temporal and spatial data, for longer survey periods, in an automatic or semi-automatic manner (Marchal et al., 2008).

All considered technologies are able to provide positional information with sufficient levels of accuracy and continuous recording of data. However, these technologies differ in their implementation costs, which include the costs of the devices themselves, as well as of positioning services and infrastructure. Table 5 summarizes the previously mentioned location-aware technologies, ordered by service coverage. Implementation costs of each technology depend on the system components required in order to guarantee the expected data standards.

The use of passive survey tools in household and personal travel surveys depends on their ability to easily provide data at the desired collection frequency with the largest possible coverage. For this reason, tracking household and individual travel behaviour with infrastructure-dependent technologies, such as RFID and Bluetooth, results in very high implementation costs. Such technologies will continue to be successfully employed at control-point and screen-line level in transport-related studies.

Household travel surveys using passive data collection tools mostly employ GPS and GSM, due to their lower implementation costs and data collection characteristics. These technologies allow transport researchers to collect data that are semantically simple – such as tracks, stops and locations-in-time – and to convert them into valuable information through post-processing.

Absolute, non-geo-referenced positioning sensors are mostly used in combination with GPS to detect movement, or when satellite signals are not available.

From the data collection point of view, positioning technologies fall into two categories – those in which users are aware of the tracking, and those in which they aren't. Transport researchers are currently studying both approaches, to assess their appropriateness for use in travel surveys. GSM is generally used for user-unaware tracing on large samples of population, while GPS is used more often for user-aware personal or vehicle tracking.

Location-aware technology	Implementation needs	Coverage
Geo-referenced global positioning service		
GNSS (GPS, GLONASS, GALILEO)	Receiver	Global
Geo-referenced positioning using 3rd party infrastructure		
GSM	Receiver	Regional
Wi-Fi	Receiver Data transfer	Urban/Local
Geo-referenced positioning using own infrastructure		
RFID	Receiver/Transmitter Infrastructure	Infrastructure-dependent
Bluetooth	Receiver/Transmitter Infrastructure	Infrastructure-dependent
Non-geo-referenced positioning		
Inertial navigation system	High precision motion and rotation sensors	N/A
Motion sensors	Device	N/A

Table 5 – Comparison of location-aware technologies for continuous location recording

2.2.1 Anonymous GSM network-based travel surveys

Mobile network data refers to information that comes from the operation of a mobile network, typically a GSM operator. The pervasive availability of GSM services makes GSM a good choice for enhancing or supporting traditional data collection techniques. This technology can be a source of information by itself, because it provides additional information (socio-economic, cell-phone use, transactions) related to the data stored by the mobile data carrier.

The main available information that mobile operators can provide includes:

- cell-phone contract information;
- transaction information;
- history of the activity of handsets;
- location information.

Several past travel surveys have used GSM as a data collection tool (Asakura and Kato, 2004; Ahas et al., 2011; Bekhor et al., 2011). These experiences showed the potential, as well as the drawbacks, of passively-collected positional data. GSM applications can provide researchers with a considerable amount of passively-collected positional data, useful for generating an overview of travel demand for traffic planning purposes, and thereby overcoming many of the problems related to traditional traffic data collection methods.

Using log files provided by the service operator, it is possible to generate OD matrixes. Passive mobile positioning log files consist of the following elements:

- customer ID, usually in anonymous form, for privacy reasons;
- time stamp;
- positional information, such as location of the antennae, angle of the received signal, and distance from transmitter.

Customers' basic demographic information (year of birth, gender, etc.) can be matched to their customer IDs, but the amount of information desired, along with the frequency of data collection, needs to be specified with the mobile service provider.

The frequency of data collection varies according to arrangements made between providers and researchers. It is based on the following factors:

- mobile service event: location is recorded during a mobile provider service request (i.e. a phone call, SMS, or UMTS data transfer) (Ahas et al., 2011);
- fixed time: location is recorded at certain time intervals or specific hours of the day (Beckhor et al., 2011);
- antennae-based positioning: locations are recorded once a handset locks in on a specific antenna.

Localization methods vary according to the number of GSM towers used for a positional estimate. The easiest way to determine the location of a handset is to use the position and transmitting power of the cell phone's antenna to access the operator's services. The locked antenna is not necessarily the antenna that is located closest to the handset (Asakura and Kato, 2004; Ahas et al., 2007).Using information from the signals from multiple antennae provides more accurate positioning – as accurate as 10-50 meters in urban areas.

Advantages

The use of mobile network data helps researchers to calibrate and supplement other means of data collection when raw data is initially unavailable. Using mobile network data in mobile applications allows researchers to observe the mobility patterns of large samples, generating large datasets of positional information. For example, one Estonian activity survey used mobile network data to study 500.000 participants (Ahas et al., 2011). Operators can estimate position of all cell phones and devices that can access the mobile network services. Temporal studies – i.e., traffic or migration studies – can also benefit from mobile network data, as it is possible to track a cell phone for durations ranging from one day to a year or more. The flexible time scale of data collection can provide a transport system overview, which can help researchers evaluate the impact of events (accidents, congestions) on travel patterns or manage historic data for transport planning purposes (Ahas et al., 2007).

Once positional data are collected, it is possible to identify significant waypoints (workplace, home, etc.), track trajectories, and study travel habits and repeat visits to certain locations, using location and time stamp information. In addition to the traditional OD matrix, which focuses on travel behaviour and locations visited, other aspects can be monitored. Examples include the following:

- tourist tracking: detecting the presence and length-of-stay of foreign mobile phone plans in the area of study (Ahas et al., 2008; Asakura and Iryo, 2007);
- chronotyping: profiling participants' hours of activity based on hours of cell phone usage (Ahas et al., 2007; Bekhor, 2011).

Being a passive survey tool, network-based GSM logs are not affected by a memory effect, and they pose no burden to the study participant. Unlike other traditional and even passive travel surveys, network-based GSM logs themselves do not cause any changes in respondents' travel behaviours.

Drawbacks

Drawbacks to the use of network-based passive location tracking include variances in accuracy, costs and privacy limitations associated with the use of carrier databases, unreliability of positional records, problems associated with short trips, and gaps in data caused by non-continuous reporting of location.

The accuracy of GSM network-based passive location tracking varies with antenna density, and is consequentially higher in urban areas and lower in rural zones. According to EU regulations, passively-collected data must be reported with an accuracy of not less than 500 meters in urban areas and not less than 5 kilometers in rural zones, regardless of the accuracy of the raw, uncorrected data.

Network data are owned and managed by third-party GSM operators, which require fees for the use of their databases. Additionally, not all operators are willing to share their network data. Respondents' data are generally provided in anonymous form, for privacy reasons and due to legal agreements between carriers and customers. Basic demographic data, such as age and gender, can be linked to each user ID.

Privacy regulations, which vary from country to country, occasionally limit researchers' access to passively-collected, network-based data. Furthermore, data obtained from different mobile networks operators, handsets and app providers can be fragmented. Despite these drawbacks, the use of mobile network-obtained data remains an attractive opportunity, as it provides the greatest penetration among potential respondents, compared to all other means of data collection. It is important to note, however, that penetration is not homogeneous across all users.

Positional records obtained through this type of location tracking can be unreliable, as they are affected when handsets suddenly switch the antenna upon which they are locked. This phenomenon is more prevalent in urban areas and with higher collection frequencies, due to higher antenna density.

The use of GSM in trips of shorter distances results in incorrect trip recording, due to more frequent antenna changes and low locational accuracy. A recent long-distance survey carried out by Technion estimated that the minimum trip distance for which GSM network-based logs could be effectively used is 2,5 km (Bekhor, 2011).

Finally, GSM network-based data cannot provide real-time tracking with frequencies comparable to other location-aware technologies, such as GPS. Network-based location data is non-continuous, which can cause gaps in activity records. Despite this potential for data gaps, network-based location data can still be used to study general trends in travel behaviour.

2.2.2 Personal and vehicle GPS-based travel surveys

GPS-based travel surveys represent a new field in transportation behaviour studies and are being used by researchers with increasing frequency. The evolution of GPS travel surveys as a research tool was made possible by advances in GPS technology and post-processing methods, which have enabled researchers to derive detailed trip information from raw GPS data.

GPS devices provide highly accurate positional information, with a frequency of location data collection that can be as high as one record per second. Standard recorded information includes the following:

- temporal information, such as time and date of the collected position;
- positional information, expressed in latitude, longitude and altitude.

Optional recorded information can include the following:

- navigational information, such as speed and heading;
- quality indicators of the temporal and spatial estimations.

Travel behaviour information is not provided by raw GPS data and instead must be derived through post-processing.

GPS positioning methods, instrumental errors and technology implementation in household and personal travel surveys will be extensively discussed in Chapter 3.

Advantages

More than 25 years of GPS-based travel surveys have yielded data that is richer and more accurate than data collected in traditional travel surveys. Trip information such as origin destination, time, distance and route choice is not affected by rounding or memory effect when collected by GPS, which results in higher trip reporting (Stopher, 2009).

The use of GPS as a data collection tool for travel surveys allows surveyors to maintain the current survey structure while augmenting current collection tools with richer data. GPS-based surveys are currently seeing wide use in a supporting role, carried out in conjunction with traditional travel surveys They are commonly used to evaluate results, discern reasons for underreporting, and observe travel behaviours of particular groups of transport users. The most recent, up-and-coming application of GPS is in stand-alone GPS travel surveys (Giaimo et al., 2010; Wargelin et al., 2012; DfT, 2012).

Drawbacks

Although GPS-based travel surveys have many advantages, some problems related to the technology itself have yet to be solved. GPS devices occasionally collect invalid data or fail to record data, due to issues including time to first fix (cold/warm start), lost or poor signal (poor satellite coverage, dense urban areas, signal degradation for multipath effects) and participants' handling errors (forgotten devices, turned off devices). Recruitment rates for GPS-based surveys are no higher than those for traditional surveys. Technology-related issues should also be considered (privacy issues, technology acceptance and willingness to participate of some population groups, etc.) (Bricka, 2008, Marchal et al., 2008, Stopher and Greaves, 2008). There is also a need for method standardization among GPS-based surveys, in all aspects of the research – from data collection and data quality standards to data post-processing tools.

Additional testing of GPS travel surveys is necessary, to discern whether they can serve as effective stand-alone survey methods with limited user interaction, capable of completely replacing traditional survey methods (DfT, 2012).

2.3 Facing challenges in the use of passive travel surveys

Transport researchers are currently exerting great effort in the development of both small-scale and large-scale passive household and personal travel surveys. Most current surveys of this type utilize GPS and GSM technologies. Data collection and interpretation tools are constantly being revised, and the recent interest in the post-processing of tracking data is resulting in richer, more complex, meaningful and usable information.

GSM network-derived data provides anonymous positional information at a low frequency, which results in a need for extra information – i.e., traffic zone data, traffic counts data, transport networks — in order to calibrate results. Although traffic planners are not always interested in precise OD locations or accurate route reconstruction, locations can be provided at levels of accuracy as specific as traffic zones. This technology is therefore appropriate for the large-scale study of transport systems and long-distance travel patterns, while it becomes increasingly unreliable as the survey scale becomes smaller (i.e., urban infrastructures and related traffic counts).

GSM network-based applications also provide data that is useful for detecting congestion volumes, time, location and other spatial and temporal characteristics of randomly sampled GSM users. Trajectories can be derived through map-matching and route estimation to find the route that connects all the GSM footprints, even if inaccuracy in recorded positions can result in derivation errors. Additional information is generally required in order to derive trip mode, due to the low-interval frequency of data recording and uncertainly of position.

Studies utilizing mobile network data must consider the following aspects:

- provider selection: not all operators are willing to share their data. Costs for access to providers' and provided data quality vary. the population representativeness of phone providers also needs to be taken into account;
- cell-phone use and ownership: a single telephonic device is not necessarily carried by the same person at all times, and conversely, a single person can carry multiple cell-phones;
- privacy concerns: network users are not aware that they are being studied, and data must be provided in anonymous form.

Today, due to the low market share of currently-available handsets with easily-implemented tracking applications, more accurate and continuous GSM handset-based data is not readily available. However, the continued widespread diffusion of new generation cell-phones, such as Smartphones, will augment handset-derived GSM data in the future, as Smartphones are continuously connected to the mobile network and thus provide continuous and more accurate data detection. It is also possible to design applications on the phones themselves which can collect data automatically (Wolf et al., 2006).

GPS and GPS-equipped devices are able to collect accurate positional and navigation data with a higher recording frequency. Despite the structural limitation against providing high-quality data in densely built urban areas, GPS-equipped devices generally provide the best possible service coverage compared to other location-aware technologies. However, they are also generally characterized by privacy and technology-divide issues.

Despite these drawbacks, the use of GPS-based travel surveys is currently the best compromise between accuracy and implementation within traditional travel survey frameworks. An in-depth observation of the potential and drawbacks of the use of GPS devices in household and personal travel surveys will follow in the next chapter.

Location-aware technologies are well-adapted for use as data collection tools, as they allow researchers a degree of control over the data collection process, and because they rely upon geographically widespread services and infrastructures. However, these technologies still pose problems in recruitment and acceptability – even when using applications for "self-reported" data (Marchal et al., 2008). The use of unconventional and unstructured data sources such as social networks and search engine databases is being considered for future research (Grignolon et al., 2011; Arentze et al., 2012).

Table 6 summarizes the advantages and drawbacks of the implementation of these previously-discussed technologies in travel surveys.

	Anonymous GSM tracking	**GPS individual/vehicle tracking**
Advantages	- Recruitment of large samples - Respondents are unaware of being surveyed - No respondent fatigue (longer surveys) - Lack of memory and rounding effects observed using traditional survey methods - Collected data can provide an overview of the transport systems	- Highly accurate spatial, temporal and navigation data - Widely implemented in household and personal travel surveys - Easy to implement in traditional survey framework - Lack of memory and rounding effects observed using traditional survey methods - High frequency (starting from second-by-second) positional recording interval
Drawbacks	- Tracking costs (data must be collected by cell-phone operators) - Low-quality user personal information (only basic demographic information) - Variable position quality standards (good in urban areas, very poor in rural areas) - Non-continuous positional recording (event-based or at low frequency recording intervals) - Unreliable for short trips	- Possible positional data gaps (e.g. cold start, signal loss, misuse, etc.) - Privacy issues - Technology acceptance/divide - Lack of standardization in data collection and processing

Table 6 – Advantages and drawbacks of GSM and GPS in travel survey

CHAPTER 3 - GPS-based household and personal travel surveys

GPS is a mature passive travel survey tool commonly employed in the travel survey field. Problems that plagued early GPS-based travel surveys – related to device costs, data storage, weight, power supply and portability – have largely been overcome. Through advancements in product design and improvements in post-processing algorithms and GIS implementation, participant interaction with surveyors has been significantly reduced. Survey results reveal the great potential and the structural biases of the survey tool. These characteristics will be analysed in the following paragraphs.

In particular, chapter 3 outlines the principles of the GPS system, describes the process of travel information derivation using raw GPS data, and evaluates the implementation of GPS in the travel survey field.

Figure 7 shows the adopted analysis framework.

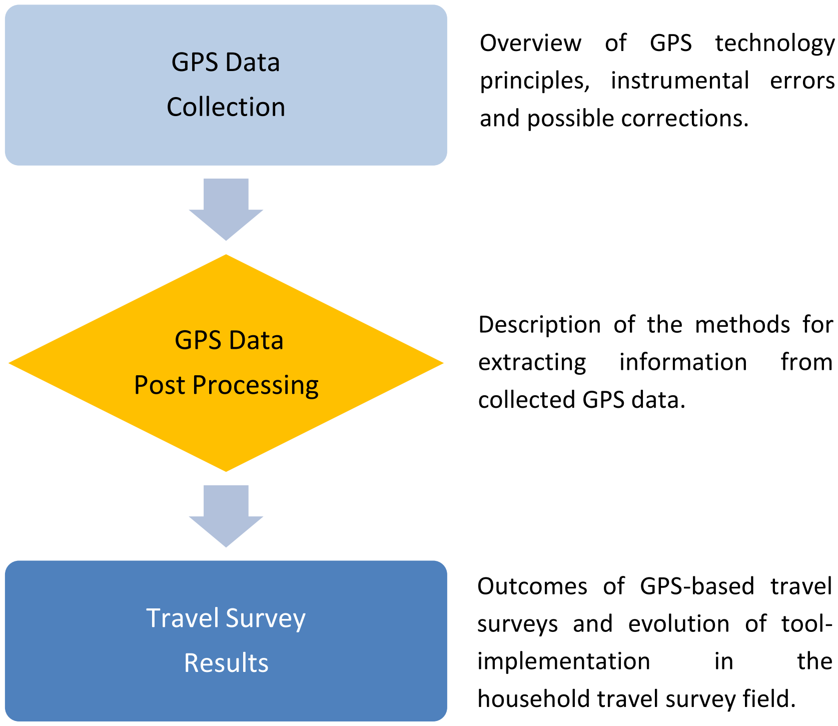


Figure 7 – GPS household travel survey process and chapter structure

3.1 GPS as a data collection tool

The Navigation Satellite Timing and Ranging Global Positioning System (NAVSTAR-GPS), developed and operated by the U.S. Department of Defense, is currently the most-used satellite-based navigation system. GPS is used to provide accurate positioning, navigation and timing services on a worldwide scale through the use of satellite signals, which are available at no cost, with a GPS/GNSS receiver (Parkinson, 1996 ; NRC, 1996).

The system consists of three segments: a space segment, a control segment, and a user segment. A more in-depth explanation of the system components is available in ANNEX 1.

Space Segment

The GPS space segment consists of a constellation of 27 operational satellites transmitting radio signals. This setting is designed to ensure the view of at least four satellites, more often six to eight (Barzaghi, 2004), at any time from any point of the planet. A representation of GPS constellation is provided in Figure 8.

Figure 8 – GPS space segment

Each satellite currently broadcasts two carrier signals, one for military (L2) and one for civilian purposes (L1). The signal carries information on the broadcasting satellite, signal starting time, orbital position of all satellites, and correction factors.

Control Segment

A global network of ground facilities monitors the functionality of the GPS satellite constellation. This ground control segment is designed to perform analyses and send commands and data to the GPS space segment. Currently, the control segment consists of several stations and antennae installed throughout the world, covering different latitudes and longitudes (GPS.gov, 2012).

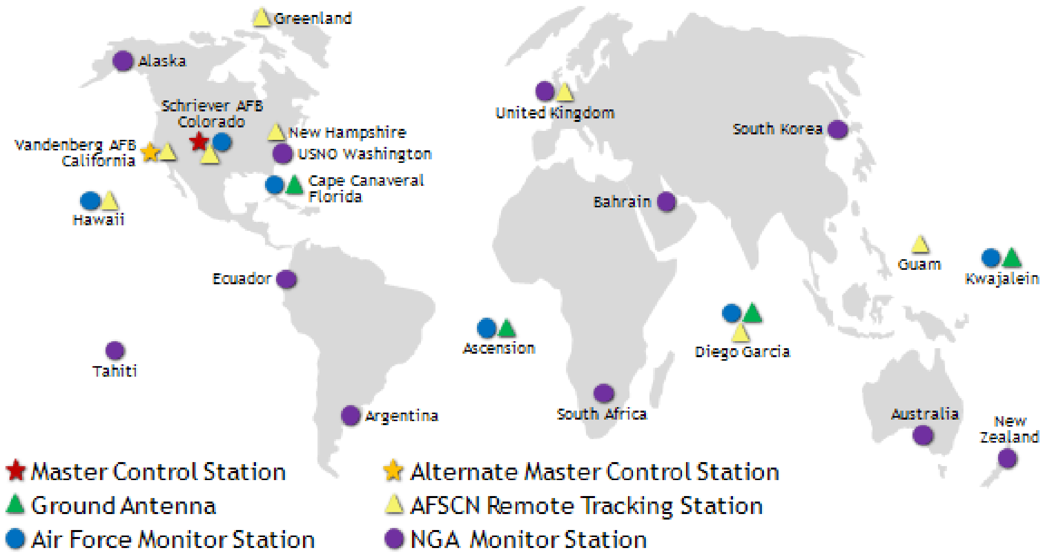


Figure 9 – GPS ground segment (GPS.gov, 2012)

User Segment

The GPS user segment consists of the specific radio receiver/processors and antennae, such as GPS/GNSS devices, which receive GPS signals and thus allow users to access the GPS positioning services. Besides specific GPS receivers, several personal products, such as cell-phones, watches and computers, embed GPS and GNSS capabilities.

Various manufacturers provide a multitude of GPS device solutions. Devices differ in receiver sensitivity, number of satellite/device signal correlators – referred to as channels – and the time necessary for the first positional estimation, referred as 'time to first fix', depending on the device's ability to predict satellite positions after being switched on (cold, warm and hot start).

Size, weight and battery life vary among GPS devices. Storage capacity is another important feature of the receivers, specifically for tracking applications (Gps.gov, 2012; Navipedia.net, 2012).

3.1.1 Positioning methods

A GPS device allows users to determine their position (the position of the receiver) on Earth using GPS satellite signals. It is possible to determine the distance of the satellites in sight by measuring the time necessary for satellite signals to reach the receiver. Satellite signals travel at light speed (300,000,000 meters per second in a vacuum) and carry certain pieces of information, including the exact position of the satellite position and the time at which the signal started. Navigation messages include positional data of each satellite in orbit (ephemeris) as well as information about the time and status of the entire GPS satellite constellation (almanac).

The satellite-receiver distance is expressed by the relationship in Equation 2.1:

$$\boldsymbol{D} = \Delta \boldsymbol{t} * \boldsymbol{c}$$ **Equation 2.1**

Where:

$\Delta \boldsymbol{t}$ is the signal propagation time;
$\boldsymbol{c}$ is the speed of light.

All possible positions from the satellites lay on the surface of a sphere whose radius corresponds to the calculated distance. The equation of such sphere can be expressed by Equation 2.2:

$$\boldsymbol{D} = \sqrt{(\boldsymbol{X} - \boldsymbol{X_0})^2 + (\boldsymbol{Y} - \boldsymbol{Y_0})^2 + (\boldsymbol{Z} - \boldsymbol{Z_0})^2}$$ **Equation 2.2**

Where:

$\boldsymbol{X_0}, \boldsymbol{Y_0}, \boldsymbol{Z_0}$ are the satellites coordinates (known);
$\boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{Z}$ are the receiver's coordinates (unknown);
$\boldsymbol{D}$ is the distance from the satellite (measured).

Therefore, it is possible to determine a position in space knowing the distance of three satellites. The receiver's position is the point where three spheres intersect. Each one of the spheres has its center in the satellite position, and radius is the measured distance from the satellite to the receiver. This relationship is defined by the following system of equations (Equation 2.3):

$$\begin{cases} \boldsymbol{D_1} = \sqrt{(\boldsymbol{X}-\boldsymbol{X_1})^2 + (\boldsymbol{Y}-\boldsymbol{Y_1})^2 + (\boldsymbol{Z}-\boldsymbol{Z_1})^2} \\ \boldsymbol{D_2} = \sqrt{(\boldsymbol{X}-\boldsymbol{X_2})^2 + (\boldsymbol{Y}-\boldsymbol{Y_2})^2 + (\boldsymbol{Z}-\boldsymbol{Z_2})^2} \\ \boldsymbol{D_3} = \sqrt{(\boldsymbol{X}-\boldsymbol{X_3})^2 + (\boldsymbol{Y}-\boldsymbol{Y_3})^2 + (\boldsymbol{Z}-\boldsymbol{Z_3})^2} \end{cases}$$

Equation 2.3

Where:
$\boldsymbol{X_i}, \boldsymbol{Y_i}, \boldsymbol{Z_i}$ are the satellites coordinates (known);
$\boldsymbol{X}, \boldsymbol{Y}, \boldsymbol{Z}$ are the receiver's coordinates (unknown);
$\boldsymbol{D_i}$ is the distance from the satellite (measured);
with $\mathbf{i}$ from 1 to 3.

This assumption is only applicable if the clocks of the satellite and receiver are synchronized. Satellites use onboard, synchronized atomic clocks, while GPS receivers commonly use considerably less accurate clocks. A synchronization error of just 1µs results in a distance estimation error of 300 metres. To prevent this error, a time correction factor, between the space segment and the receiver, must be collected from a satellite signal. Variables the device must determine are four:

- longitude;
- latitude;
- height;
- time.

Computing four variables requires the solution of a system of at least four equations. The variables are derived from the signals of four different satellites. For this reason, the GPS constellation is designed to provide at least four visible satellites at any time from any point on Earth.

Position estimation for civilian users can be determined with an accuracy better than 10 meters, under typical conditions with receivers from any manufacturer. Factors that contribute to this positional measure are described in the following paragraphs (FAA, 2008).

Additional data obtained can include information on speed and navigation. Both are estimated using the Doppler Effect principle applied to the frequency change of the satellite signals received, as measured by GPS devices. This estimation adds data on the following two characteristics:

- instant speed;
- instant bearing, expressed as the measured angle between the current direction and north.

The GPS receiver can provide the user with a positional and time-data quality indicator based on satellite position. The values and meaning of this measure, referred to as dilution of precision (DOP), will be discussed in the following paragraph.

Positional and navigation information that can be obtained using GPS, relying on the satellite signals observed by the receiver, are summarized in Figure 10.

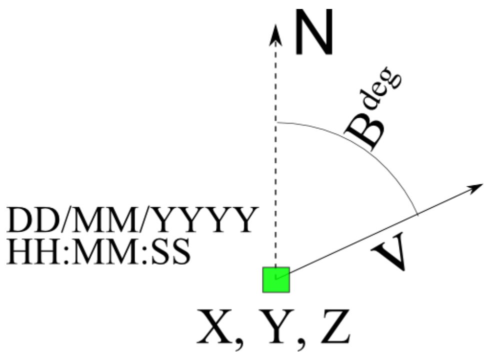


Figure 10 – GPS location and navigation information

3.1.2 GPS measurement errors

Various measurement errors can occur in the use of GPS. A device's positional accuracy is derived from the sum of all its measurement errors. The most common measurement errors fall into two categories: instrumental and systematic. Additional potential degradation of measurement accuracy can be attributed to the GPS system operator (US Department of Defence) or local interferences.

Instrumental errors

Despite using satellite signals to determine the time synchronization factor necessary to guarantee expected accuracy, GPS receivers still result in time synchronization and rounding errors that can be estimated in 1-2% of the wavelength of the satellite signal. The civilian signal, broadcast with a wavelength of 300 m, carries a positioning error of about 3 meters for a standard receiver.

System Biases

Several systematic biases can occur with use of GPS. These include orbital, atmospheric, observational and satellite geometry errors.

Orbital errors

Correct positioning requires accurate knowledge of the satellite position. Satellite positions are estimated by the control stations and are contained in the GPS signal. Estimation error can degrade real time navigation by 2 meters. The use of supplementary sources, such as DGPS or real-time satellite orbit correction services, reduces the error to 1 meter. Using more precise satellite positioning (e.g. IGS Final Orbits) in post processing eliminates the satellite positioning error, but it is not available for real-time use.

Atmospheric biases

GPS signals travelling to Earth are subjected to signal refraction and reduced propagation speed when reaching the ionosphere and troposphere, respectively. This prevents the signal from reaching the receiver following a direct straight line with constant speed (speed of light), resulting in ranging errors that could degrade positioning by 5 meters.

Signals with different wavelengths are affected in different ways (speed reduction is inversely proportionate to the square of the signal frequency). Using dual-frequency GPS receivers (using L1 and L2 carriers) virtually eliminates refraction, resulting in an error of 0.5 meters. Single frequency receivers can still rely on differential correction to reduce refraction errors.

Observation errors

Receivers can receive reflected or bounced signals due to the interference of surrounding obstacles (e.g. buildings, foliage, water sheds, metal structures, etc.). This phenomenon, known as multipath effect, adds supplementary noise to the signal and causes ranging errors that can result in additional positioning errors of 1 – 2 meters. If the resulting noise is too high, a satellite signal cannot be used by the receiver for positioning. To prevent multipath effect, it is necessary to screen the receiver from reflected signals.

Satellite Geometry Errors

Proper positioning on Earth depends on the strength and availability of a signal, and also on the distribution of the satellites in sight. Suboptimal satellite geometric configuration, deriving from alignment or dense concentration of satellites, can result in poor positional estimation or total failure to determine the receiver's location, even when a sufficient number of satellites is present. Geometric error is measured using the Dilution of Precision, which determines the multiplying factor of positional uncertainty (expressed by standard deviation) as shown in equation 2.4. DOP values should be as small as possible. In fact, in the case of a DOP of 1, the satellites' geometrical configuration does not have any effect on the receiver's location accuracy.

$$\boldsymbol{\sigma = DOP\ \sigma_0}$$ **Equation 2.4**

Where:
$\boldsymbol{\sigma_0}$ is the signal-based standard deviation;
$\boldsymbol{DOP}$ is the dilution of precision value;
$\boldsymbol{\sigma}$ is the resulting standard deviation.

DOPs can be separated into Global (GDOP), Horizontal (HDOP), Vertical (VDOP), and Time (TDOP) components.

External Error Sources

In addition to systematic and instrumental biases, other external factors can affect proper positional estimation by degrading or preventing position estimation.

Denial of accuracy

Denial of accuracy refers to the act of intentionally degrading GPS navigation signals, thereby increasing navigation errors. This degradation of positional accuracy can be performed at a system level by the U.S. Department of Defence (DOD), or locally, by interfering with the original satellite signal.

Selective Availability: Selective Availability (SA) was an intentional degradation of public GPS signals implemented by US DOD for national security reasons. Errors were intentionally added to the satellite clock and the constellation positional information, resulting in a degradation of the typical positioning accuracy of standard receivers to 100 meters. The U.S government discontinued the use of Selective Availability in 2000 (Clinton, 2000) in order to make GPS more responsive to civil and commercial users worldwide. It has not stated any intent to use Selective Availability again. In September 2007, The U.S. government announced its decision to manufacture the next generations of GPS satellites, known as GPS III, without the SA feature, in order to make the 2000 policy decision permanent. This decision eliminated a source of uncertainty in GPS performance that had been of concern to civil GPS users worldwide (DOD, 2008).

Spoofing: A GPS spoofing attack consists of the creation of fake GPS signals, structured to resemble a set of normal GPS signals and broadcast to cover and substitute the original signal the receiver reads. The structure of these deceived (spoofed) signals causes the receiver to determine an incorrect position, as desired by the attacker.

Denial signals

Low-cost, specially-designed radio frequency transmitters (jammers), and interferences from satellite-based or earth-based services that broadcast at radio frequencies in the same range of GPS signals, have the potential to degrade or cancel the GPS signals in some areas. To date there is no evidence of large-scale use of GPS jammers. Instances of conflicts between GPS service and other satellite services are currently being investigated. Such conflicts have the potential to cause unintentional local system disruption.

3.1.2 Correction of GPS measurement errors

Positional data estimation can be improved through local or regional augmentation, using supplementary information in the calculation process. The most common augmentation methods are the Ground-based Augmentation System (GBAS) and the Satellite-based Augmentation System (SBAS).

GBAS, such as differential GPS (DGPS), uses correction data transmitted to devices from well-surveyed ground reference stations, improving GPS results to an accuracy of approximately 5 meters, degrading as the ground points increase in distance from the device. Correction can be performed in real-time with devices capable of receiving the ground station's correction via radio signal, or through post-processing after data acquisition.

SBAS is a system provided in specific areas like WAAS in North America and EGNOS in Europe. It can guarantee an accuracy of approximately 3 meters, relying on ground correction information directly sent by dedicated satellites to the enabled receivers. There are no additional costs beyond the purchase cost of the device, making SBAS a cost-effective potential solution for travel survey use. In recent years, even some low-cost units have begun to include SBAS.

Additional augmentation can be provided with the use of Assisted GPS (AGPS), a GPS augmentation method which provides precise time and satellite information to the device using data available from a cellular network. This process consistently reduces 'time to first fix' and improves positional accuracy by providing correction parameters to the GPS devices.

3.1.3 Future system developments

The NAVSTAR GPS system continues to be improved, gradually guaranteeing better performance for both military and civilian uses.

The US government is currently funding GPS modernization programs and is adding three new signals (L2C, L5, and L1C) specifically designed for civilian use. The new signals will improve GPS positioning accuracy to sub-centimeter levels (using dual-frequency receivers and differential correction), provide navigation services for transportation needs (e.g. aircraft navigation), and improve interoperability with other positioning systems (e,g, EU Glonass, Galileo, Compass).

In addition to the current GPS constellation, the future GNSS system constellation will consist of the following global navigation systems:

- GLONASS, operated by the Russian Aerospace Defence Forces;
- GALILEO, under development by the European Space Agency;
- COMPASS, or BeiDou Navigation System, currently operating locally and under development by the China Space Administration.

The rapid development of existing and future navigation systems will guarantee better GNSS service across the board. Future GNSS receivers will receive signals from more than 100 satellites orbiting in medium Earth orbit, as shown in Table 7. This will result in dramatic improvements in coverage and accuracy.

GNSS	Number of Satellites
NAVSTAR GPS	31
GLONASS	24
GALILEO	30
COMPASS	30
TOTAL	115

Table 7 – GNSS expected number of satellites

3.1.4 Issues in the use of GPS in household travel surveys

Travel survey researchers need accurate temporal and spatial data on survey respondents' movements, in order to support or substitute traditional survey tools with GPS.

In particular, surveyors look for data regarding:

- trip beginnings and endings (locations, times, etc.);
- trip information (length, speed, etc.);
- route;
- stops.

Several common problems arise in the use of a GPS-based tracking system in a travel survey. The most common data collection issues are described as follows:

Cold/Warm start: Delays in initial position determination by the GPS device result in delays in the start of tracking, which cause a loss of data on the initial parts of trips. This problem is particularly common in areas with low satellite availability, e.g. urban areas. If this problem is not fully addressed, with the use of AGPS or location augmentation (Wi-Fi. GSM, etc.), it could result in several minutes of lost tracks and a consequential loss of precise departure time information. Despite having the lowest degree of accuracy, currently available non-augmented GPS devices have been shown to be accurate enough for use in travel surveys. GPS-based augmented devices mitigate, but are not able to successfully overcome, the common problems related to GPS technology (cold/warm start, urban canyon and multipath effects).

Urban canyons: Positional accuracy depends on several factors, as previously mentioned. Observation and satellite positioning errors occur most often in densely-built areas, resulting in erroneous or unreliable positioning, and even signal loss. Possible solutions could include the use of Wi-Fi or GSM augmentation, widely available in urban areas.

Tunnels and Metro lines: The lack of signal in tunnels and underground environments prevents any kind of tracking there. In these situations, actual paths can be imputed using road, train or underground network information. Another solution is the use of a paired inertial navigation system, such as an accelerometer, which allows researchers to observe movement when a GPS signal is lost.

Non-stationary receiver: GPS devices are deployed to respondents to track their movements. A non-stationary device adds an additional error to the positional estimation, in proportion to the speed and acceleration of the device itself. On the other hand, multipath errors are mitigated because the antenna more successfully distinguishes the stable direct satellite signals from the quickly changing reflected signals.

3.2 GPS data post-processing

The successful use of GPS devices or GPS-equipped devices in large-scale travel surveys largely depends on the use of proper post-processing methods. Post-processing includes all the steps necessary to derive travel behaviour information from raw GPS data. Starting from positional information provided by a data stream of single points, researchers can derive additional information, as demonstrated in Figure 11.

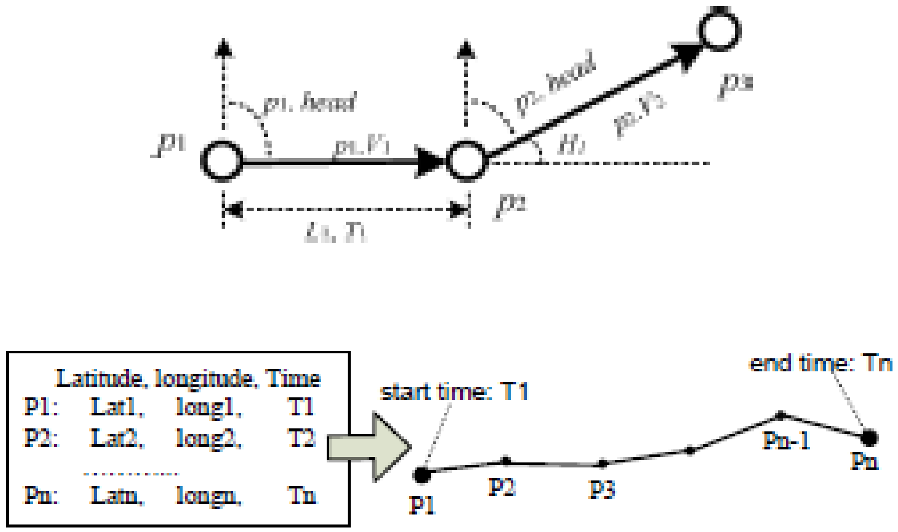


Figure 11 – GPS outcomes, feature calculations and basic trip information (Zheng et al, 2008b)

The final outcome is to generate a more detailed picture of a trip than can be recorded by a traditional survey tool. Post-processing is a crucial step for GPS-based travel surveys, affecting data quality, survey results and overall burden on participants. In fact, increasingly accurate trip information identification algorithms have allowed for a decreased reliance on travel diaries. The basic travel information that can be derived from post-processing includes:

- trip-chain: the identification of different trips and stages of trips depends on the type of survey (fleet or personal survey) and on variable definitions of trips and subdivisions of trips;
- mode of transport: research has consistently proven the possibility to successfully derive mode of transport from raw GPS data;
- purpose: the derivation of purpose still represents the biggest challenge for researchers, due to its complexity and the need for external information.

Once raw data are available, post-processing consists of several phases:

- data filtering, to clean the data from systematic and random errors;
- trip information identification, to derive from the raw GPS data the necessary travel parameters, such as origins, destinations, transport modes, etc.;
- estimation and fix of missing data, to check data integrity and correct possible identification errors;
- validation, to ask respondents for a feedback on the outcomes of the post-processing phase.

The post-processing phase can rely solely on raw GPS data or use a combination of GPS and GIS layers. The choice usually depends on the availability of supplementary data on transport networks and land-use. Supplementary data augmentation occurs during trip information identification and fix of missing data. Validation can benefit from the use of supplementary data such as cartographic layers, to help survey participants understand survey results, and to allow them to report possible missing or erroneous trips and/or stops to surveyors.

Post-processing design depends on data collection frequency and data continuity; availability of external data sources, such as land use and transport network layers; and the use of various sensors and technologies to overcome possible GPS technological problems. Each of these factors is considered when designing the steps of the post-processing phase.

3.2.1 Data filtering

Systematic and random errors are excluded from datasets, in order to guarantee better identification results. One preliminary cleaning step erases data with low quality indicators (HDOP and satellite number). Once this initial screening is complete, data smoothing corrects the points that have acceleration and speed values not compatible with neighbouring points, even if they had been considered valid during the cleaning phase. Smoothing can consider both speed and positional information, depending on the researchers' needs. Providing high-quality data as an input to the trip information identification algorithm enhances the chances of successful trip information identification, and will result a lower burden on respondents during the validation process.

Cleaning

GPS data quality is dependent upon the various factors contributing to overall GPS positional accuracy. GPS devices can record information on their estimated positional accuracy. Researchers must define their standards of acceptable quality in order to prevent the use of data of substandard quality.

The cleaning phase utilizes the information provided by the GPS devices or calculated from the raw GPS data to remove systematic errors. This is usually performed by deleting records with low quality indicators.

Satellite Number

Position determination with GPS devices depends on satellite signals. A reliable position and navigation record requires signals from at least four different satellites (as previously explained in paragraph 3.1). A two-dimensional positioning estimation is still possible with three satellites, but the estimation error caused by this simplification can result in high positional errors.

For these reasons, all records utilizing less than three satellites' signals to determine the position of the device are generally discarded, as shown in the flow chart in Figure 12.

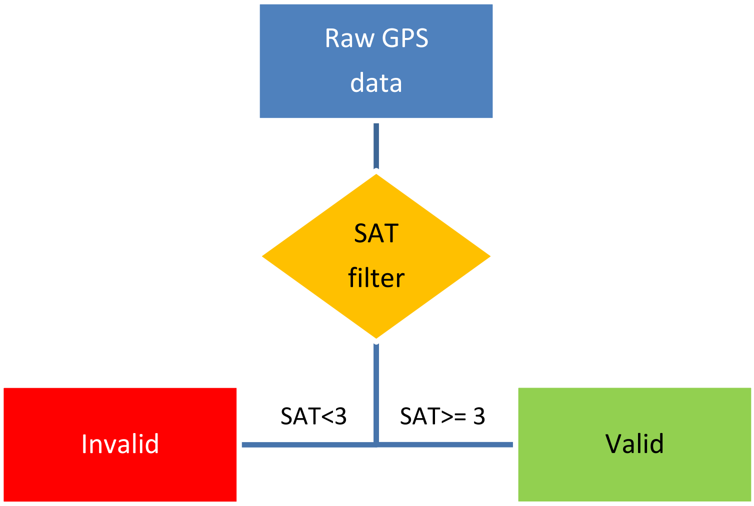


Figure 12 – Satellite filter

Horizontal Dilution of Precision

The use of a sufficient number of satellite signals alone is not the only requisite for providing a reliable positional record. Geometric errors caused by sub-optimal satellite constellation distribution affect the results of the estimation. Even in the case of the most favourable accuracy measured by the GPS device, positional dilution of precision due to geometric errors results in a multiplying degradation factor that raises the probability of misplacement, as described in Table 8. GPS travel survey applications generally filter high values of the horizontal component of the GPS Dilution of Precision (HDOP).

DOP Value	Rating	Description
<1	Ideal	Highest possible confidence level, used for applications demanding the highest possible precision at all times.
1-2	Excellent	Positional measurements are considered accurate for most applications.
2-5	Good	Positional and navigation measurements can be used with a satisfactory level of confidence.
5-10	Moderate	Positional measurements can be used for calculations, but the fix quality can still be improved.
10-20	Fair	Low confidence level. Positional measurements should be only used to provide a very rough estimate of the current location.
>20	Poor	At this level, measurements are inaccurate and should be discarded.

Table 8 – DOP values

Considering the need for reliable data for post-processing purposes, HDOP values below 5 are considered satisfactory for travel survey purposes, as shown in the flow chart in Figure 13.

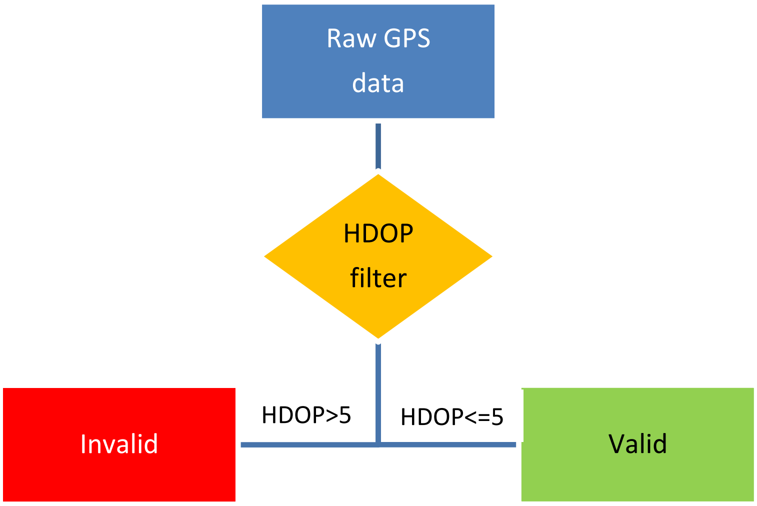


Figure 13 – HDOP filter

A low HDOP value does not by itself guarantee satisfactory positional estimation, it being just one of many possible GPS errors.

Aberrant point detection

In general, the cleaning phase is dedicated to the check of unreliable values in the GPS data stream. Whenever quality indicators are not recorded by the GPS device, or in the case of additional data cleaning needs, it is possible to verify the presence of unreliable data or sudden positional changes in the recorded data, resulting in aberrant points.

The detection of aberrant points can be performed by comparing raw GPS readings with existing threshold data. Speed (Yuan, 2010), elevation (Schüssler and Axhausen, 2008) or coordinate value ranges are set to filter all possible unreliable recordings. An example of aberrant point filtering based on elevation is shown in Figure 14.

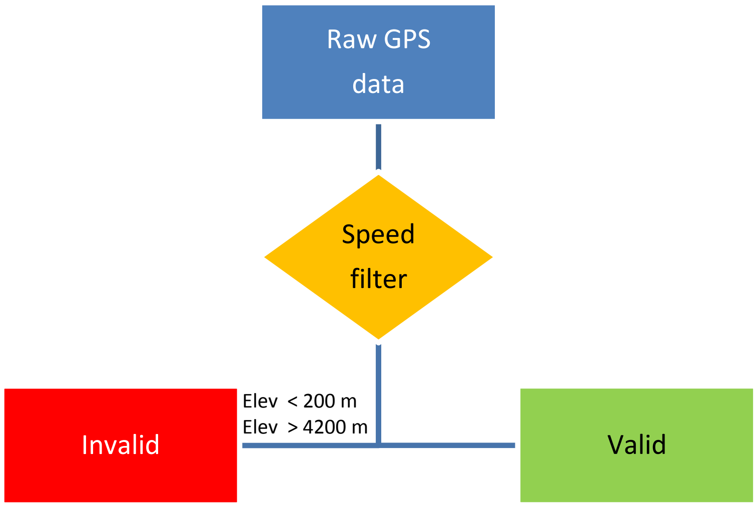


Figure 14 – GPS altitude filter (Swiss case study – Shuessler and Axhausen, 2008)

Another approach for aberrant point detection uses both GPS data readings and measured information. An algorithm developed for aberrant point detection compares the speed variation between two consecutive segments with a threshold value dependent on the time interval between collected points. The general principle of aberrant point detection is described in Figure 15.

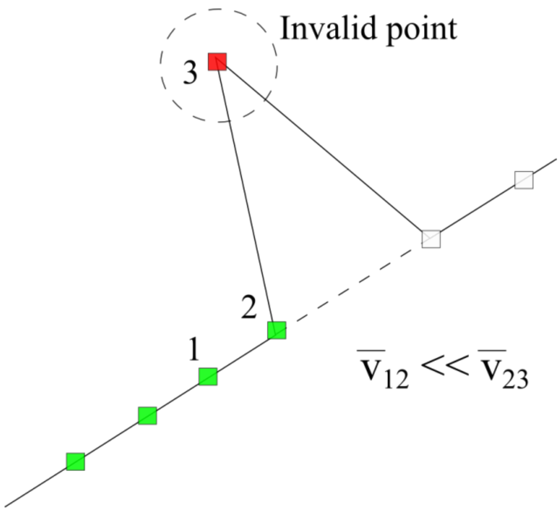


Figure 15 – Example of MAV aberrant point detection principle (Yuan, 2010)

One example of aberrant point data filtering is the MAV (Méthode Accélération-Vitesse), employed during the French national travel survey GPS sub-sample (Yuan, 2010; Marchal et al., 2011). In this application, the mean acceleration estimated from the values of two consecutive segments cannot exceed 10 kilometres per second, as described in Equation 3.1. 100 kilometres has been set as the maximum acceptable speed change.

$$\left|\overline{v}_{(i+1,i+2)} - \overline{v}_{(i,i+1)}\right| \leq 10km/s \cdot \frac{1}{2}\left(T_{(i+1,i+2)} + T_{(i,i+1)}\right) \qquad \text{Equation 3.1}$$

Where:
v is the average speed of a segment threshold value;
T is the value of the estimator.

An alternative approach based on the same principle is to compare the measured distance between two consecutive GPS points with a fixed distance threshold, assuming a maximum speed and considering the expected GPS device random error. Previous experience (Schüssler and Axhausen, 2009) used 50 m/s as the maximum allowed speed and a GPS-device random error buffer of 30 metres.

Data Smoothing

Once data cleaning is complete, a further data smoothing phase is sometimes required. Data smoothing removes random positional and speed noise from the GPS readings by applying a smoothing filter, such as a Gauss kernel (Schüssler and Axhausen, 2009); a customized smoothing algorithm based on statistical assumptions (Marchal et al., 2011); or a Kalman filter, if GPS is coupled with motion sensors (Chiou et al., 2009).

The data smoothing step allows derivation algorithms to perform better by providing noise-free data distribution and eliminating possible outliers in the data stream. Some examples of smoothing used in GPS-based applications are illustrated as follows.

Least-Squares Spline

Least-square fitting can be successfully applied for speed smoothing (Jun et al., 2005). This fitting method aims to minimize the residual sum of squares (RSS) of the Euclidean distance between the value of a regression function with the estimator Y_i, as described in equation 3.2.

$$MIN\ (RSS) = MIN \sum_{i=1}^{n} [f(x_i) - Y_i]^2 \qquad \text{Equation 3.2}$$

Where:
$f(x_i)$ is the result of the regression function for i values;
Y_i is the value of the estimator.

Parting a GPS data stream in intervals with a specific sample size ***N* = 2k + 1** results in a sample of ***n*** speed values. It is possible to fit the observed data for each interval with a polynomial function with *r* degrees, as in the function illustrated in Equation 3.3. The degree of the polynomial function should follow the general rule ***N* > *r*** to prevent unreliable outcomes (Jun et al., 2005).

$$f(X_i) = \beta_0 + \beta_1 X_i + \beta_2 X_i^2 + \cdots + \beta_i X_i^r + \varepsilon$$

Equation 3.3

$$for\ i = 1\ to\ n$$

Where:
β_i are the regression coefficients for the sample;
ε is the unobserved random error;
X_i is the time i of the observation.

The solution of the polynomial for every X_i in the partition range will be the resulting smoothed value.

Gaussian kernel smoothing

Gaussian kernel is a particular case of kernel smoothing that has been used successfully for position smoothing in previous GPS studies (Jun et al., 2005; Schüssler and Axhausen, 2009). Kernels differ by the shape of the distribution that determines the weighting factors of each value before and after the smoothing. Any symmetrical function with area 1 and mean 0 can be used as a kernel. The function width determines the number of values that contribute to the estimation of the smoothed values.

The shape of the Gaussian kernel is expressed by Equation 3.4:

$$K(t_j) = \frac{e^{-\frac{(t-t_j)}{2\sigma^2}}}{2\pi\sigma} \qquad \text{Equation 3.4}$$

Where:
$K(t_j)$ is the equation of a Gaussian distribution function centred in t with a width 2σ;
σ is the standard deviation of the distribution, that determines the smoothing range.

Once the kernel is defined it is possible to weight each GPS point coordinates or speeds according to Equation 3.5:

$$\tilde{c}(t) = \frac{\sum_j K(t_j) \cdot c(t_j)}{\sum_j K(t_j)}$$ **Equation 3.5**

Where:
$c(t_j)$ is the raw GPS speed or location value $[X, Y[, Z]]$ at time j;
$\tilde{c}(t)$ is the resulting smoothed value of the coordinate.

The width of the distribution affects the number of points sampled before and after each smoothed point, as well as the contribution of each sampled point to the determination of the smoothed value. Figure 16 shows some examples of Gaussian distributions with different widths.

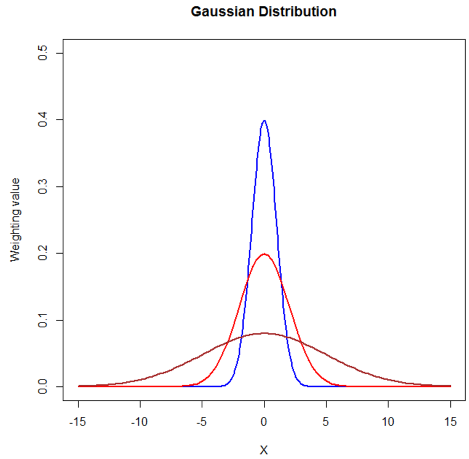


Figure 16 – Shapes of the Gaussian kernel

Real speed estimation

Instant speed is generally provided by the device. However, it is possible to calculate an average speed based on the variation of GPS positions in time. This average speed value results in less accurate speed detection for small recording intervals, compared to the GPS-measured speed. However, the average speed can be considered more reliable for longer logging intervals. Researchers involved in the French NTS GPS sub sample described the relationship between the instant GPS speed and the average speed by calculating an estimated real speed, weighted according to the set and observed data collection interval (Marchal et. al, 2011).

$$v_{es\,(i)} = v_i \cdot e^{0.09531\left(\frac{Int \cdot \sqrt{Int_i}}{Int_i - 1}\right)} + \overline{v}_{(i-1,i)} \cdot \left(1 - e^{0.09531\left(\frac{Int \cdot \sqrt{Int_i}}{Int_i - 1}\right)}\right)$$ **Equation 3.6**

$$for\ Int > 1$$

Where:
$v_{es\,(i)}$ is the weighted speed at time i;
v_i Is the instant speed measured by the GPS at the instant i;
$\overline{v}_{(i-1,i)}$ Is the calculated average speed between point two consecutive points $(i-1, i)$;
Int is the GPS sampling interval or minimum time interval between two consecutive GPS records;
Int_i is the measured time interval between two consecutive point with $Int_i \geq Int$.

Using this method, in the case of a 10 second lag in data collection (Int_i), given a 1 second GPS recording interval (Int), the instant speed will account for 42% of speed values, while the average speed will account for the remaining 58% of speed values. In the case of a recording gap of 60 seconds or more, the average speed will represent the estimated speed.

3.2.2 Trip information identification

After a data quality check has been completed, it is possible to derive trip information, such as origin, destination, starting and arrival times, distances, routes, travel patterns, etc. The derivation of trip information is the core of the post-processing analysis. Trip identification can be fulfilled using rule-based, fuzzy or statistical/stochastic methods for classification of GPS data in trip and activities. Post-processing can be optimized with the help of training data, tuning the process through a quality index threshold (e.g. membership function of variables) or by setting derivation parameters (e.g. characteristics of transport modes).

The use of external data sources, such as GIS layers, allows researchers to perform better and more in-depth identification of trip information. In particular, comparing GPS data with transport networks and extensive land use geographic databases helps researchers to more accurately identify means of transport and trip purpose. Map-matching algorithms allow researchers to better isolate distance and route-choice information.

Steps for travel and activity information consist of:

- trip identification, distinguishing stops and moving segments in the GPS data stream and determining the basic trip information such as start, end and travelled distance;
- identification of means of transport by observing the characteristics of moving segments;
- identification of purpose/activity by analyzing stops.

Figure 17 summarizes a possible trip information, purpose and transport mode identification phase. The example shows how it is possible to derive information from the reliable and cleaned data. The first step consists of distinguishing between records that can be classified as stationary points, and GPS records, which are characterized by speed and location changes in time to identify them as moving. Stationary points help researchers identify activities within the positional data. Moving segment information is used to determine trip length, duration and mode. Augmentation with external sources is possible. Purpose identification relies on multiple sources and utilizes all available GPS and external trip and activity information.

Several derivation methods can be used, and multiple augmentation layers can be included in the process. The following paragraphs will illustrate several possible approaches that have been used previously in household travel surveys.

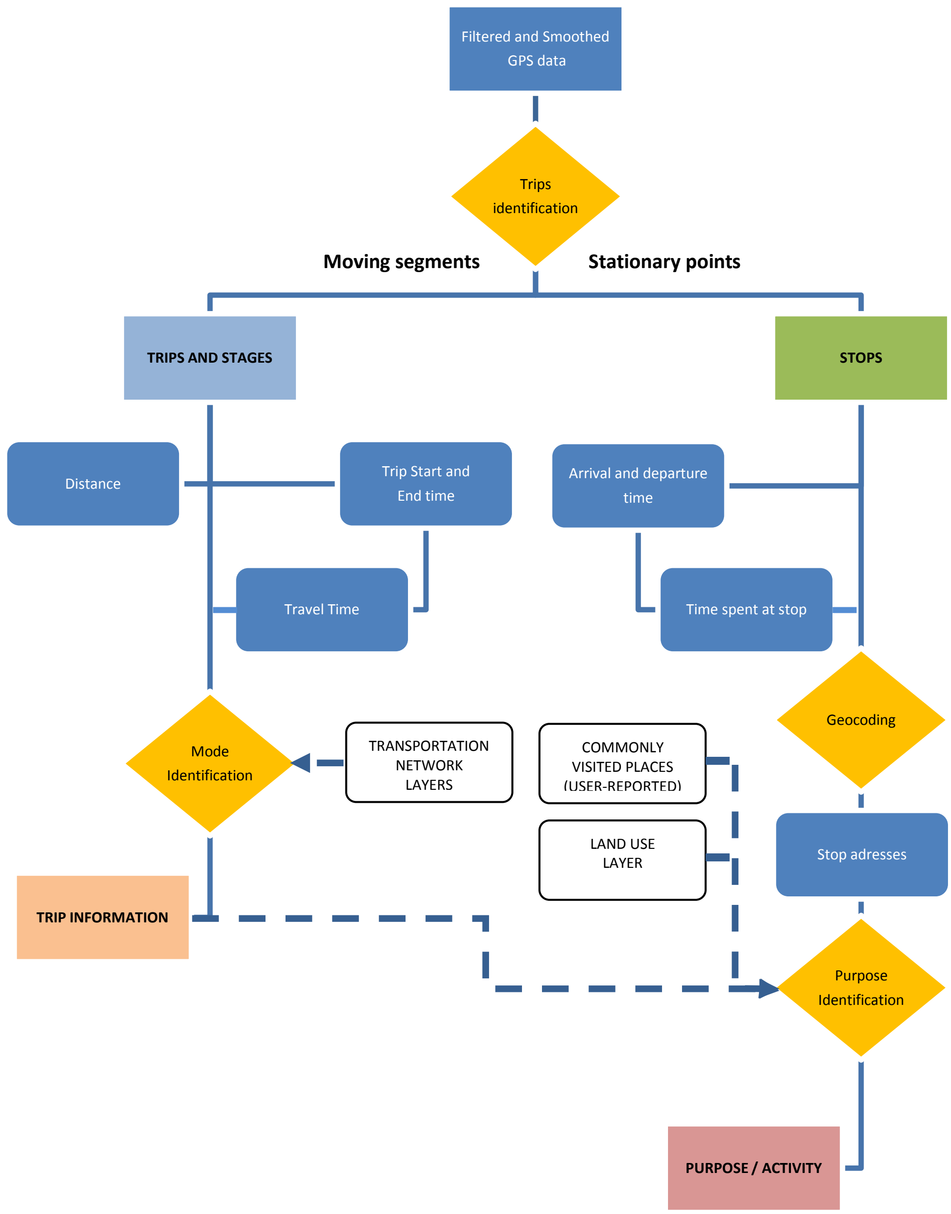


Figure 17 – Example of trip identification phase within post-processing phase

Trip identification

The first step in the trip identification process includes the distinction of moving from stationary points. Various methods are used to inspect the GPS data stream, with the purpose of identifying different trips and activities.

The trip identification phase generally starts with a comparison of time values between consecutively-logged records, identifying potential trip ends when a pre-determined time gap exceeds a defined dwell time, as shown in Table 9.

LAT	LON	T (hh:mm:ss)	Delta T (s)	TYPE
45.XXXXXX	7.XXXXXX	17:08:34	10	MOVING
45.XXXXXX	7.XXXXXX	17:08:44	10	STOP
45.XXXXXX	7.XXXXXX	17:35:18	1594	NEW TRIP START
45.XXXXXX	7.XXXXXX	17:35:28	10	MOVING
45.XXXXXX	7.XXXXXX	17:35:38	10	MOVING

Table 9 – Example of trip start and stop Identification observing dwell time.

Different dwell time values affect the determination of stops. While previous research has used a time threshold ranging from 45 seconds (Pearson, 2001) to 900 seconds (Schüssler and Axhausen, 2009), the dwell time value is commonly assumed as 120 seconds, defined as the minimum stopping time needed for completing an activity.

The temporal gap occurs when a GPS device stops recording movement; i.e., if the GPS is switched off by a user or by a motion detection sensor within the GPS, or if no signal reception is possible due to an indoor environment. Signal loss can also take place during movement phases, i.e., in the case of insufficient GPS signal coverage, or due to the effects of cold/warm start, GPS misuse, etc. Figure 18 shows an example of signal loss exceeding the 120 second dwell time. Once temporal gaps have been identified, it becomes necessary to determine the nature of these gaps. Temporal and spatial elements of GPS data, recorded before and after stops, can be used to evaluate the possibility that temporal gaps are actually missing portions of previous trips (Marchal et al., 2011).

Figure 18 – Example of signal loss resulting in a detected stop

When both time interval and the geographic distance between the end of one segment and the start of the next segment exceed a fixed threshold, it is impossible to infer information on stops and activities during signal loss without additional augmentation (e.g. habitual routes). GPS data on transport networks can help researchers to infer a lost trip-stage, i.e., in the case of long galleries (for railways and highways) or underground movement. Figure 19 shows an example of signal loss due to the use of the metro lines in the city of Torino.

Figure 19 – Example of signal loss due to metro use

Activities can be also “hidden” within a continuous GPS data stream, and must then be spotted using different approaches.

The presence of several consecutive zero or low-speed records in the GPS data-stream is one way to determine stops, especially in the case of short duration activities, when the GPS device continues collecting data. Table 10 shows the presence of a possible trip stop in the GPS recording log.

LAT	**LON**	**T (hh:mm:ss)**	**Delta T (s)**	**Speed**	**Accumulated Time (s)**	
45.XXXXXX	7.XXXXXX	13:23:23	10	2	MOVING	
45.XXXXXX	7.XXXXXX	13:23:33	10	0.1	0	**STOP**
45.XXXXXX	7.XXXXXX	13:23:44	11	0.5	11	
45.XXXXXX	7.XXXXXX	13:23:54	10	0.3	21	
45.XXXXXX	7.XXXXXX	13:24:04	10	0.6	31	
45.XXXXXX	7.XXXXXX	13:24:15	11	0.2	42	
45.XXXXXX	7.XXXXXX	13:24:25	10	0.4	52	
45.XXXXXX	7.XXXXXX	13:24:35	10	0.1	62	
45.XXXXXX	7.XXXXXX	13:24:46	11	0.3	73	
45.XXXXXX	7.XXXXXX	13:24:56	10	0.7	83	
45.XXXXXX	7.XXXXXX	13:25:07	11	0.7	94	
45.XXXXXX	7.XXXXXX	13:25:17	10	0.7	104	
45.XXXXXX	7.XXXXXX	13:25:27	10	0.7	114	
45.XXXXXX	7.XXXXXX	13:25:37	10	0.7	124	
45.XXXXXX	7.XXXXXX	13:25:49	12	5	MOVING	

Table 10 – Stop detected from consecutive low-speed points

Analysis of the spatial distribution of points, using rule-based or pattern-recognition algorithms, allows researchers to determine where activities are performed. This method is generally implemented when speed information is not recorded directly by the GPS device, and is instead derived by observing temporal and spatial intervals between points. This process evaluates the total time spent remaining in the vicinity of a certain location and classifies a point concentration as a stop – or a stage – whenever a time threshold is exceeded, as illustrated in Figure 20. The time and spatial threshold values for determining the stop largely vary across GPS studies (Wolf et al., 2001; Bohte and Maat, 2009; Yuan, 2010).

Figure 20 – Stop determination observing GPS record distribution

Once potential trip ends are flagged, it is necessary to identify and eliminate identified stops that result in no activity, such as in the case of GPS data recorded during extended traffic delays.

Identification of transport mode

Travel modes used in each identified segment can be assigned using various classification techniques. Mode detection methods generally consist of different phases, such as segmentation of trips into stages, mode assignment, and mode-chain verification. Derivation of means of transport is achieved through the use of travel information such as speed and acceleration patterns, trip lengths, stop frequency, and GPS quality indicators (Marchal et al., 2011). Table 11 reports a set of variables used for mode identification derivation (Zheng et al., 2008b).

Features	Significance
Dist	Distance of a segment
Max*Vi*	The *i*th maximum velocity of a segment
Max*Ai*	The *i*th maximum acceleration of a segment
AV	Average velocity of a segment
EV	Expectation of velocity of GPS points in a segment
DV	Variance of velocity of GPS points in a segment
HCR	Heading Change Rate
SR	Stop Rate
VCR	Velocity Change Rate

Table 11 – Variables considered for mode derivation (Zheng et al., 2008b)

Modal detection methods include:

- rule-based algorithms: algorithms that rely upon trip characteristics, proximity to certain network elements (e.g. bus stops or train stations), or deviation from the street network (Wolf, 2000; Marchal et al., 2011; Bohte and Maat, 2008; DfT, 2012);
- fuzzy rules and membership function (Tsui and Shalabi, 2006; Schüssler and Axhausen, 2009);
- statistic and probabilistic models, such as decision trees (Zheng et al., 2008a), Bayesian networks (Moiseeva et al., 2010), neural networks (Gonzales et al., 2008), conditional random fields (Zheng et al., 2008b), etc.

In general, the use of ad-hoc rules for mode detection does not properly capture the stochastic nature of the collected GPS data; whereas less-employed approaches, such as data mining and statistical analyses, provide derived results (Feng et al., 2011). However, deterministic approaches are easier to implement and require lower resources for running and maintaining the derivation algorithms.

Table 12 illustrates the mode detection parameter values used in the UK NTS pilot survey post-processing phase (DfT, 2012).

Table I2	Mode parameter values			
CODE	MODE	MAX_SPEED	AVG_SPEED	STD_SPEED
1	Walk	9.32	2.81	1.06
2	Bicycle	35.79	10.44	5.07
3	Bus	39.77	8.27	7.39
4	Car	65.48	15.92	10.66

Table 12 – Mode parameters values (DfT, 2012)

Detection methods can also require the use of training data, generally collected from respondents through traditional methods, or of GPS processing validation through prompted-recall interviews, which can help researchers to correct possible identification errors.

Researchers can also use rule-based algorithms to more accurately derive trips. These algorithms can perform a hierarchic mode detection; for example, identifying walking trips first, then associating other travel modes in successive steps (Zheng et al., 2008b; Stopher et al. 2008a).

Identification of purpose/activity

Identification of travel purpose is the biggest challenge in the post-processing phase. This derivation can be performed using land-use GIS layers (Wolf et al., 2001; Bohte and Maat, 2009) or by inferring purpose information from users' feedback (Stopher and Collins, 2005) or self-declared responses. The sole use of raw GPS data allows researchers to determine the purpose of trips related to home and work activities, through observation of the temporal pattern of identified stops (Stopher et al. 2008a). Researchers are challenged to successfully identify trip purpose while keeping interaction with respondents to a minimum, in order to reduce burden and fatigue and to allow for longer-term data collection. The desired level of detail of derived trip purpose depends on researchers' needs and detection algorithm design (Stopher et al., 2008c).

Methods for trip-purpose attribution using GPS/GIS data currently include the same set of techniques used for modal derivation. These include:

- deterministic algorithms, which rely upon deterministic rules based on spatial and temporal information collected during GPS stationary intervals. These algorithms can be augmented with socio-demographic information (Axhausen et al., 2004), as well as respondent-declared 'most-visited places (Stopher et al., 2008c). When available, researchers can use a parcel-level GIS land use layer (Wolf et al., 2001; Marchal et al., 2011; Schönfelder and Samaga, 2003), as illustrated in Figure 21;
- Statistical and probabilistic methods – such as Decision trees (Lu et al., 2012) and Bayesian networks (Scuderi and Clifton, 2005) – which use several variables of trip attributes, respondent characteristics, and land use information to classify activities into trip purposes. (McGowen and McNally, 2007).

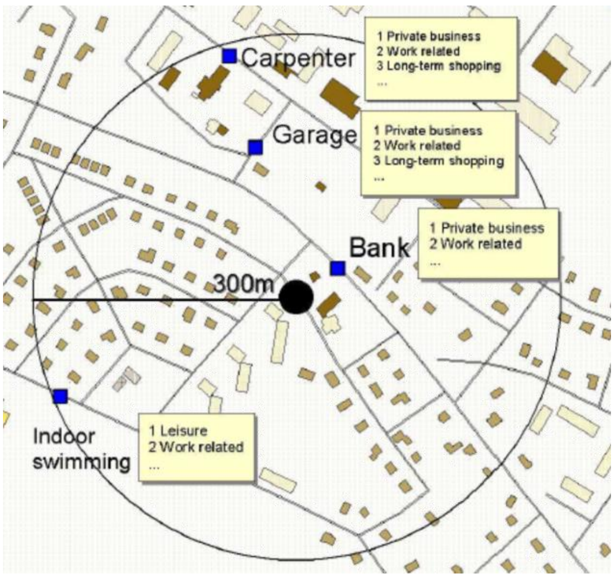


Figure 21 – Identification of potential trip purpose by land use (Schonenfelder and Samaga, 2003)

Purpose derivation poses more challenges to researchers; however, results are promising. Researchers can use multiple data sources to integrate GPS data, which can increase the accuracy of algorithm-based purpose derivation.

Figure 22 illustrates improvement of the purpose derivation process through the use of multiple sets of information, such as trip characteristics and land use information, augmented with user information, trip chain data and trip end location.

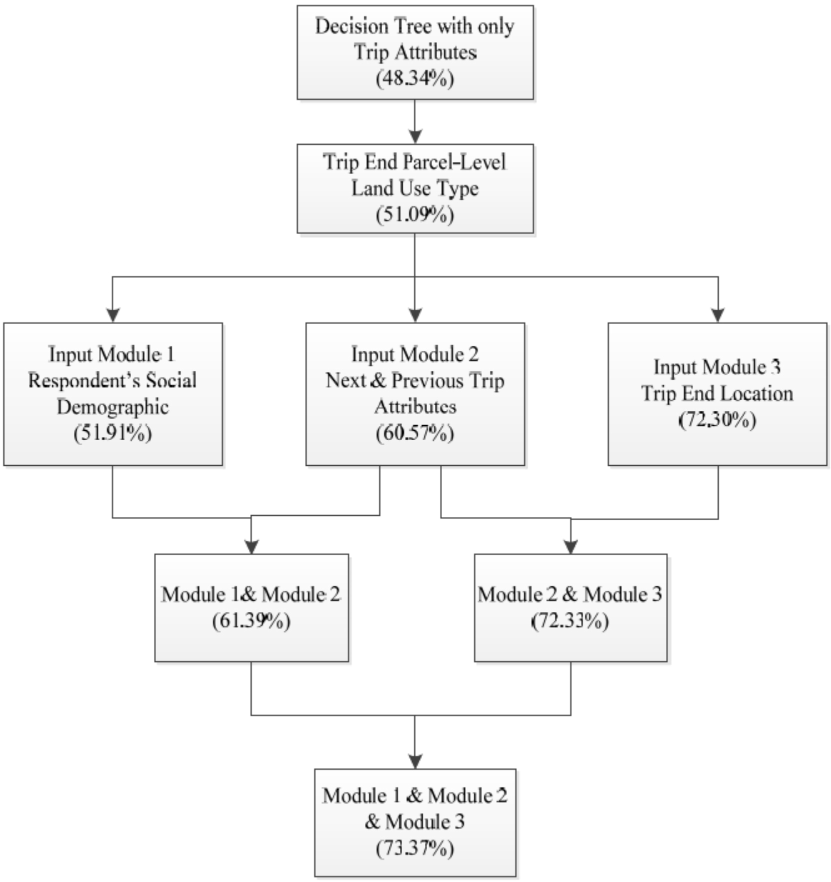


Figure 22 – Results of decision tree for purpose imputation (Lu et al., 2012)

When extensive, parcel-level land use information is not available, it is possible to build a location database through reverse geo-coding for future use (Feng et al., 2011).

3.2.3 Estimation and repair of missing spatial data

Once trips and activities are detected and classified, the need arises for spatial data quality-control and possible imputation of missing segments of a trip. This 'spatial data fix' phase allows researchers to verify data completeness and impute missing data, if possible, using available alternative data.

Missing data fix

Managing a multi-day survey data allows researchers to detect habitual trips and to repair gaps in data continuity through imputation, as shown in Figure 23. Using GIS network system databases, it is also possible to fix gaps related to underground trips (tunnels, metro, etc.). This post-processing step mitigates data gaps caused by GPS cold/warm start and signal loss.

Figure 23 – Example of possible missing data fix

Positional data fix

Matching GPS data to actual transport network information can further enhance data quality. This process consists of aligning the collected positional data with existing transport network data, as demonstrated in Figure 24.

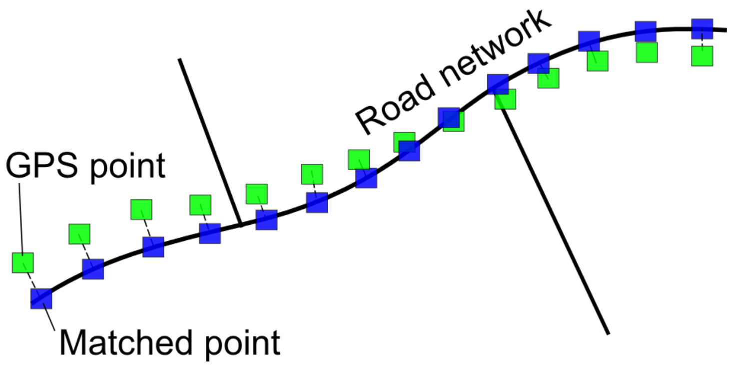


Figure 24 – Map matching example

The determination of the matching point is performed by calculating a distance indicator of the recorded GPS points from the transport network segments, assigning the original points to the closest segments. Point-segment proximity can be evaluated using various distance measures, such as point-to-point, point-to-curve (GPS point linked to a series of many network point sequences) or curve-to-curve (GPS point sequence matched to transport network point sequence) (Bernstein and Kornhauser, 1996). In the simplest point-to-point approach, the distance of a GPS point from an oriented segment of a transport network is equal to the distance of the GPS point from its projection on the network segment. If no projection is possible, the distance is measured from the GPS point to the closest vertex of the segment. Equation 3.6 illustrates an example of map-matching distance calculation (Marchal et al., 2004):

$$d(Q,AB)=\begin{cases} d_\epsilon(Q,Q') & if\ Q'[AB] \\ \min\{d_\epsilon(Q,A),d_\epsilon(Q,B)\} \end{cases} \qquad \text{Equation 3.6}$$

Where:

d_ϵ is the calculated Euclidean distance;

Q is the GPS point coordinate;

AB is a segment of the transport network;

Q' is the projection of point Q on AB.

In all cases, the GPS point is matched to the network segment AB that minimizes the distance from the segment, or is matched using a distance function that can be based on multiple variables. Researchers can augment matching results using a variety of algorithms, based on networks' topologic features and trip information (Marchal et al., 2004; Quddus et al., 2006). Network segment selection can follow a topological, statistical or fuzzy approach to determine the closest segment, depending on the factors contributing to the cost function (Quddus et al., 2006).

When matched to the actual transport networks, GPS tracks provide researchers with more reliable distance and route information. For this reason, results of this map-matching process can be used to validate the trip-determination process using classification algorithms (Tsui and Shalaby, 2006), as shown in Figure 25.

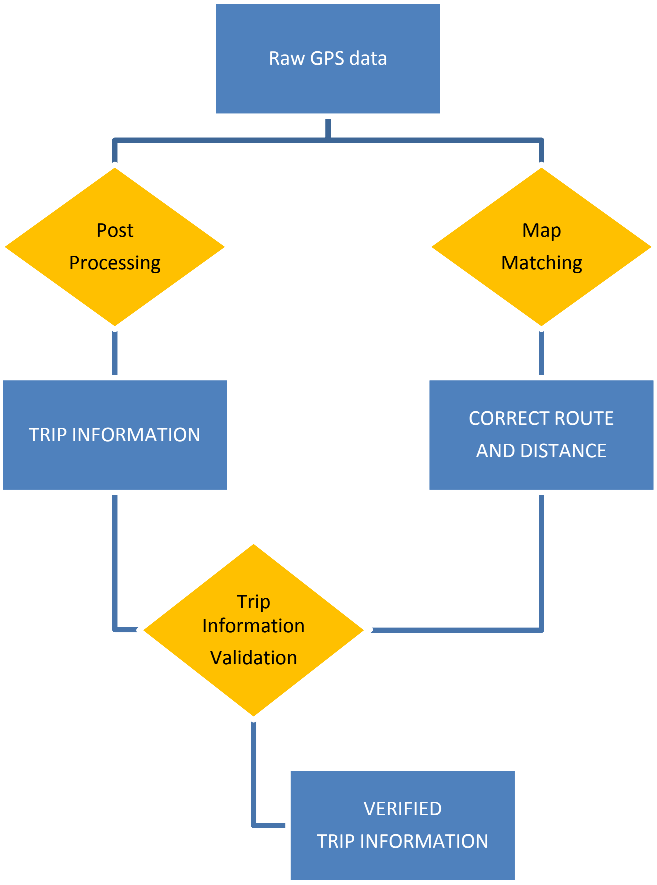


Figure 25 – Validation of trip information using matched GPS points

Validation

Once data are interpreted, researchers can ask survey participants for data validation through prompted recall surveys, in order to repair data and tune algorithms. Prompted-recall surveys are carried out using all possible survey methods, including personal interviews (Marchal et al., 2011), CATI (Wolf, 2006), paper-and-pencil surveys, (Bricka et al., 2009) and web-based aided interviews (Stopher and Collins, 2005; Doherty et al., 2006).

The validation process is gaining importance, as researchers are now carrying out GPS-only surveys, relying solely upon passive tracking for the duration of the survey (Wolf, 2006). Validation results improve the derivation algorithms by adding supplementary data as the survey progresses (Moiseeva et al., 2011), as schematized in Figure 26.

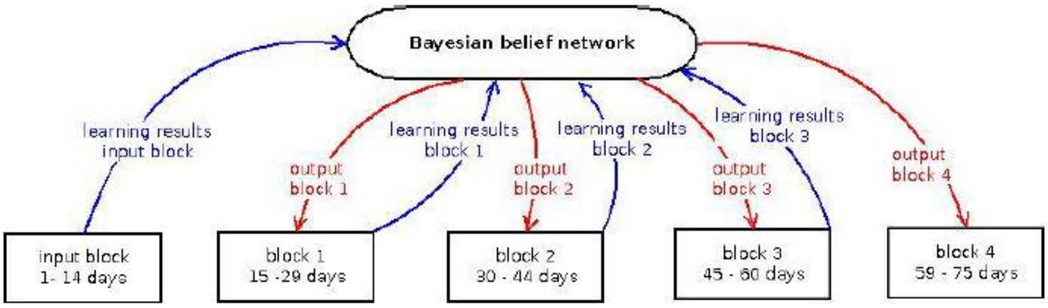


Figure 26 – Learning scheme of training algorithm (Moiseeva et al., 2010)

3.2.4 Considerations in post-processing

Technological advancements in post-processing methods have resulted in the drastic reduction of surveyor-participant interaction, by allowing researchers to derive trip information directly from GPS-collected data.

Major challenges in post-processing are related to the quality of collected data, availability of quality GIS databases, and correct design and tuning of identification algorithms. Quality standards for each of these elements should be implemented.

Travel surveyors have adopted many diverse post-processing methods, and there are currently no harmonized data collection processes or post-processing guidelines due to structural differences in the executed surveys (Lawson et al., 2010). This lack of a standardized procedure makes trip information derived from raw GPS data difficult to compare between surveys and in different locations.

Post-processing methods endeavour to reconstruct traditional trip and activity diaries. New perspectives on data analysis of GPS data, such as trajectory patterns and spatial utilization distribution (Giannotti and Pedreschi, 2008), can be further explored, to enrich survey outcomes with more in-depth perspectives on respondents' travel behaviour.

3.3 GPS implementation in household and personal travel surveys

Travel surveys have benefitted from the use of GPS devices as survey tools since the first pilot test in Lexington, Kentucky in 1996. They have since proved themselves as a feasible tool for surveying travel behaviour. GPS-derived data are generally more accurate than respondent-reported data, particularly regarding the collection of trip ends, travel times, distances, stop locations, route choices and vehicle use profiles (Doherty et al 2006; Madre et al 2008; Wolf et al 2003). In addition, GPS devices have dropped in cost and have become more accepted by test subjects, due to the wide market penetration of the technology (Kracht 2006).

Table 13 lists notable past GPS studies in chronological order. GPS-based travel surveys have been carried out as part of studies in North America, Australia, Europe and many other countries (Israel, Japan, South Africa). First used as a feasibility study for vehicle tracking, the GPS-based survey rapidly developed into a survey supplement, helping researchers to determine necessary correction factors. Recently, the tool has been used as a GPS-only travel survey, tracking both vehicles and individuals.

GPS-BASED STUDIES	COUNTRY	YEAR	TOTAL SAMPLE	GPS SAMPLE	TYPE
Lexington Area Travel Data Collection Test	**USA**	**1996**	Pilot	100 Households	In-Vehicle
GPS Pilot Test - The Netherlands	**NED**	**1997**	Pilot	151 Individuals	Personal
Austin Household Travel Survey	**USA**	**1998**	1750 Households	203 Households	In-Vehicle
GPS Pilot Test - Quebec City	**CAN**	**1999**	Pilot	4 Individuals	In-Vehicle
California Statewide Household Travel Survey	**USA**	**2001**	16990 Households	517 Household	In-Vehicle
Atlanta Household Travel Survey	**USA**	**2002**	8069 Households	542 Individual	Personal
Post-Census Regional Travel Survey - Southern California	**USA**	**2002**	23302 Households	820 Household	In-Vehicle
Swedish Intelligent Speed Adaptation (ISA) - Borlänge dataset	**SWE**	**2002**	186 Vehicles	186 Vehicles	In-Vehicle
Pittsburgh Travel View Household Travel Survey	**USA**	**2002**	2554 Households	74 Households	Personal
London GPS Pilot Travel Survey	**GBR**	**2002**	Pilot	154 Individuals	Personal
Household Travel Survey for the St. Louis Region	**USA**	**2002**	5094 Households	313 Households	In-Vehicle
Ohio Statewide Travel Study	**USA**	**2002**	6338 Households	230 Households	In-Vehicle
Laredo / Webb County Texas Household Travel Survey	**USA**	**2002**	1971 Households	187 Households	In-Vehicle
Tyler / Longview Texas Household Travel Survey	**USA**	**2003**	2336 Households	367 Households	In-Vehicle
Mobile Activity Logger with GPS-Equipped Cell Phone (MoALS) - Matsuyama JPN	**JAP**	**2004**	Pilot	31 Individuals	Personal
Sidney Continuous Household Travel Survey	**AUS**	**2004**	2461 Households	72 Households	Personal
GPS Mobile Phone Based Activity Diary Survey - Tokyo JPN	**JAP**	**2004**	Pilot	50 Individuals	Personal
Cyclists Route choice - Zurich	**SUI**	**2004**	2435 Individuals	2435 Individuals	Personal
Kansas City Regional Household Travel Survey	**USA**	**2004**	3049 Households	294 Households	In-Vehicle
Commute Atlanta Instrumented Vehicle GPS Data	**USA**	**2005**	268 Households	268 Households	In-Vehicle
Washoe County Travel Characteristics Study - Reno	**USA**	**2005**	1207 Households	106 Households	In-Vehicle
Continuous Survey for Modeling in Oregon (COSMO) - Portland GPS Pilot	**USA**	**2005**	Pilot	299 Households	Personal
Puget Sound Household Activity Survey	**USA**	**2006**	4700 Households	285 Households	In-Vehicle
Land Use and Travel Behaviour GPS-based Study - Amersfoort, Meenendaal, Zeewolde (NED)	**NED**	**2007**	1104 Individuals	1104 Individuals	Personal

Table 13 – Household and personal travel survey studies (continues on page 65)

GPS-BASED STUDIES	COUNTRY	YEAR	TOTAL SAMPLE	GPS SAMPLE	TYPE
Activity-Travel Diary Survey - Flanders (BEL)	BEL	2007	2500 Households	2500 Households	Personal
GPS Pilot Project - New York Metropolitan Transportation Council	USA	2007	Pilot	28 Individuals	Personal
TravelSmart - South Australia Panel	AUS	2007	Panel	359 Households	Personal
Chicago Metropolitan Agency for Planning Travel Tracker Survey	USA	2008	10552 Households	300 Households	In-Vehicle
				160 Households	Personal
Halifax Space Time Activity Research (STAR)	CAN	2008	2000 Households	2000 Households	Personal
Washington DC/Baltimore Regional Household Travel Survey	USA	2008	15000 Households	1600 Households	In-Vehicle
French National Travel Survey	FRA	2008	19000 Households	1500 Individuals	Personal
Victorian Integrated Survey of Travel and Activity (VISTA)	AUS	2008	16000 Households	190 Individuals	Personal
Harbor Communities Time Location Study - California - Low Income Communities	USA	2008	Pilot	51 Individuals	Personal
Western Cape GPS Travel Survey	RSA	2008	Pilot	130 Individuals	Personal
Central Indiana Travel Survey	USA	2009	3929 Households	136 Households	Personal
GPS-based Travel Behaviour on Campus - Toronto	CAN	2009	Pilot	94 Individuals	Personal
Greater Cincinnati Area HTS GPS Pilot **Survey**	USA	2009	Pilot	120 Households	Personal
NTS GPS Feasibility Test - United Kingdom	GBR	2009	Pilot	134 Individuals	Personal
Front Range Travel Counts - Denver Regional Council of Governments	USA	2010	12000 Households	437 Households	In-Vehicle
				200 Households	Personal
Urban Travel Route and Activity Choice Survey - Chicago	USA	2010	102 Households	102 Households	Personal
Greater Cincinnati Area Household Travel Survey	USA	2012	2608 Households	2608 Households	Personal
Massachussetts State Travel Survey	USA	2011	15000 Households	600 Households	Personal
Atlanta Regional Household Travel Survey	USA	2011	10278 Households	727 Households	In-Vehicle
				334 Households	Personal
NTS GPS Pilot - United Kingdom	GBR	2011	Pilot	897 Individuals	Personal
Jerusalem Household Travel Survey	ISR	2011	8800 Households	8800 Households	Personal
New York/New Jersey/Connecticut Regional Household Travel Survey	USA	2011	18800 Households	1880 Households	Personal
ACTUM Copenhagen	DEN	2011	903 Households	100 Households	Personal
MOBIFit Austria (GPS Pilot Survey)	AUS	2011	224 Individuals	124 Individuals	Personal
Greater Minneapolis Travel Survey	USA	2012	5000 Households	500 Households	Personal
California Statewide Travel Survey	USA	Ongoing	32486 Households	3719 Households	Both
Northeast Ohio Regional Travel Survey	USA	Ongoing	4250 * Households	4250 * Households	Personal
Long-Term Monitoring of Travel Behaviour Change - Australia	AUS	Ongoing	Panel	120 Households	Personal

* Expected sample size

Table 13 – Household and personal travel survey studies

Frequency of GPS data collection varies according to researcher needs and the technical limitations of the devices. Such technical limitations were most evident in early individual tracking attempts that used wearable GPS devices (Kochan et al, 2005; Stopher et al., 2008c). Current surveys use higher data-logging frequencies, as frequent as once per second, for both in-vehicle and wearable devices, as summarized in Table 14.

Researcher Survey	Year	Type	Interval
Lexington, KY	1996	In-Vehicle	1 sec
Transport Research Centre (AVV), Netherlands	1997	Wearable	NA
Austin, Texas	1998	In-Vehicle	NA
Quebec City, Canada	1999	In-Vehicle	5 sec 4 sec
Georgia Institute of Technology	1999	Wearable	NA
Georgia Institute of Technology	2000	In-Vehicle	NA
California State	2001	In-Vehicle	1 sec
London	2002	Wearable	NA
University of California Irvine	2002	In-Vehicle	NA
New South Wales	2003	Wearable	NA
Kansas City	2004	In-Vehicle	1 sec
Oregon State	2005	Wearable	5 sec
Puget Sound	2006	In-Vehicle	10 sec
Chicago Metropolitan Agency	2007	In-Vehicle	1 sec
		Wearable	5 sec
TU Delft	2007	Wearable	6 sec
INRETS - French NTS	2008	Wearable	10 sec
University of Toronto	2009	Wearable	NA
TfL - NTS Feasibility Test	2009	Wearable	4 sec
Denver Regional Council of Governments	2010	In-Vehicle	NA
Atlanta Regional Household Travel Survey	2011	Wearable	NA
Jerusalem Household Travel Survey	2011	Wearable	NA
California Statewide Travel Survey	2012	Wearable	1 sec

Table 14 – GPS logging interval

Another difference among surveys carried out using GPS technology is the approach towards users' data. Regardless of whether they track vehicles or individuals, GPS-based survey tools fall into two different categories:

- active GPS travel survey: respondents are tracked by the GPS but need to record additional trip information, typically filling in an Electronic Travel Diary (ETD) using a Personal Data Assistant (PDA) coupled with a GPS receiver or an GPS-equipped smartphone;
- passive GPS travel survey: respondents are tracked by the GPS and no additional information is required. Trip information is derived from GPS data. Respondent feedback can be sought through a prompted-recall interview.

Depending on surveyors' needs, GPS data can be sent during the survey period, either in real-time or according to a certain schedule, or collected at the end of the survey. Both real-time data collection and delayed data collection follow the same procedure:

- GPS device deployment;
- GPS data recording;
- GPS device retrieval;
- GPS data post-processing.

Device deployment and retrieval typically involve device mail-in/mail-out; alternatively, researchers can deliver devices in-person, especially if training or settings-adjustment are required.

Positional data recorded by the GPS device can be collected at the end of the survey period of each respondent or household once researchers retrieve the devices (Marchal et al., 2008), or can be periodically sent to researchers by the user (Doherty and Miller, 2000; Moiseeva et al., 2008). Automated data transfer can be implemented in devices and applications, allowing participants to send positional data to a server at fixed time (Itsubo and Hato, 2006) or at specific stationary or moving events (Barbeau et al., 2008). However, transmission of data in real time is not yet widely used in travel survey applications, due to additional data transfer costs, privacy issues and supplementary burden on users (Stopher et al., 2008b).

Determination of trip information occurs in the post-processing phase, in which positional data are prepared and analyzed and trip information is derived. The following types of trip information can be derived from GPS data:

- trip origin and destination;
- trip length;
- trip duration;
- transport mode.

Utilizing GIS layers, learning algorithms, and additional user-provided information – most commonly-visited places, activities performed, etc. – it is possible to derive trip purpose (Wolf et al. 2001; Stopher et al., 2005; Bohte and Maat, 2008; Moiseeva, 2008; Stopher, 2008a).

Evolution of the GPS-based travel survey has been closely tied to the technological development of GPS, and in general, GNSS technology. Improvements in accuracy have allowed researchers to improve the quality of positional data. Longer-lasting batteries and improved storage space have made GPS units more portable, so that they are no longer only appropriate for in-vehicle application. At first, wearable GPS devices were bulky and heavy, resulting in low device acceptability. Size reduction reduced the burden on respondents during individual passive tracking, while additional storage space and device autonomy provided researchers with a tool that could record information for longer survey periods (Stopher et al., 2008).

Today, commercially-available GPS devices guarantee positional accuracy and performances fully compatible with researchers' needs, at cost that makes them affordable for large-scale surveys. Table 15 summarizes the evolution in characteristics and the cost reduction of GPS devices employed in household travel surveys.

Researcher Survey	Year	Type	Description	Cost *
Lexington, KY	1996	In-Vehicle	Sony MagicLink PIC-2000 + Garmin TracPak-30 GPS 2 MB storage, 454 grams	1400 $
Transport Research Centre (AVV), Netherlands	1997	Wearable	ETD with handheld data logging devices equipped with a combined GPS / DGPS receiver and battery pack	NA
Austin, Texas	1998	In-Vehicle	Passive in-vehicle GPS-system	NA
Quebec City, Canada	1999	In-Vehicle	Trimble GeoExplorer DGPS Garmin GPS48 + DGPS DBR 21	NA
Georgia Institute of Technology	1999	Wearable	Psion WORKABOUT, 16 MB storage, 240x100 px display with key input, 330 grams, 2 AA batteries	NA
Georgia Institute of Technology	2000	In-Vehicle	ETD + GPS + engine monitoring sensors	NA
California State	2001	In-Vehicle	GeoStats GeoLogger: Passive logger with Garmin 35 GPS sensor. Storage: 4 MB Weight: 450 grams	NA

Table 15 – Evolution of GPS device features and cost (continues on page 68)

Researcher Survey	Year	Type	Description	Cost *
London	2002	Wearable	GeoStats Wearable Geologger + PDA. 1 kg total weight with palm PDA	875 $
University of California Irvine	2002	In-Vehicle	X86 133 MHz CPU 16 MB of storage for 28 hours data logging, GPS + modem.	1200 $
Ohio State	2002	In-Vehicle	Battelle GPS Leader ETD + GPS 12 MB of storage for 70 hours of 1 second data logging	1650 $
New South Wales	2003	Wearable	Neve-Steplogger: UBlox receiver, 103 grams 12-16 hours battery life	724 $
Kansas City	2004	In-Vehicle	GeoStats GeoLogger	NA
Oregon State	2005	Wearable	GeoStats Wearable Geologger: Garmin GPS18 LVC – 110 grams 61 diameter 19,5 height mm	500 $
Puget Sound	2006	In-Vehicle	Size: 102 x 51 x 25 mm	NA
Chicago Metropolitan Agency	2007	In-Vehicle	GeoStats Geologger V4 86x66x27mm. 794 grams	800 $
		Wearable	GlobalSat Data Logger: 70 X 80 X 18 mm. 170 grams 18-22 hours data collection. Powered with AA batteries.	129 $
New York Metropolitan Agency	2007	Wearable	i-Blue 747 46.5x72.2x20mm,	150 $
TU Delft	2007	Wearable	Amaryllo Trip Tracker 90 x 58 x 25 mm, 98 grams. 16 hour of use	150 $
INRETS - French NTS	2008	Wearable	Royalteck 3000 BT	100 $
University of Toronto	2009	Wearable	Atmel BTT08 GPS Data Logger 77x46x23mm, 68grams	249 $
TfL - NTS Feasibility Test	2009	Wearable	Atmel BTT08 GPS Data Logger 72x46.5x20mm	249 $
Denver Regional Council of Governments	2010	In-Vehicle	QStarz BT-Q1000x Travel Recorder. 72x46x20 mm	120 $
Atlanta Regional Household Travel Survey	2011	Wearable	GlobalSat Data Logger DG-100	129 $
Jerusalem Household Travel Survey	2011	Wearable	GlobalSat Data Logger DG-100	129 $
California Statewide Travel Survey	2012	Wearable	MTK MT3329 GPS Chip 66 Ch 77x46x22, 68 grams 18 hours of use	90 $

* Cost information was gathered from official reports, presentations and papers. When not otherwise available it was necessary to consult manufacturer's websites.

Table 15 – Evolution of GPS device features and cost

At present, commercially-available, low cost GPS devices are equipped with chipsets from four main vendors:

- Sirf
- MediaTek (MTK)
- Ublox
- SkyTraq

Unaugmented position precision of the most recent devices can be as accurate as 3 metres (FAA, 2012), with time for first positional acquisition (time to first fix with no information of satellites in view) as fast as 30 seconds (u-blox, 2012). High receiver sensitivity allows GPS devices to collect satellite data in unfavorable conditions, even indoors. Despite this high sensitivity, urban canyons, multipath effects and indoor environments still pose a threat to the precision and continuity of the positional data.

In addition to the evolution of GPS devices, more reliable post-processing methods allow researchers to record GPS data passively and later verify trip information. Earlier applications had largely relied on Electronic Travel Diaries (ETD) with real-time travel information requests (Murakami et al., 1997, Battelle Memorial Institute, 2000) or daily CATI interviews (NuStats, 2002; NuStats, 2011; DfT, 2012). Current GPS surveys are able to rely on more accurate trip detection algorithms and can ask respondents for data validation in prompted-recall surveys at the end of the survey period (Hato, 2006; Greaves et al., 2012; Moiseeva, 2010; Stopher, 2005).

Survey experiences can be divided into five different chronological phases, according to sample/subsample sizes, GPS characteristics, costs and post-processing development.

1. GPS-based surveys degraded by Selective Availability (1997 – 2000)

At first, GPS travel surveys were limited to vehicle-only surveys, and were affected by the accuracy degradation of Selective Availability. Personal digital assistants (PDAs) were used to record trip information directly from individuals as they were travelling (active GPS travel surveys).

The first GPS test using wearable devices was carried out in the Netherlands. Wearable GPS devices used for the test weighed 2 kg, exclusive of the separate battery pack.

In Quebec City, in-vehicle tests revealed several equipment problems, including GPS acquisition times, power supply stability, data storage limits, and cold temperature tolerance issues with LCD screens (Doherty et al., 2001).

2. Positioning accuracy improvement; Weight and cost issues (2000 – 2003)

With the end of Selective Availability, device cost dropped marginally, and positioning accuracy improved. Researchers were then able to use commercially-available GPS devices without the need for additional correction from DGPS modules. The prohibitive size and weight of devices still hindered their use for personal tracking, while in-vehicle applications benefited from technological advancement. Devices used for in-vehicle applications laid the foundation for the eventual development of the first individual GPS devices.

3. First in-vehicle GPS for large HTS subsamples (2003 – 2006)

Decreasing device costs led to the carrying out of the first large-scale in-vehicle travel survey. Devices decreased in size and weight, which made them compatible for use with individuals, outside of vehicles. Feasibility tests were performed for individual applications. Also during this period, post-processing methods were finessed, allowing researchers to ask respondents for less trip information.

4. Use of large scale GPS sub-sample in HTS (2006 – 2009)

Commercially-available miniaturized GPS receivers appeared during this period, both with and without additional movement sensors. Sensitivity of the receivers improved, additional channels became available, battery life was extended, and storage space increased. These improvements allowed for longer data collection periods with higher data collection frequency. As a consequence, the first large-scale individual tracking surveys were performed during this period.

5. First GPS-only regional travel surveys (2009 – Present)

Lower cost and reduced size and weight of the devices, coupled with increasing receiver sensitivity and improving satellite lock speed, allow researchers to collect continuous data with an increasingly lower burden on respondents.

Researchers can benefit from miniaturized combinations of high-sensitivity GPS logger, accelerometer, and GSM modem at costs starting around $100 U.S.. Power can be saved by collecting data only when the device detects movements from the accelerometer's readings. AGPS and UMTS data transmission of GPS traces are possible at lower costs via specific GSM data transfer plans.

While initial applications of individual tracking surveys first used devices adapted from in-vehicle applications, now the reverse is occurring: devices first used in individual tracking surveys are currently being adapted for use in vehicles. These developments led to the first feasibility tests for a 100% GPS-based travel survey. Today, GPS can be used as a primary survey tool for the collection of trip information.

3.3.1 GPS survey outcomes

GPS-based surveys in the field of transportation have demonstrated the potential of passive tracking as a support tool for traditional travel surveys. GPS-based surveys allow researchers to:

- successfully include respondent groups that are not usually willing to participate;
- evaluate the differences in trip-reporting between groups, and within groups not willing to participate or who are difficult to contact;
- lower the burden on all participants;
- record more trips, especially short trips, which tend to be underreported;
- find correction factors for traditional travel surveys;
- augment trip information with a geographic dimension.

Recent and on-going research has demonstrated the feasibility of GPS-only surveys, designed to replace conventional survey methods (Stopher and Wargein, 2012, Olivera et al., 2010). Trip information derived from raw GPS data is further validated by contact with survey respondents, through prompted recall interviews or web-based interactive travel logs. This step is necessary because GPS is generally not able to capture all attributes of the travel survey, despite its success in capturing detailed mobility and travel time data.

GPS is widely used to estimate trip underreporting, by comparing responses from passive surveys with responses from traditional surveys (Bricka et al., 2011). Underreporting is typically higher for trips that last less than 10 minutes, and are higher for specific demographic types. Households that commonly underreported trips had 3 or more vehicles, 2 or more workers, 3 or more students, and/or had a low income. Younger individuals also tended to underreport trips (Bricka, 2008).

Determination of trip underreporting depends on the trip information estimated from raw GPS data. Various post-processing methods derive data in different ways, resulting in different trip underreporting figures (Bricka et al, 2003). These gaps in information make necessary the additional step of asking respondents for further information or clarification, and they underline the necessity for GPS-based survey standards. Table 16 reports values of trip underreporting observed in different GPS-based travel surveys.

GPS-BASED STUDIES	YEAR	UNDER-REP %	TYPE
Austin Household Travel Survey – Processing Method 1	1998	12	In-Vehicle
Austin Household Travel Survey – Processing Method 2	1998	31	In-Vehicle
California Statewide Household Travel Survey	2001	23	In-Vehicle
Post-Census Regional Travel Survey - Southern California	2002	35	In-Vehicle
Pittsburgh Travel View Household Travel Survey	2002	31	Personal
Household Travel Survey for the St. Louis Region	2002	11	In-Vehicle
Ohio Statewide Travel Study	2002	30	In-Vehicle
Laredo / Webb County Texas Household Travel Survey	2002	81	In-Vehicle
Mobile Activity Logger with GPS-Equipped Cell Phone (MoALS) - Matsuyama JPN	2004	5	Personal
Sidney Continuous Household Travel Survey	2004	7	Personal
Kansas City Regional Household Travel Survey	2004	10	In-Vehicle
Washoe County Travel Characteristics Study - Reno	2005	5	NA
NTS GPS Pilot - United Kingdom	2011	16	Personal

Table 16 – Respondents trip underreporting in GPS augmented travel surveys

3.4 Other GPS uses in the transport field

The reliability and accuracy of GPS technology have made it available to, and widely used, in transportation-related applications other than GPS-based travel surveys. Some of these applications are listed below:

- road safety: GPS allows researchers to obtain accurate data within a defined interest area, facilitating the study of roadway safety. Through analysis of precise speed and acceleration data, researchers can evaluate drivers' behaviour and attention to safety regulations and can locate critical points throughout the network. The possibility to monitor speed is also used for intelligent speed adaptation applications to avoid user exceed speed limit;
- traffic monitoring: the use of probe vehicles equipped with GPS integrates data collected through video cameras and loop detectors and can provide better-quality real-time results;
- infrastructure monitoring: GPS is successfully used to determine the precise position of probe vehicles in infrastructure monitoring, providing useful information to evaluate and forecast their performances;
- transport services: transport companies are able to use location-aware technologies to evaluate users' demand, combining GPS-equipped vehicles with fare card readers or other access-monitoring devices. Transport companies can also directly share real-time service information with users equipped with GPS-enabled mobile phones or PDAs;
- fleet management: transport, commercial and freight companies can equip their vehicles with GPS, enabling them to collect real-time data for use in managing the service and more precisely calculating service performance indicators;
- environmental monitoring: the ability of GPS to obtain precise acceleration and speed data with a short logging interval makes it an effective tool for collecting data on vehicle emission models.

The increasing accuracy and affordability of GPS devices has led to their rapid diffusion in several fields. Further technological innovation in location-aware technologies will provide more accurate data that will in turn spur further improvement of GPS-based application capabilities.

3.5 Considerations in the use of GPS in travel surveys

Mobility surveys require a standardization and inventory of all existing research, to compare results from studies conducted using different methodologies and in different locations. Currently, differences in survey period, sampling frames, methods and other survey steps make results difficult to compare.

There is a need for further development of reliable identification algorithms that can guarantee GPS-only travel surveys with limited self-reporting phases. Currently, the need for prompted recall interviews – either face-to-face (Madre et al., 2008), CATI, or internet based (Lee-Gosselin et al. 2006; Bohte and Maat, 2008; Auld et al., 2012) – still result in a heavy burden on respondents. On the other hand, GPS devices are becoming increasingly accurate, less expensive, more widely-used and widely-available. The augmentation of GPS devices with increasingly-available supplementary motion sensors, such as accelerometers and gyroscopes, can contribute to the enhancement of data derivation accuracy.

Advantages

GPS-equipped smartphones are becoming cheaper and widespread, and will allow researchers to develop smartphone-specific tracking applications that can rely on GPS receivers and augmented location estimation (AGPS, GSM and WiFi positioning).

GPS data allow researchers to calculate trip rate correction factors for diaries, and to perform longer-duration studies (Doherty 2006; Wolf 2006; Bricka, 2008). Researchers recognize the extremely rich added-value of GPS data, noting its help in studying different in-depth aspects of travel behaviour, such as route choices, speed distribution, habitual behaviour, etc.

Active GPS-based surveys, in which researchers still ask participants directly for information that cannot be derived from raw GPS data, can create burdens on participants similar to those associated with traditional survey methods. These burdens can be significantly lessened through use of passive or low-interaction surveys, which use advanced post-processing techniques rather than direct surveyor-participant interaction, to obtain data. These passive and low-interaction surveys allow researchers to carry out longer surveys while placing less of a burden on participants, thereby decreasing survey fatigue. Higher-quality data and a longer survey length allow for the consistent reduction of sample size without affecting the quality of survey results.

Though the use of GPS-only travel surveys is feasible, traditional and GPS-augmented methods still play important roles. The establishment of common GPS standards for data collection and post processing will allow researchers to collect data and outcomes in the same format, across surveys methods and study locations, thereby increasing comparability of results.

The use of wearable devices for personal tracking, while feasible and widely used, is not the only solution. In-vehicle tracking remains the most suitable choice for specific driving and car use studies (Ogle et al., 2002; Schönfelder et al., 2005) and results in a lower burden on respondents (Shuessler and Axhausen, 2009).

One possible future development in the use of GPS technology in transport behaviour studies is the use anonymous positional databases. An increasingly large number of organisations (e.g. Insurances) are creating datasets containing logs of the movement of GPS-equipped vehicles. Access to this data can provide information on the representativeness of traditional travel survey outcomes (Wolf, 2008).

Disadvantages

Although they offer solutions to various data collection-related problems typical of traditional surveys, GPS-based travel surveys contain their own structural biases. Younger people and larger, more-educated households are more willing to participate to a GPS travel surveys, while the elderly and persons with lower education levels are still not as comfortable with the use of the survey tool. Issues contributing to sampling bias are related to privacy issues and technology divide, which largely affect low-income households and the elderly. Correlations between acceptance rates and mobility behaviour must be further analyzed. The use of specific surveys for specific population groups is likely the best compromise for minimizing the sampling biases of the survey tools (Bricka and Bhat, 2006; Bricka, 2008; Marchal et al., 2008; Stopher and Greaves, 2008).

Acceptance issues are related to privacy concerns and lack of control over personal data. Possible remedies include a better explanation of the survey objectives and methods, better training for interviewers, and the possibility for respondents to have more control over their personal data.

In addition to respondents' privacy concerns, privacy regulations can affect data use and collection. Certain legal requirements can even prevent the use of geo-coded personal data. One possible solution is data 'fuzzyfication,' which will degrade data quality and can confine GPS to a supporting role, augmenting self-reporting diaries.

Operational issues can arise due to improper respondent device-management and handling. The most effective way to limit the impact of these problems on survey outcomes is to limit respondent interaction with devices (switching on/off, battery charging, etc.) as much as possible.

Survey organizational challenges must be further explored. Definition of operating instructions, the number of devices that need to be used and their update rates, possible confusion within households, and send-out and pick-up procedures are new tasks that must be added to the survey process. One structural problem related to these tasks is the need for replacing damaged, stolen or lost devices as the travel survey goes on. Lower device costs limit the impact on the survey budget, but replacement of devices still poses a logistical challenge to the survey team.

Implementation costs of GPS devices must also be considered. It is difficult to compare cost between the different available survey tools (traditional tools, GPS, multi-instrumental). Currently, GPS surveys are more expensive than active report diaries due to economies of scale and the necessity of additional traditional travel survey tools for data collection and validation. Nonetheless, GPS surveys allow researchers to easily collect multi-day reports and reduce sample numbers.

CHAPTER 4 - A GPS-based travel survey in the city of Torino

Politecnico di Torino’s transport planning research group carried out a GPS survey in 2010 to study the implementation of passive devices, alone or as complementary tool for use with travel surveys, for future Italian applications. Results from field tests can provide researchers with valuable context-specific information on the tool’s implementation process.

The selected survey area was the Torino metropolitan area, and in particular, the city of Torino. Torino is the capital of the Piemonte region, located in northwest Italy. The city itself has a population of approximately 1.000.000 inhabitants, while the entire metropolitan area has a population of approximately 1,7 million inhabitants. Almost 40% of the population of the entire region of Piemonte resides in the city of Torino, which covers just 4% of the region’s surface.

Surveyors sought respondents who were residents of the survey area and were expected to travel to and from the Torino city centre during the survey period. This allowed researchers to evaluate the characteristics of GPS data collection for trips performed in a densely-built environment. Respondents were asked to declare any expected travels inside the survey area for most of the duration of the survey. However, for the purpose of the survey, trips outside the survey area were also considered.

Figure 27 illustrates the geographic position of the Torino metropolitan area and the city of Torino, in relation to the Piemonte region.

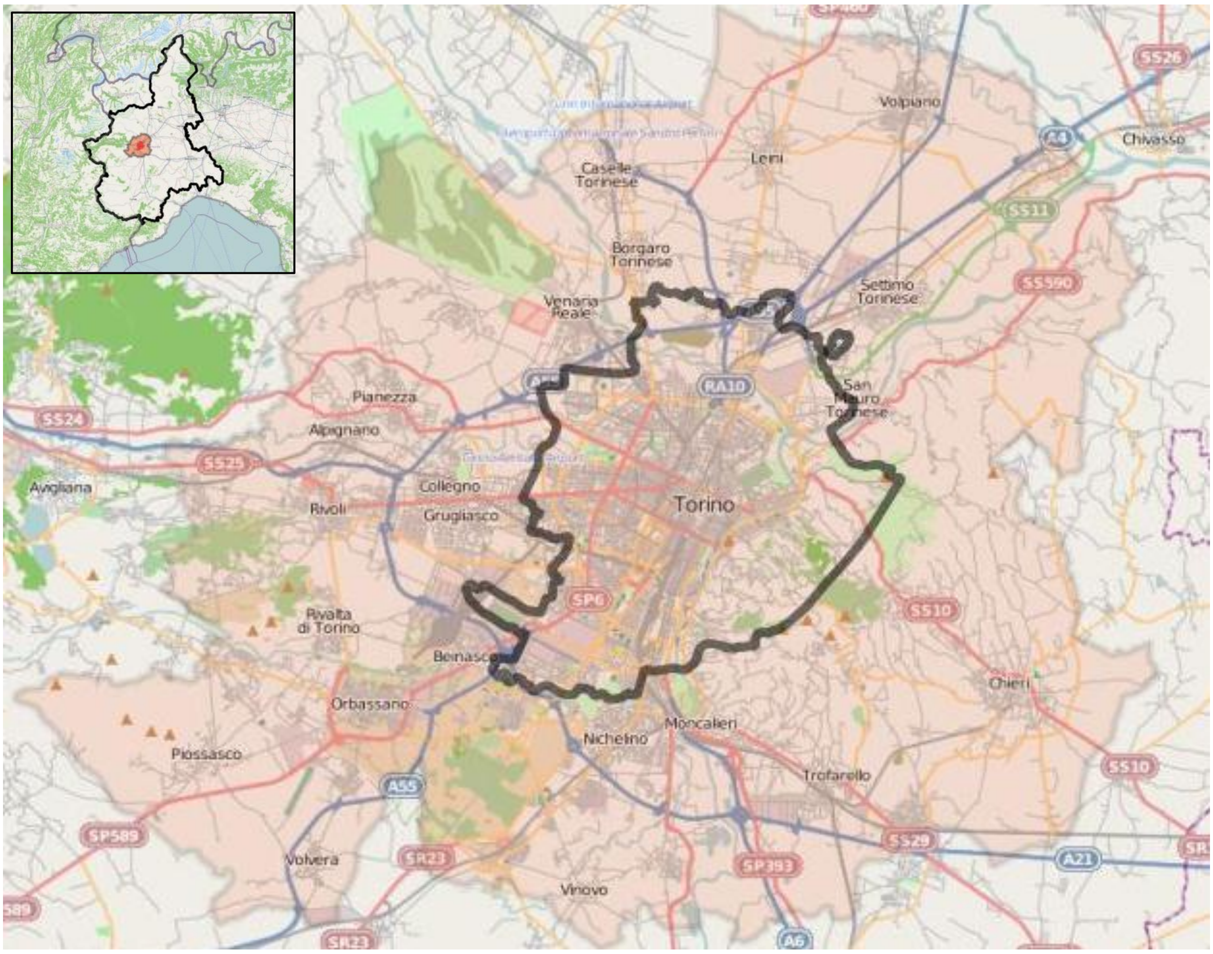


Figure 27 – Survey Area

The following paragraphs will describe the survey planning, survey methodology and survey administration phases, as well as the data analysis plan designed for the collected data. The planning phase dealt with the identification of survey goals and various factors that affect survey implementation. Survey needs and resource limits were also defined in this phase. Given these survey requirements and constraints, the research team designed a specific survey methodology to collect the desired data from the selected survey sample. Data collection will be explained within the discussion of the survey administration phase. In the data analysis phase, researchers used collected data to assess the effectiveness of the observed survey tools and to identify possible ways to improve observed results. Figure 28 illustrates the steps contained in each research phase.

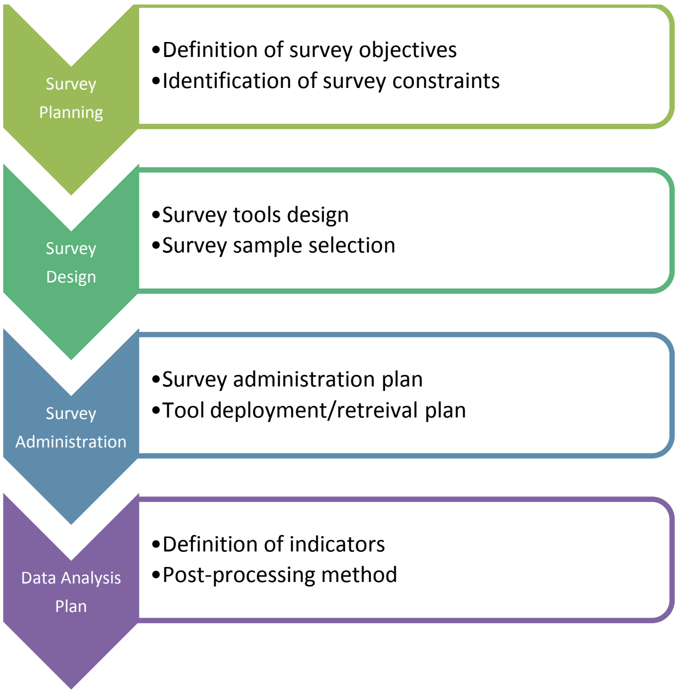


Figure 28 – GPS survey scheme

4.1 Survey planning

Politecnico di Torino researchers were interested in exploring the extent to which it is possible to replace traditional travel diaries with passively-collected positional data. To explore this possibility, it was necessary to design a set of instruments that would allow the research team to identify potential solutions to anticipated problems associated with the use of GPS-based travel surveys. These instruments would also allow researchers to evaluate the data quality of GPS-derived travel behaviour information, comparing it with data derived using traditional survey tools. The use of both GPS data collection and traditional survey tools on the same survey sample was deemed necessary, as comparable outcomes were required in order to study the structural differences between survey tools.

The research team agreed on a survey period of 2 weeks, in order to gather enough data to properly compare outcomes between survey instruments, and to observe day-to-day variability in respondents' travel patterns. This relatively long survey duration was expected to result in a high burden on survey participants.

To achieve the greatest possible degree of comparability, researchers needed to recruit participants who could successfully undertake a burdensome survey effort with a high cooperation rate. This would limit respondent underreporting related to the use of traditional survey tools for the entire duration of the survey.

Before undertaking a survey effort, researchers had to address expected technological problems inherent to GPS data collection. In particular, the specific urban environment chosen as a study area posed numerous threats to the expected continuity of positional data.

The research team also had to properly address survey constraints related to limited technical and human resources, including the availability of GPS devices and the employability of research team members. These limitations strongly affected survey characteristics, as explained below.

Human resources

The research team consisted of four individuals involved in the overall survey process. The team was able to employ only one surveyor during the survey administration phase. This constraint limited the survey to one survey wave, due to the time requirements of deploying survey tools, explaining survey instructions and supervising data collection.

Technical resources

A total of 10 devices, used in the 2008 French NTS GPS subsample, were available to researchers. This limited device availability affected the overall number of respondents.

Device specification

The survey duration was affected by technical characteristics of the GPS device. Considering that each device had a storage capacity of approximately 30.000 positional records and 10 hours of battery life, it was necessary to find a proper compromise to guarantee a satisfactory survey length and proper logging interval.

Given 2 weeks as the length of the GPS device survey, the average daily recording period can be evaluated using Equation 4.1:

$$\boldsymbol{Avg\ Rec\ Time\ \left(\frac{h}{day}\right) = \frac{\left(\frac{30000\ GPS\ records}{14\ days} * Rec\ Interval\right)}{3600\ sec}} \qquad \textbf{Equation 4.1}$$

Suitable data collection intervals ranged from approximately 3 hours per day with a 5-second recording interval to approximately 6 hours per day with a 10-second logging interval. Certain logging frequencies can result in depletion of device storage or scattered positional observation. Based on previous tests and a literature review, the research group agreed to collect positional data with a 10-second frequency, which they considered sufficient to provide an overview of travel behaviour and accurate information on travel times and routes.

Technology structural biases

Several problems can arise in the use of GPS for passive data tracking in the most densely-built areas, as described in Chapter 3. Signal loss and unreliable data were expected during the survey period in such areas, in particular in the city centre of Torino. The presence of numerous buildings was expected to limit both the accuracy of GPS devices and the continuity of data collection while respondents' trips were being tracked.

The impact of this data stream disruption needed to be evaluated in order to properly manage limited resources and maximize survey outcomes. For this reason, the research team agreed to carry out a preliminary GPS pilot test.

4.1.1 Considerations and survey framework

The identification of survey needs and constraints allowed the research team to design a list of the survey features that were used as a basis for the survey design. Table 17 summarizes the defined survey characteristics and the reason for their selection.

SURVEY NEEDS		SURVEY CONSTRAINTS	
Item	**Survey feature**	**Item**	**Survey feature**
Compare results between traditional and passive survey tools and evaluate their possible concurrent use	Multi-instrumental survey	Limited number of GPS devices	Only 10 respondents can be surveyed each survey wave
Carry out a long-term survey to observe travel variability throughout the survey period, limiting fatigue and item non-response	Survey sample consisting of highly-cooperative respondents	Limited number of surveyors during the administration phase	Survey limited to one wave
Evaluate possible data collection problems with GPS devices	Design of specific GPS pilot survey	GPS device has a limited capacity for record storage	10-second logging interval with a 2-week survey duration

Table 17 – Survey needs and constraints and resulting survey features

The Torino GPS survey was conceived as a multi-instrumental survey. The use of both traditional and new passive data collection tools helped researchers to comparable results and to evaluate the degree to which the different methods could be integrated. The survey consisted of two stages: a GPS pilot test, limited in survey sample and survey length, and a main GPS survey.

The GPS pilot required the concurrent use of a self-administered travel diary and a GPS device, as illustrated in the survey framework in Figure 29.

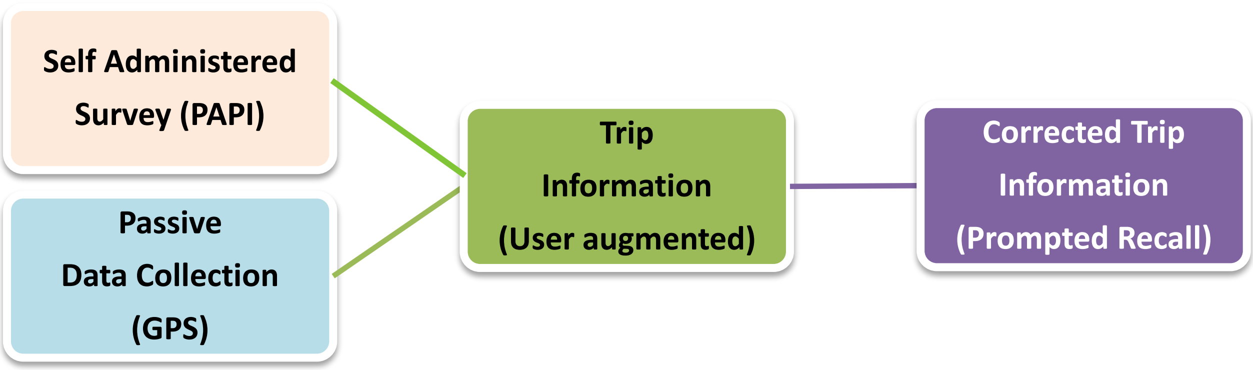


Figure 29 – GPS pilot framework

Researchers identified missing or uncertain data entries and learned of trip underreporting and GPS-related problems directly from the participants at the end of the data processing phase.

The scheme adopted for the main GPS travel survey, illustrated in Figure 30, consisted of the parallel use of traditional and passive survey tools. Subsequent comparisons were made between results reported by the user, observed by the GPS, and with the use of GPS as a supplement to users' declared data.

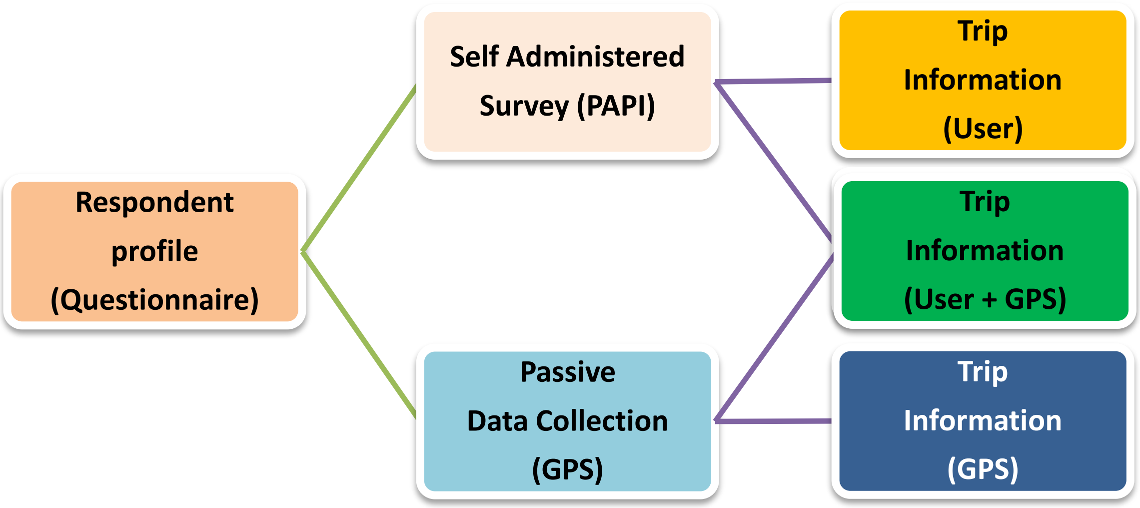


Figure 30 – GPS travel survey framework

The survey methodology for both tests was developed according to the guidelines defined in Table 17.

4.2 Survey methodology

The research team developed this survey methodology based on the survey framework and guidelines defined during the planning phase. The following paragraph describes survey characteristics, such as sample size, duration and detailed survey steps.

4.2.1 Sample selection

According to expected survey features and outcomes, researchers had to select a proper sample. Considering the various objectives of the GPS-based test and survey, described in the previous paragraphs, the research team identified two survey-specific sampling units.

GPS-pilot test – 4 Day Survey – Sample selection of 4 respondents

The GPS pilot test was designed to be performed prior to the main GPS survey in order to assess possible GPS device-implementation issues and to define guidelines for overcoming these problems. The survey was designed with a survey length of 4 days.

Considering the need for feedback and ease of contacting respondents, researchers decided to recruit participants within the Politecnico di Torino transport research group. Defined selection criteria included users' travel patterns and expected use of varied means of transport, in order to guarantee a proper observation of different trip distances, performed trips-per-day, modal choice, etc.

The first recruitment contact was performed on March 15th 2010. Four researchers with the required characteristics agreed to participate in the pilot survey.

GPS travel survey – 14 Day Survey – Sample selection of 10 respondents

The main GPS personal travel survey was designed to study the issues of the implementation of a larger GPS-based survey in the city of Torino.

Considering all possible respondents, researchers decided to recruit participants to the focus group of a research project dealing with the development of a GPS-based Public Transport Navigation application, known as the SMART-Way project[1].

The recruitment phase is summarized in Table 18.

	23/05/2010	**24/05/2010**	**25/05/2010**	**25/05/2010**
SURVEY PHASE	Email reminder	Telephonic contact	Expected deployment	Expected start of survey

Table 18 – GPS survey recruitment phase

The first recruitment contact took place during the SMART-Way focus group. The focus group was held in Torino on April 20th, 2010, during which participants were asked for their interest in being included in the upcoming GPS-travel survey. 10 individuals out of 14 participants agreed to be contacted to carry out the GPS survey. Potential respondents agreed to provide surveyors with a phone number and email address.

The 10 respondents were contacted by phone on May 24th , 2010, to define a specific deployment plan. Each respondent received a brief description of the survey plan by email prior to the survey. One individual declined to participate to the study, thereby reducing the total number of survey participants to 9 individuals. Due to implementation limits, no sample replacement action was taken.

4.2.2 Survey tools

The research group agreed to provide respondents with a set of paper-and-pencil data collection tools (PAPI) to gather socio-economic information, and to measure travel behavior characteristics such as travel habits and attitudes. GPS devices were supplemented with specialized diaries for recording information on device functionality. Respondents used two complete survey methods at the same time, a traditional PAPI and a GPS-based passive survey. The total set of data collection tools consisted of the following data collection tools:

- socio-economic questionnaire, to understand users' travel habits and attitudes;
- travel diary, to collect data on performed trips directly from respondents;
- GPS device, to collect positional data;
- GPS diary, added as a supplementary survey tool to collect data on possible GPS issues.

Socio-economic questionnaire

The selected socio-demographic questionnaire was designed to verify travel and activity patterns, observe respondents' attitudes towards various transport modes, and record users' movement requirements for reaching basic services.

The questionnaire collected data focusing on the following four categories:

[1] The SMART-WAY project deals with the development of a GNSS-based mobile passenger navigation application for Smartphones. The application offers an interactive navigation service in public transport systems. Further information can be found at: http://www.smart-way.mobi

- demographics: individual characteristics and household information;
- use and ownership of various means of transport;
- most-visited locations and services;
- travel behaviour attitudes and habits.

The questionnaire provided useful information for the post-processing phase of the GPS-based travel surveys. A profile of expected travel behaviour was associated with each respondent and was used in the GPS post-processing phase to help researchers derive further trip information.

For example, knowing a respondent's home and workplace addresses allows researchers to easily impute purpose information for habitual trips. Likewise, acquiring information on the availability of various means of transport and preferred travel modes provides researchers with supplementary information to support the detection of transport mode.

Travel diary

The travel diary used for the GPS pilot study was designed as a trip-based self-administered questionnaire, illustrated in Figure 31 (see ANNEX 6 for details). Important information included:

- date and day of the week;
- number of the stage (within the trip);
- indication of an habitual trip;
- origin and destination of the trip stage, expected at street-level precision, including departure, end time and travelled distance. Desired accuracy was at the minute-level for time, kilometre-level for trips exceeding 1 km, and 100-meter for the trips below that threshold;
- transport mode;
- trip purpose.

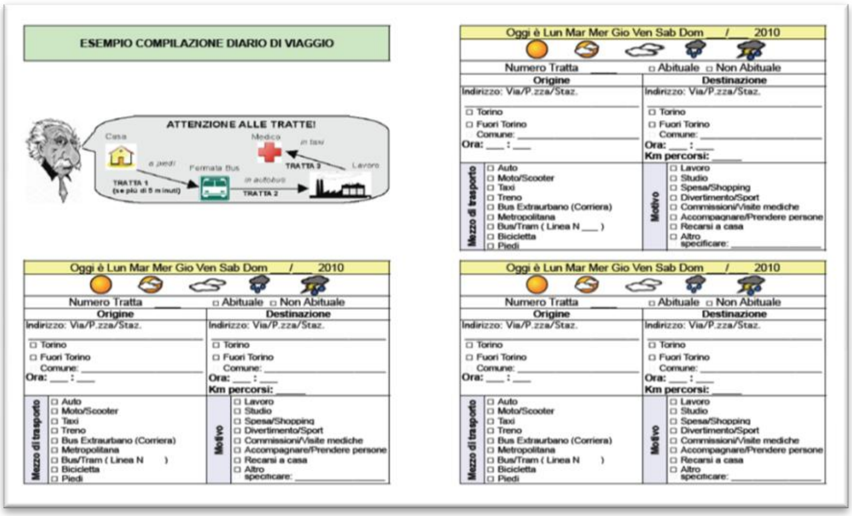


Figure 31 – Travel diary

The survey instrument employed in the Torino GPS surveys had already been used by Politecnico di Torino transport researchers in previous travel surveys.

GPS receiver

The GPS receiver was the survey's main data collection tool and is the survey tool evaluated in this study. Respondent burden was reduced as much as possible by using a light, small, and easy-to-use GPS logger. Main features of the device are illustrated in Figure 32.

The device was comparable to a cell phone in size and weight. Respondents had no direct interaction with the device aside from the power switch and the need to recharge it. Respondents were asked to turn the device on a couple of minutes prior to trip start, and to switch it off and recharge it at the end of the day. The device was equipped with a movement sensor capable of powering off the device, to avoid unnecessary battery depletion when the device was stationary.

According to the GPS manufacturer, the RoyalTek Blue GPS used in the surveys can provide more than 10 hours of continuous GPS data collection. The standard positional accuracy is 10 meters (RMS) and the speed error is 0,1 m/s.

Figure 32 – GPS device features

Considering known device-related issues, it was important for the research team to guarantee satisfactory positional accuracy, logging starting speed, battery life and storage. Judging from the specifications, the chosen GPS device was expected to be able to record accurate data for the survey purpose, locking satellite and recording data in less than a minute (45 seconds of cold start). These characteristics allowed researchers to avoid missing trips and to collect data at street-level accuracy.

The device provides data using the NMEA-0183 format, which records a large number of positional and navigational parameters (see ANNEX 2 for NMEA sentences available for the adopted GPS device). Information used in the survey is reported in Table 19.

Name	Unit	Description
Date	ddmmyy	Date
UTC Time	hhmmss.sss	Time
Latitude	ddmm.mmmm	Latitude
Longitude	dddmm.mmmm	Longitude
Speed	Km/h	Horizontal Speed
Satellites Used	Num	Range 0 to 12
HDOP	Num	Horizontal Dilution of Precision

Table 19 – NMEA information used in the GPS survey

GPS diary

The research team designed a specific questionnaire on the subject of GPS operation and functionality, to collect additional information on possible device-related problems. An example of the GPS diary is shown in Figure 33 (see ANNEX 7 for further details).

The diary recorded information on:

- date and day of the week;
- proper GPS functioning;
- issues with GPS functioning.

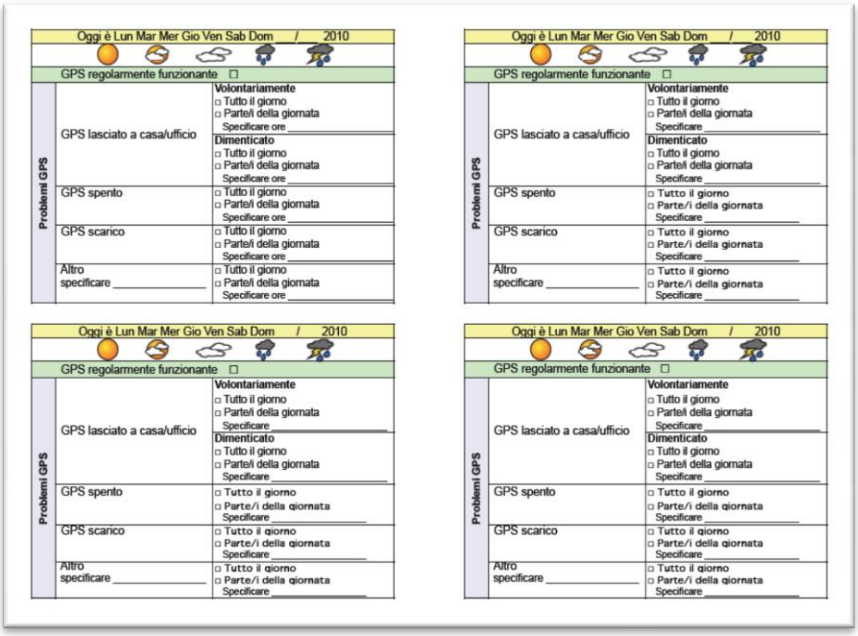


Figure 33 – GPS diary

Respondents filled in the questionnaire during the entire survey duration of the GPS pilot, as well as during the GPS-only week of the main GPS travel survey.

The GPS diary was designed to help researchers understand the reasons for gaps in the availability of GPS data for the whole or part of the survey day. The ability to detect and understand reasons for GPS item non-response is useful when analysing GPS-only travel surveys; it allows researchers to avoid recording a non-moving day when, in fact, missing data was attributable to a GPS technical problem or user error.

4.3 Survey administration

Implementation of the GPS travel survey followed the framework defined in the survey planning phase. The GPS pilot test was carried out from March 16th to 26th 2010, while the first contact with potential survey participants for the GPS survey occurred on April 20th. Final arrangements for confirmation of survey participation and scheduling of tool deployment took place on May 24th, prior to the start of the survey. The Torino GPS travel survey required the work of four researchers from May 23rd to June 16th,2010.

4.3.1 GPS pilot test

The GPS pilot survey covered 4 days from deployment to the end of the survey. The use of survey tools for each survey day is shown in Table 20.

	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5
GPS	■	■	■	■	
Travel Diary	■	■	■	■	
Face to Face PR					■

Table 20 – GPS-pilot survey plan

Face-to-face prompted recall interviews were used at the end of the survey period to assess possible technical problems and discuss with respondents possible improvements to GPS data collection (recharging intervals, device placement, etc.). Respondents were also asked to confirm and validate the results of GPS post-processing derivation.

Observing results from both survey tools, it is possible to evaluate the differences in data collection between traditional travel diaries and GPS-derived trip information, and to understand the ways in which the main GPS travel survey can be improved.

Participants reported trips using a wide variety of private and public means of transport and in different areas of the city of Torino for four weekdays, from Tuesday to Friday. The first and last days were dedicated to device deployment and retrieval, with data collection limited to half a day. The survey was carried out in March, 2010. Detailed survey periods for each respondent are shown in Table 21.

GPS	Start	End
28312F	16/03/2010	19/03/2010
282DBC	23/03/2010	26/03/2010
282FFB	23/03/2010	26/03/2010
285898	23/03/2010	26/03/2010

Table 21 – GPS-pilot schedule

Researchers did not witness any major problems during the pilot survey that would prevent the research group from carrying out the main GPS survey; nor were there any reasons for changes in the survey framework. GPS devices and traditional survey tools were carried with no particular problem and device handling was generally easy. Problems arose from the limited battery life of some of the devices, which require daily charging but were not always charged by participants. GPS data collection was not continuous, but researchers were able to detect underreported trips and to complete missing travel diary information. Data analysis focused on understanding the collected data, and on finding possible biases and solutions to address those biases during the actual travel survey.

Survey issues

Observation of collected data showed several GPS data collection problems during the pilot survey. Researchers defined guidelines to limit the impact of collection biases on the subsequent main GPS survey.

General suggestions for proper device management included turning on the GPS receiver or reactivating it a few minutes before trip start, to prevent the effects of warm/cold start. Devices had to be kept as free of obstacles as possible, to allow for better signal reception. Thus, respondents were asked to keep the devices in front or lateral pockets while they were carried during on-foot tracking, and outside pockets whenever possible. Because the devices had a lower battery life than was actually reported by the manufacturer, respondents were asked to recharge them at the end of every travel day and to keep chargers with them as often as possible, to facilitate recharging as needed.

4.3.2 GPS survey test

The survey start and conclusion were scheduled during weekdays, from Wednesday to Friday, and timing was personally arranged with each respondent. The first deployment took place between May 25th and June 1st, while the final retrieval phase lasted from June 9th to 16th. Recognizing the high burden faced by participants during the 2-week survey, each respondent was compensated with Politecnico di Torino merchandise worth 50 € when tools where collected at the end of the survey.

Researchers instructed participants on GPS operational features and device handling. Surveyors showed respondents how to check for GPS status using device lights, in order to allow respondents to observe and report long recording gaps. Researchers also provided users with suggestions on possible GPS placement for optimal signal reception, based on the experiences of the pilot study. The survey was structured to give researchers multiple chances to support respondents and detect possible problems during device deployment and retrieval phases, described as follows.

The Torino GPS survey consisted of a 2-week GPS-based travel survey, and a 1-week self-administered travel diary concurrent with the first week of the GPS-based survey. Respondents also filled out a GPS functionality diary during the second survey week.

The tool deployment and retrieval consisted of 3 phases:

- Day 0: first tool deployment;
- Day 8: second tool deployment. Retrieval of traditional survey tools;
- Day 15: final tool retrieval.

A detailed survey timeframe and tool deployment/retrieval plan are shown in Table 22.

	DAY 0	DAY 1	DAY 2	DAY 3	DAY 4	DAY 5	DAY 6	DAY 7	DAY 8	DAY 9	DAY 10	DAY 11	DAY 12	DAY 13	DAY 14	DAY 15
Socio-Demographic	IN								OUT							
GPS	IN															OUT
Travel Diary	IN								OUT							
GPS Diary									IN							OUT

Table 22 – GPS survey and deployment plans

Face-to-face survey explanation took place during the first survey instrument deployment step (Day 0). The second deployment retrieval stage (Day 8) gave the research team an opportunity to detect and overcome possible unexpected implementation problems. Surveyors were able to ask respondents about problems with the GPS-only data collection, and to award respondents with Politecnico di Torino gifts, on the final day of the survey (Day 15).

The detailed GPS travel survey deployment schedule for each respondent is shown in Table 23.

Respondent ID code	Initial deployment	Survey Start	GPS-only survey start	Survey End
N0002	25/05/2010	26/05/2010	02/06/2010	09/06/2010
N0030	25/05/2010	26/05/2010	02/06/2010	09/06/2010
N0003	26/05/2010	27/05/2010	03/06/2010	10/06/2010
N0033	26/05/2010	27/05/2010	03/06/2010	10/06/2010
N0035	26/05/2010	27/05/2010	03/06/2010	10/06/2010
N0037	26/05/2010	27/05/2010	03/06/2010	10/06/2010
N0032	27/05/2010	28/05/2010	04/06/2010	11/06/2010
N0034	27/05/2010	28/05/2010	04/06/2010	11/06/2010
N0001	01/06/2010	02/06/2010	09/06/2010	16/06/2010

Table 23 – GPS travel survey deployment schedule

Following the previously-designed deployment and retrieval plan, researchers delivered and retrieved the survey tools at respondents' homes unless otherwise arranged. Two respondents had preferred to surrender the survey tools at the Politecnico di Torino building.

Survey issues

After the first deployment phase, available devices were reduced to 8 due to technical problems. Battery and device charger problems prevented researchers from keeping one of the participants in the survey.

Respondents reported problems with cold/warm start at the beginning of each trip by witnessing delays in data collection, evident in the device's lights. Participants dealt with limited device battery duration (indicated by a blinking 'battery power light'), a problem that had not been witnessed during the first study.

GPS diaries indicated occasional mishandling and forgotten devices, both of which affected the survey outcomes, as described in paragraph 4.6.2.

4.3.3 Supplementary data collection tests

Reported data collection issues during both pilot and main GPS surveys spurred researchers to design a GPS data collection evaluation test with various GPS and GPS-equipped devices, to evaluate potential data collection under non-ideal circumstances using the most up-to-date GPS devices. Results of this test can help guide researchers in selecting data collection tools in the future.

A supplementary test, specifically designed for the assessment of data collection, can help researchers to study the future possibility of implementing GPS-equipped Smartphones in travel surveys.

This supplementary test included specific data collection tests in controlled routes for the GPS devices, and a multi-day tracking test using a Smartphone application.

4.4 Data analysis design

Data analysis represents a key step in both traditional and passive travel surveys. The overall objective of this study was to evaluate ways to implement GPS survey tools within a traditional travel survey framework, assessing the necessary amount of information that respondents would have to provide. Data analysis measured the quality of data provided by each tool, compiled travel behaviour information, and compared reported with derived values to assess the impact of imputation on travel survey results.

Analysis was performed separately on the travel diary, GPS-only data, and GPS-augmented travel diary outcomes. Data analysis methods were applied following a different data analysis plan for the pilot and GPS travel surveys. Researchers used a simplified analysis framework for the GPS pilot test and evaluated all the designed indicators for the main GPS survey.

The pilot test was carried out to collect the necessary data to design the subsequent data analysis phase of the GPS survey, as described in Paragraph 4.2. The complete data analysis plan is reported in Table 24.

Travel diary	GPS-based diary	Travel diary and GPS
QUALITY INDICATORS **Trip underreporting** **Item non-response** **Non derivable information** **Rounding** **Address quality** **TRAVEL BEHAVIOUR** **Trips per user per day** **Use of transport modes** **Travel time** **Activity duration** **TRAVEL BEHAVIOUR (IMPUTED)** **Derived length** **Derived time** **Derived route** **TRAVEL BEHAVIOUR (AUGMENTED)** **Augmented travel diary**	**POST-PROCESSING RESULTS** **Filtering stage results** **GPS detected trips** **GPS trip quality** **QUALITY INDICATORS** **Trip underreporting** **Item non-response** **Non derivable information** **Rounding** **Address quality** **TRAVEL BEHAVIOUR** **Trips per user per day** **Use of transport modes** **Distance** **Travel time** **TRAVEL BEHAVIOUR (AUGMENTED)** **Augmented travel diary**	**DATA COMPARISON** **Matched trips** **Diary trip underreporting** **Item-non response** **Trip number comparison** **Time entries comparison** **Duration comparison** **Activity duration comparison** **TRAVEL BEHAVIOUR (AUGMENTED)** **Improved reporting** **Reduced non response** **Augmented travel diary** **TRIP INFO DERIVATION** *PURPOSE DETERMINATION* **Most visited locations** **Derivation results** *TRANSPORT MODE DETECTION* **Classification rules**

Table 24 – GPS pilot data analysis plan

The purpose of data analysis was to test the designed processing methods and to detect possible problems in GPS derivation. Data analysis also allowed researchers to fine-tune trip derivation methods, understand transport mode classification, and identify trip purpose.

Data analysis of the main GPS survey benefitted from the experience of the GPS pilot survey in terms of data filtering and trip and stage determination. Table 25 shows the indicators used in the data analysis process.

Travel diary	GPS-based diary	Travel diary and GPS
QUALITY INDICATORS **Trip underreporting** **Item non-response** **Non derivable information** **Survey fatigue** **Rounding** **Address quality** **TRAVEL BEHAVIOUR** **Trips per user per day** **Use of transport modes** **Distance** **Travel time** **Activity duration** **TRAVEL BEHAVIOUR (IMPUTED)** **Derived length** **Derived time** **TRAVEL BEHAVIOUR (AUGMENTED)** **Augmented travel diary**	**GPS PROCESSING QUALITY** **Filtering stage results** **GPS detected trips** **GPS trip quality** **QUALITY INDICATORS** **Trip underreporting** **Item non-response** **Non derivable information** **Survey fatigue** **Rounding** **TRAVEL BEHAVIOUR** **Trips per user per day** **Use of transport modes** **Distance** **Travel time** **Activity duration** **TRAVEL BEHAVIOUR (IMPUTED)** **Derived length** **Derived time** **Derived route** **TRAVEL BEHAVIOUR (AUGMENTED)** **Augmented travel diary** **TRAVEL BEHAVIOUR INDICATORS** **Time loss** **Extra travelled distance**	**DATA COMPARISON** **Matched trips** **Diary trip underreporting** **Item-non response** **Trip number comparison** **Time entries comparison** **Duration comparison** **Activity duration comparison** **TRAVEL BEHAVIOUR (AUGMENTED)** **Improved reporting** **Reduced non response** **Augmented travel diary** **TRIP INFO DERIVATION** *TRANSPORT MODE DETECTION* **Classification rules** **Mode detection results** *PURPOSE DETERMINATION* **Most visited locations** **Derivation results** *QUESTIONNAIRE INFO (DERIVED)* **Travel habits and attitudes**

Table 25 – GPS survey data analysis plan

The indicators reported in the previous frameworks will be described in the following paragraphs. Data analysis indicators for both traditional and GPS data are grouped into the following four categories:

- quality indicators;
- travel behaviour measures;
- travel behaviour imputation;
- augmented travel behaviour.

Additionally, a specially-designed post-processing phase allowed researchers to identify travel behaviour measures using GPS data, as described in the GPS diary paragraph. The following two data analysis toolsets will be described in the GPS-based diary section:

- GPS processing quality toolset, for evaluation of post-processing results;
- travel behaviour indicators, for description of possible uses of GPS data beyond standard travel behaviour measures.

The research team was able to compare the outcomes of the two surveys, illustrating the differences between GPS and travel diary outcomes, while outlining possibilities for integration and comparison of the two.

Researchers were then able to assess the degree to which GPS could completely substitute a traditional data collection method. Indicators were grouped into the following two categories:

- data comparison: researchers assessed differences between the two survey methods (for both pilot and main GPS surveys);
- GPS-based trip information derivation: researchers evaluated the potential for derivation of travel information, such as transport mode, purpose and travel habits and attitudes, from raw GPS data.

The following paragraphs will describe each family of indicators by data collection method, as reported in the two data analysis plans.

4.4.1 Travel diary

Travel diary information provided the basis for comparison. Unreliable data were removed from self-administered diaries, which were then coded and fixed through a process involving the following steps:

- data coding: transcription of the reported information into an electronic format according to pre-determined information coding;
- travel data check: screening data for reporting errors and missing information;
- travel data imputation: filling in, wherever possible, of missing data using other available information.

Information in the travel diaries provided surveyors with a complete picture of reported travel behaviour; specifically, of performed trips and activities. Results of trip reporting were compared with and augmented by GPS data in a later stage of data analysis.

Quality indicators

The first quality indicator used for analysis of travel diary information was the degree of data completeness. Accuracy of final results hinges upon respondents' ability to report information at the expected level of quality. Assessment of data completeness and quality was performed using a set of indicators, reported as follows.

Travel diary completeness was evaluated by observing missing information identified during the imputation phase, using indicators such as:

- percentage of trip underrerporting: Reported trip chains were searched for data inconsistencies, such as a trip start not matching with the previous destination;
- overall percentage of missing items: Researchers identified overall item non-response and noted which items were more likely to be unreported.

In general, survey fatigue affects reporting more as the survey goes on. Observation of the trends of reported trip values and item non-response throughout the survey duration can provide researchers with information to assess the existence of this phenomenon. If a general trend towards lower trip and item reporting is identified as the survey proceeds, surveyors can prove survey fatigue.

Diary completeness indicators can measure the overall number and impact of missing items, using both the total number of missed entries as well as missed entries in single information categories. For the purpose of this analysis, reported times, trip lengths and location information were studied.

Single items can be used in combination in order to determine other measures. In particular, the Torino GPS survey considered travelling time and time spent at destination as derived measures, determined by combining information from multiple single items. Lack of correct temporal information, as well as trip underreporting, can prevent researchers from calculating such derived variables. Every missing temporal entry results in the loss of trip duration information for the related trip, and the loss of one 'time at destination' entry. An example of the impact of missing temporal information is illustrated in Table 26.

Trip start	Trip end	Trip duration	Time at destination
NA	23:40	NA	9 hours 40 minutes
9:20	9:35	15 minutes	NA
NA	NA	NA	NA
18:00	18:10	10 minutes	2 hours 10 minutes
20:20	21:00	40 minutes	

Table 26 – Impact of time information on activity duration calculation

Based on the previous considerations, it was possible to assess the impact of item non-response on derived measures by calculating the following indicators:

- percentage of missing travel time values ;
- percentage of missing information on time spent at destination.

Similarly, the percentage of unreported travelled distance and addresses were observed, in order to evaluate the completeness of the single information category.

Rounding is another common problem in traditional travel surveys. One possible method for identifying rounding problems in time values is to observe the distribution of the reported values and detect possible non-random effects, such as the concentration of times around particular values. In particular, researchers studied the number of reported time entries that were multiples of 5 or 10 – typical rounding increments. Similarly, the distribution of distance values was observed in order to identify possible rounding effects related to trip length.

Another data quality problem common to the travel diary is related to reported spatial information. Users were required to report addresses at the building level or by using the name of a well known point of interest. Location information is used by transport modelling applications to estimate travel demand in terms of origin and destination, and to derive the travelled distance using routing algorithms. Inaccurate geographic origin and destination information can result in inaccurate route and travel distance derivations. Researchers categorized reported addresses into 3 groups based on the expected quality of location information. Table 27 shows a sample evaluation of address quality.

Street Level	Point of Interest	Town / Neighborhood Level
Via XX Settembre, 74, Torino, TO	Politecnico di Torino, Torino, TO	Rivoli, TO
GOOD	**FAIR**	**INCORRECT**

Table 27 – Examples of address reporting

Assessment of the geographic accuracy of reported data was performed by calculating the percentage of locations that were reported inaccurately.

This first phase allowed surveyors to evaluate possible problems with the travel diary, testing whether biases commonly observed in traditional surveys had affected the Torino surveys. Further missing trip identification was possible during the trip-diary GPS augmentation.

Travel behaviour

Results of the travel diary data analysis, completed through imputation of missing trips and information, provided surveyors with a picture of users' travel behaviour during the survey period.

Data coding and data repair, utilizing user-reported data, allowed researchers to construct an overview of travel behaviour for each respondent by transport mode, survey day, day of the week, etc., based solely on travel diary information. For the purposes of this research, this overview of personal travel behaviour included the following elements:

- performed trips;
- means of transport used;
- travelled distance;
- time spent travelling;
- time spent at destination.

Outcomes of the analysis of travel behaviour using the trip diary were generalized as a reference for results of traditional survey tools, and provided a basis for subsequent analysis and comparison with GPS as a passive survey tool.

Travel behaviour imputation

Once traditional analysis steps were performed, researchers explored the potential of augmenting self-reported diary data with a geographic dimension, using GIS tools and additional available information. Steps in this augmentation process included:

- data geocoding: to associate geographic coordinates with trip and stage origins and destinations, as illustrated in the example in Figure 34;
- trip and stage geographic augmentation: to estimate distances and possible routes travelled by respondents during the survey period. Routes are determined by querying a transportation network database that finds the shortest path for a given (reported) mode of transport.

Figure 34 – Geo-coding process

Surveyors used geocoding and routing tools to derive characteristics such as distances and estimated time of reported trips, based on user-reported addresses. The designed method follows the principles of the assignment phase of origin/destination matrix data to a transport network, which can be performed using transport modeling software. An example of this routing schema is illustrated in Figure 35.

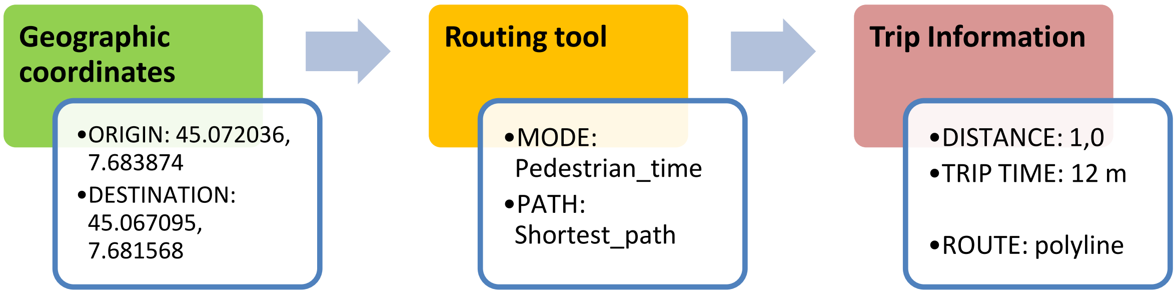


Figure 35 – Routing process

Various tools can be used to determine the coordinates of each location, as well as the travelled distance, using self-reported data (Greaves, 2003; Bonnel and Armoogum, 2005). For the Torino survey, the selected routing applications relied on ArcGIS network analysis capabilities for the assignment of motorized, bicycle and on-foot trips to a Navteq street network. Public transport information was derived separately using a PostGIS database fed by Google Transit Feed Specification data, provided by the metropolitan transport company (Gruppo Torinese Trasporti). Both private and public trip assignment provided surveyors with information on the shortest possible trips.

Routing tools yielded the following results:

- derived travel information, such as distance and time;
- derived route.

Comparison of reported and GIS-derived information helps researchers to understand the differences between self-reported and derived measurements, and to assess the potential for integration of derived travel behaviour information with traditional travel diary data.

Augmented travel behaviour

The use of imputed distance and travel times can successfully augment the travel diary without a need for additional user interaction. Information (travelled distance and trip duration) missing from the travel diary can be calculated using routing tools. Researchers evaluated the benefits of the use of imputed travel behaviour information on data completeness and travel behaviour variables.

Combining both data sources, it was possible to reconstruct a more complete overview of survey participants' travel behaviour, in terms of trip number, distance and times. GPS augmentation thus maximized the utility of the traditional travel diary in the context of this study.

4.4.2 GPS diary

Raw GPS data requires a post-processing phase in order to prepare data and derive necessary information on trips, as described in previous chapters. The following paragraphs will explain post-processing steps designed specifically for the Torino GPS surveys. The post-processing framework was based on previous GPS tests and methods reported in previous research (refer to Section 3.2 for an overview of travel behaviour derivation methods, drawn from a literature review of available GPS data).

The three basic post-processing steps include:

- data filtering: to remove unreliable and incorrect data from raw GPS data;
- trip and stage determination: to derive basic information on trips, such as origins, destinations and possible modal change points;
- trip information derivation: to derive trip purpose and mode of transport used.

The preliminary pilot test followed a simplified data analysis process due to its simpler test objectives. Results from the GPS pilot test were used to evaluate and improve post-processing methods for the main GPS survey.

GPS Post-processing results

The objective of a GPS post-processing phase within a GPS travel survey is to extract data that can be compared with trip diary data, in order to evaluate the possible impacts of GPS on a personal survey effort. Figure 36 summarizes the analysis steps that must be performed on travel diaries and GPS data in order for resultant information to be truly comparable.

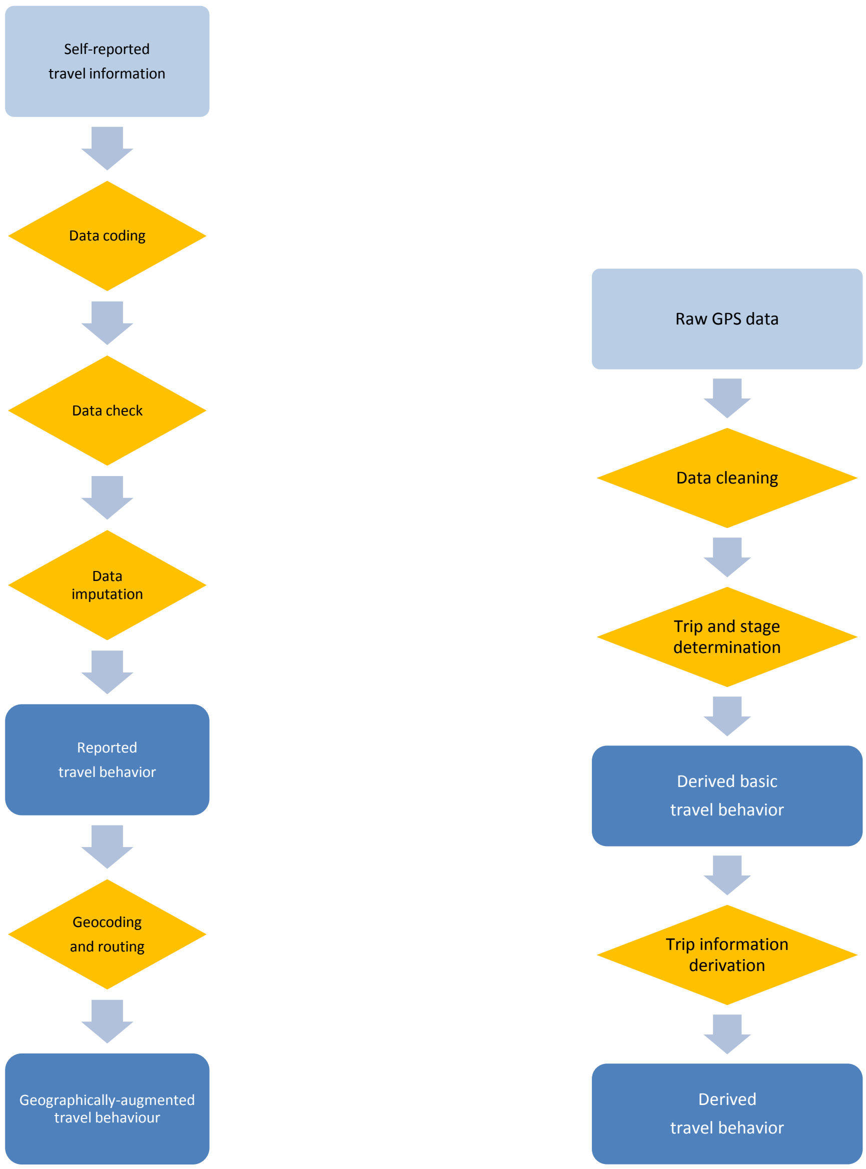


Figure 36 – Data analysis procedure

GPS data can easily provide basic travel behaviour information, such as duration, trip length, origins and destinations. The derivation of information including transport mode and purpose, referred to as trip information derivation, requires additional analysis that will be discussed during the comparison of GPS with traditional travel diaries.

Data cleaning

The data filtering phase consists of three main tasks: filtering, aberrant point identification, and outlier detection.

Data filtering: In the filtering phase, researchers eliminate non-random errors, such as records with high measurement uncertainty. Previous research had suggested the use of recording quality indicators provided by the GPS, such as the number of satellites contributing to the positional estimation and dilution of precision.

A minimum of three satellites is considered satisfactory for a proper two-dimensional positioning (see paragraph 3.3.1 for more details). GPS devices can determine position with fewer satellite signals relying on previous data, but the GPS devices employed in the survey were not considered reliable when providing such position estimation. Therefore, any position in the data stream collected using less than 3 satellites was automatically discarded. The condition used in the Python script used for selecting the valid GPS data according to GPS satellites is reported in Condition 4.1.

IF SAT >=3:
Point[3] = "VALID" **Condition 4.1**

Royaltek GPS devices provided several quality indicators, such as positional and horizontal dilution of precision (see ANNEX 4 for more information about GPS data and paragraph 3.3.5 for information about dilution of precision). Considering the need for fair two-dimensional positioning, horizontal dilution of precision (HDOP) was selected as the main quality indicator. This measure estimates the receivers' degree of positioning uncertainty based on the geometric position of the satellites locked by the GPS device.

Previous GPS survey experiences suggested a typical threshold value for HDOP of 5 or less, which allows for a satisfactory positioning estimation. However, high HDOP values largely impact stationary or low-speed data (Marchal et al. 2008, Yuan, 2010), especially in areas where a signal is not clearly received; for example, indoors. This results in poor satellite reception, non-ideal positioning of visible satellites, and consequentially, in unreliable location estimation recorded by the GPS device. Positional estimation uncertainty diminishes at higher speeds and where there is a stronger signal reception (typically in open spaces). In fact, lower dilution of precision values cannot by themselves guarantee positional accuracy if signal strength and clarity is not known. Observation of GPS data suggested the use of differentiated GPS dilution of precision filters, discriminating between stationary and non-stationary points. Stationary or low speed points, identified when recorded speed was below 1,1 km/h, were considered valid for HDOP values below 5. Condition 4.2 exemplifies the filter applied to GPS data.

IF SPEED < 1.1 AND HDOP <=5:
Point[3] = "VALID" **Condition 4.2**

A HDOP threshold of 20, which is considered the limit of poor satellite positioning (see Table 8), was selected for all other points in the data stream. Values exceeding this threshold were considered unreliable and were deleted from the positional dataset. Selection criteria used in this context are exemplified by Condition 4.3.

```
IF SPEED > 1.1 AND HDOP <=20:
    Point[3] = “VALID”
```

Condition 4.3

Aberrant point removal: after selecting valid points using GPS quality indicators, it was necessary to perform specific analyses on GPS records in order to remove possible aberrant points. Such detection relies on the observation of the acceleration value measured between consecutive GPS points. Whenever observed speed difference is greater than 10 km/h/s, the point is not selected. A threshold of a 15-second gap was set to allow meaningful calculation of acceleration. Condition 4.4 illustrates the structure of the detection rule.

```
IF TIME_INTERVAL <15:
    IF 0.5 ABS (Speed2-Speed1) / (T2-T1) < 10:
        Point[3] = “VALID”
```

Condition 4.4

Similar approaches had been used in other GPS-based travel surveys (Marchald et. al, 2011) and are used whenever quality indicators are not provided by GPS devices.

Outlier removal: a filter on speed readings was used at the end of the cleaning process in order to delete possible outliers in the dataset. This process considered the speed recording distribution before and after a checked point, creating a sample of speed recordings. The point was considered valid if it fell within the interval of 1.5 times the samples' inter-quartile range (IQR), as exemplified by Condition 4.5. The sampling interval was set to 60 seconds, 30 seconds prior to and 30 seconds after the inspected GPS record. A minimum of 5 values were needed in order to consider the sample valid. The filter was structured in order to detect and discard outliers, i.e., for low speed recordings.

```
IF  (Speed1>Q1-1.5*IQR) AND (Speed1<Q3+1.5*IQR):
    Point[3] = “VALID”
```

Condition 4.5

Overall performance of the filtering phase was assessed by observing the percentage of valid records over the total number of recorded data.

Trip and stage determination

Once uncertain measurements were removed from raw GPS data, it was possible to use a trip identification algorithm. The determination of trips from GPS positional data was based on 3 criteria: time interval, low speed and point density.

Time interval: whenever the observed time interval between two consecutive points exceeded 120 seconds, a new trip end was identified. Condition 4.6 illustrates the labeling process based on time.

```
IF Time2-Time1 >= 120:
    Point[4] = “TRIP_End”
```

Condition 4.6

Speed: if the cumulative time of consecutive low-speed points (below 1.1 km/h) exceeded the dwell time of 120 seconds, a new trip was detected. Speed exceeding the low-speed threshold set the time back to zero. The chosen method is shown in Condition 4.7.

```
WHILE SpeedX < 1.1:
        Time = TimeX + Time
        IF Time >= 120:
                Point[4] = "TRIP_End"
```

Condition 4.7

Position: GPS speed records of more than 1,1 km/h (threshold value of stationary points) can also occur in the case of a trip end, due to erroneous speed measurements or indoor movement during performance of an activity. Surveyors adopted a position-based detection mode in order to detect these potential trip stops.

A cursor was set to scroll throughout the filtered GPS dataset at the end of the trip identification phase. All points within a 20-meter search radius were selected. Whenever consecutive GPS points detected within the search radius totalled 120 seconds or more, the buffer area – a circle with 20 meters radius, centred on the sampled point – was identified as a possible stop**.** Whenever a stop was detected, the cursor restarted the search for stops, beginning from the first point not included in the buffer. Overlaying consecutive buffers were merged. The value of the search radius was determined to be twice the GPS receiver's standard accuracy. Figure 37 illustrates this detection process. Once a trip-end area was identified using this method, trip stop and successive start times were derived from the timestamp of the first and last time information present in the selected sample of points.

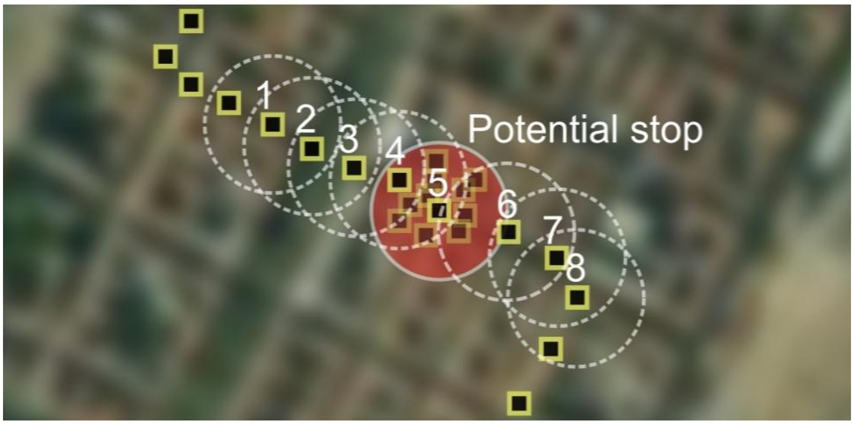


Figure 37 – Example of trip/stage detection according to point spatial distribution

Similar methods had been adopted in past GPS-based research (Stopher et. al, 2005; Shuessler and Axhausen, 2009; Marchald et al., 2008).

Cleaning of erroneous trips: once the trip detection phase was completed, points belonging to each trip (consisting of all GPS points from one trip end to the successive trip end) were grouped together and became the vertexes of the final trip segments. After the creation of polylines from GPS points, it was necessary for researchers to eliminate short segments incorrectly detected as trips, or segments which provided inconsistent information. Figure 38 shows an example of discarded trip.

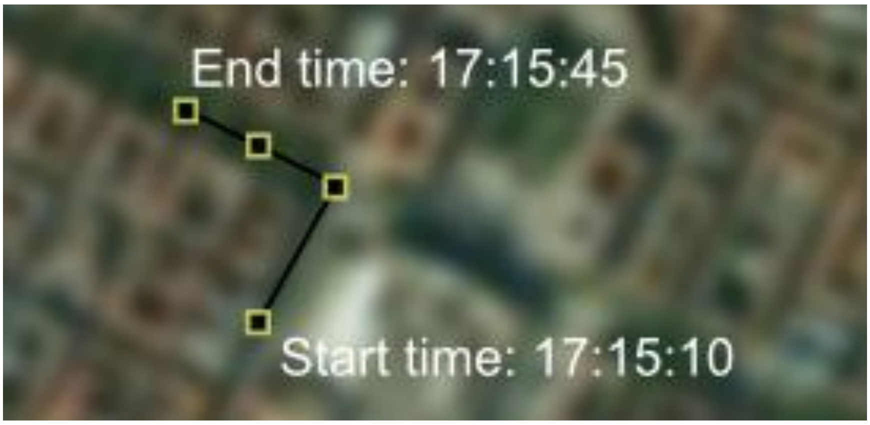


Figure 38 – Example of an incorrectly-detected trip

A minimum of 1 minute of recording, 5 vertexes (GPS points) logged, and a length of at least 500 meters were needed in order for a trip to be considered valid. Segments that did not respect these conditions were deleted.

Verification of automatically-derived trips: Researchers were able to verify post-processing results, and to merge segments that had been mistakenly identified as different trips due to GPS signal loss but were actually segments of the same trip. Surveyors performed this process manually in order to guarantee the best possible trip derivation results, and to increase the comparability of travel behaviour between GPS-derived information and self-reported travel diary data.

Extraction of basic trip information: Data on distance and times were easily obtained using GIS tools once the trip determination phase was completed. Other variables, such as acceleration and speed variability, were extracted for transport mode derivation purposes.

Reverse geocoding is the process by which trip origins and destinations are determined. This step provided surveyors with trip start and end addresses, obtained using the GPS coordinates of the starting and end points of complete GPS trips, as illustrated in Figure 39.

Figure 39 – Reverse geocoding process

GPS processing quality

In this step, researchers tallied the overall number of trips identified using GPS data in the detection phase. Surveyors reported the number of segments that needed to be merged during the manual verification phase and the resulting number of trips that were finally included in the GPS-based diary, as an indicator of the quality of the results of GPS-data trip-identification.

Additionally, researchers were able to evaluate the quality of travel information identified after the trip determination phase, by observing the number of completed trips compared to the number of trips characterized by degree of incompleteness. The percentages of completed trips, trips affected by cold start issues (missing the first minutes of recording), and partial trips were assessed. Figure 40 shows examples of a cold start and a partial trip.

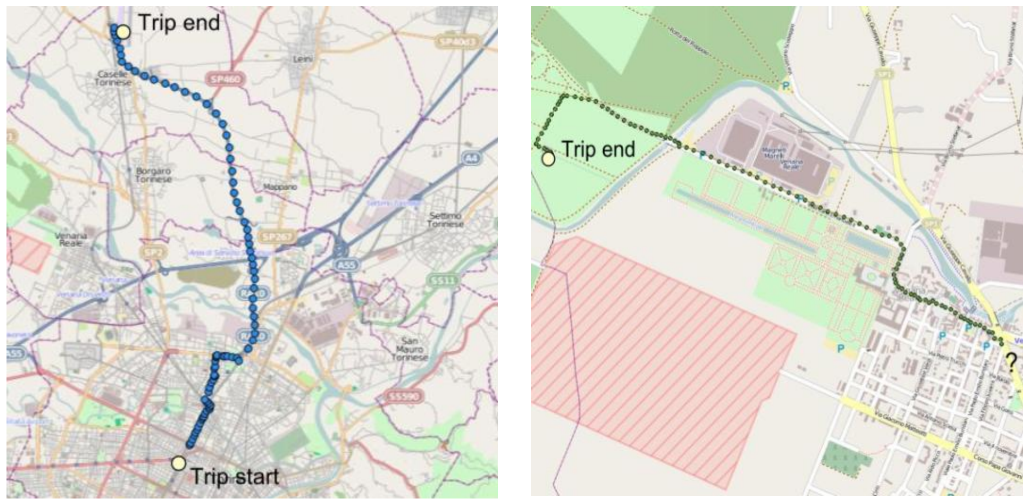


Figure 40 – Example of GPS cold start and partial trip

Cold start occurs whenever a spatial gap occurs between the end of one trip and the start of the next. This problem often results in a one- to two-minute loss of the initial part of a trip. For the purposes of this GPS survey, trips were said to be characterized by cold start problems when the distance between the end of one trip and the start of the next trip exceeded 10% of the total length of the trip. The minimum value for this cold start gap was 50 meters; the maximum value was 500 meters. Partial trips – trips in which larger portions of tracking data – can only provide researchers with limited trip information.

GPS-derived information was assessed according to its degree of data quality and completeness, following the same framework used for the traditional travel diary.

Observation of the trip chains provided by GPS data can help surveyors to detect possible underreporting of trips, thereby contributing to the improvement of collected data. The magnitude of trip underreporting in GPS-only data collection was evaluated by observing the percentage of unreported trips over the overall trip count.

The percentage of observed missing information was evaluated by tabulating the total number of entries that were not directly derived. Item non-response was observed for distance information, time items and trip duration.

Travel behaviour (GPS-derived)

GPS data provided researchers with an overview of respondents' travel behaviour throughout the survey period. Number of trips, trip length, trip duration and activities will be discussed in the following paragraphs.

Travel behaviour imputation (GPS-based)

Surveyors used GPS data to reconstruct paths using a GIS routing application, relying on GIS tools using Navteq transportation networks and a database provided by the public transport service. This process was performed using all available information on trip starts, ends and route choices, as observed from the GPS data.

Augmented travel behaviour

GPS-derived information and GPS-based imputed travel data were used to reconstruct augmented travel behaviour, in order to assess the maximum possible utility of a GPS travel diary with limited user interaction.

Travel behaviour indicators

Results of the derived travel behaviour phase provided surveyors with the value of the real travelled distance and travel time at free-flow speed, calculated along actual routes. This information can be used to calculate travel performance indicators.

Comparing free-flow speed time with GPS time provided an estimation of time loss related to users' travelling choices, as illustrated in Equation 4.1. This phenomenon can be observed only for GPS-detected completed trips, subtracting the GPS real time value with the shortest possible time spent travelling from $\boldsymbol{O_i}$ to $\boldsymbol{D_{i,}}$ using the chosen route $\boldsymbol{R_i}$ as described in Equation 4.1.

$$\boldsymbol{T_{loss} = GPS\ Time\ (O_i D_i) - GPS\ Routing\ Time\ (O_i D_{i,}, R_i)} \qquad \textbf{Equation 4.1}$$

Additionally, an indicator of the percentage of extra travelled distance can be obtained by observing the differences of the GPS-based distance derived from routing (GPS-based imputed distance) compared to the shortest path distance, given a pair of origin and destination locations ($\boldsymbol{O_i D_i}$). Equation 4.2 shows this calculation.

$$\boldsymbol{Extra_{Dist} = \frac{GPS\ Routing\ distance\ (O_i D_{i,}, R_i)}{Shortest\ path\ (O_i D_i)} * 100} \qquad \textbf{Equation 4.2}$$

A similar approach had been employed for the assessment of travel behaviour in a previous GPS-based Italian study (Spissu et al., 2011).

4.4.3 Comparison of trip diary and GPS-derived diary

Finally, surveyors compared information from the traditional travel diary with that from the GPS travel diary, which had been derived from raw GPS data.

Data comparison

Data comparison indicators assessed differences in travel behaviour as observed by the two survey methods.

Researchers noted the share of trips in the travel diary that were matched in the GPS derived diary, as well as the trips detected only by the GPS that were not reported by users in the traditional travel diary. The final results of this phase were a precise assessment of trip underreporting in self-reported travel diaries, and an evaluation of the ability of GPS devices to successfully record user movement.

In addition, it was possible to compare collected and derived information in order to understand the differences among reported, derived and GPS-measured data.

Researchers observed variability among trips distances and travel times as reported or derived by the following four methods:

- reported by survey participants;
- derived from survey participants' self-reported information;
- GPS-derived;
- derived using GPS information on origin, destination and observed route choice.

Researchers assessed the degree to which actual travel observation, as provided by GPS, had improved trip and item reporting (origin and destination times and addresses).

Augmented travel behaviour

The possibility of using multiple data collection tools allowed researchers to improve the travel diary, by completing missing information and providing higher-quality data. Even when travel information is provided by the user, GPS data still offers a better measurement of time and distance.

GPS-based trip information derivation

The research group developed several methods for the determination of transport mode and trip purpose using GPS data. These methods will be described in the following paragraphs.

Transport mode detection

Once GPS trips were identified and validated, it was possible to determine transport mode. Speed and acceleration data were extracted, and a learning algorithm was trained to classify the trips. This process consisted of two detection phases:

- identification of on-foot movement within GPS trips, detecting consecutive speed recordings below 8 km/h observed for at least 5 minutes, to match the instruction of on-foot trips defined by researchers in the travel diary. When an on-foot trip was detected, the original trip was separated into different stages;
- extraction of relevant speed and acceleration information for all identified trip segments.

Relevant information selected as parameters for mode detection parameters included the following:

- Standard deviation of GPS speed values;
- 95th percentile of GPS speed readings;
- 95th percentile of maximum and minimum acceleration values (calculated from GPS speed).

The choice of parameters for mode detection depended on researchers' need for robust indicators that were less-affected by peak data, and their need for a variability measure that could provide valuable information for discriminating between public and private modes of transport. The logging interval of 10 seconds did not allow researchers to successfully study acceleration and speed patterns, and should thus be adjusted in future studies. Stop-frequency and trip segment length should also be studied in future applications.

Once relevant data were extracted from GPS trips, it was necessary to train a decision tree algorithm, using a sample extracted from respondent data. Rules derived by decision trees using the training set were subsequently applied to rest of the dataset. Researchers analysed the identified classification rules and assessed the quality of the transport mode identification process (percentage of correct transport modes) within the data analysis phase.

Purpose determination

Determination of purpose of GPS-derived trips relied solely on self-reported information. Whenever a GPS-derived trip destination fell within the vicinity of a user-declared destination, the user-reported activity was associated with the trip. If no respondent information was available, trip purpose was not derived. In the socio-economic questionnaire, respondents reported information on trips to their home, place of work, and to many common services, such as grocery stores and pharmacies.

In order to evaluate the number of addresses necessary to ascertain purpose information from GPS trips using the described determination method, researchers observed the number of reported visited locations for each respondent. To determine the success of trip purpose derivation, researchers calculated the percentage of explained trip purposes according to the number of visited locations. Various purpose-derivation percentage targets were tested to evaluate a possible satisfactory compromise between data completeness and burden on respondents.

Derivation of questionnaire information

Respondents were asked to provide information on their travel habits and attitudes in the socio-economic questionnaire. These data were used to supplement GPS data processing. However, GPS data can also provide researchers with the information needed to derive some of the requested information. The final data analysis step studied the extent to which data from the questionnaire can be derived from passively-recorded location data.

4.5 Survey results

Following the data analysis plan, the research team was able to successfully measure and compare travel behaviour as recorded by different survey tools, and to collect the results necessary to assess the potential for use of GPS in future travel research. The following paragraphs will discuss relevant findings from the GPS pilot test, main GPS survey, and supplementary data collection test.

4.5.1 GPS pilot test

Travel diary

During the pilot test, respondents recorded the following basic travel information in a simplified travel diary:

- date;
- start and end time of trip;
- origin and destination;
- transport mode.

Distance values were imputed with routing tools, using user-reported information and extracting data from GPS tracks, while purpose-derivation methods were studied in order to find rules to implement during the main GPS travel survey.

Quality indicators

Based on observation of the reported travel behaviour, trip underreporting did not occur, and all trip chains were consistent. This preliminary assessment did not consider possible trips detected by GPS, relying solely on observed reported data.

A total of 55 trips were reported during the 4-day survey period. Total trips per user and their distribution across survey days are reported in table 28.

USER	TOT	Tue	Wed	Thu	Fri
282DBC	23	4	7	8	4
282FFB	11	2	4	4	1
285898	8	1	3	2	2
28312F	13	1	4	6	2
TOT	55	8	18	20	9

Table 28 – Reported trips

Trip data throughout the survey period were highly variable for 2 of the surveyed users. However, considering that the first and last survey day included the tools' retrieval and deployment, thus shortening the observation time, it is only possible to compare the survey days of Wednesday and Thursday. This comparison shows a lower degree of variability.

Table 29 shows the number of performed trips segments by user and transport mode. All transport mode choices were reported.

USER	Car	Bike	PT	Train	On-foot
282DBC	11	10	0	0	2
282FFB	5	5	0	0	1
285898	8	0	0	0	0
28312F	3	0	3	1	6
TOT	27	15	3	1	9

Table 29 – Reported stages by transport mode

Despite an observed 100% reporting of stages and trips, a high degree of item non-response occurred. This phenomenon negatively affected the quality of data on trip departure and arrival time. In particular, 27 items were not reported. These missing temporal items account for 25% of the total information on departure and arrival time, as shown in the chart in Figure 41. Temporal missing items largely impacted trip duration, which was calculated from reported data. A full 35% of duration values were missing. 36% of arrival entries went unreported, while less than 8% of departure times went unreported.

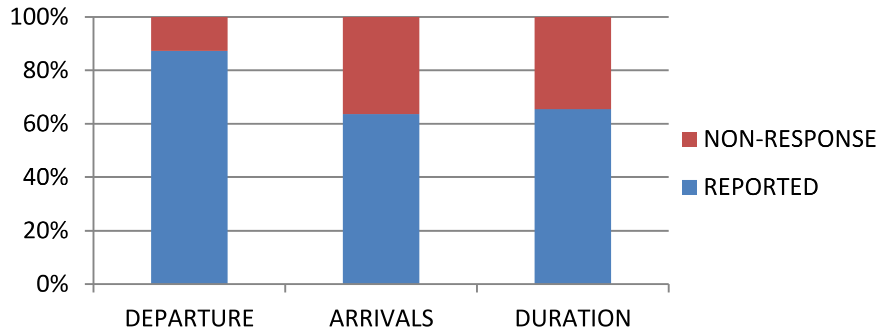


Figure 41 – Item non response and missing trip duration information

Studying the occurrence of missing entries, it was possible to discern a larger share of item non-response among specific users, as illustrated in Table 30. This gap suggested the potential for loss of entire trip time information for specific user groups. Researchers had to address this issue in the main survey.

USER	TOT items (D/A)	Departure	Arrivals	% Missing items	% Missing duration
282DBC	46	1	1	4%	4%
282FFB	22	6	12	82%	100%
285898	16	0	7	44%	88%
28312F	26	0	0	0%	0%
TOT	110	7	20	25%	35%

Table 30 – Departure, arrival time and duration item non response

Single-trip segment information, which contributes to the correct observation of trip duration, can be imputed by observing previously-reported movements with the same characteristics same stage or trip origin and destination, transport mode, etc – in order to increase travel diary completeness. However, this method is most suitable for imputing information from habitual trips, and is less suitable for use with incidental trips. In the pilot survey, imputation of duration information resulted in a data improvement of 8%, thanks to 4 imputations of missing trip travelling times. Figure 42 illustrates the final share of available trip duration information. No imputation was possible for users who failed to provide complete pairs of trip starts and ends.

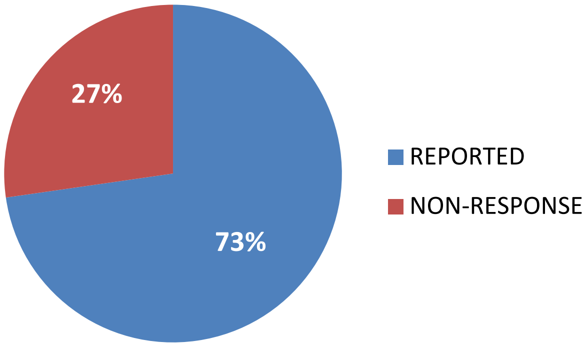


Figure 42 – Overall reporting of trip segment duration

Researchers also evaluated potential rounding effects among self-reported temporal data, regarding the starts and ends of trips and trip segments. Further, observing the frequencies of reported information allowed researchers to evaluate possible polarization within the data. Figure 42 shows the frequencies of reported minutes of arrival and departure.

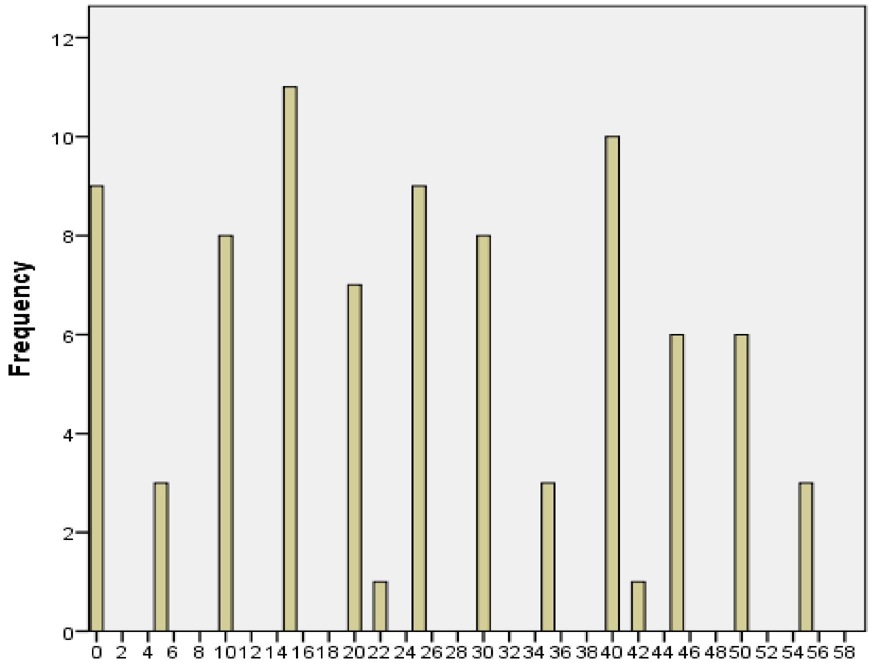


Figure 43 – Reported time frequency (reported minute)

Looking at the histogram of the reported minute frequency, a rounding effect is evident. Reported times are polarized around time-values that are multiples of 5, as is generally witnessed in surveys. Multiples of 5 account for approximately 95% of all time values reported in this study.

The rounding effect observed in time values was expected to impact duration as well. Figure 44 shows the distribution of available duration values.

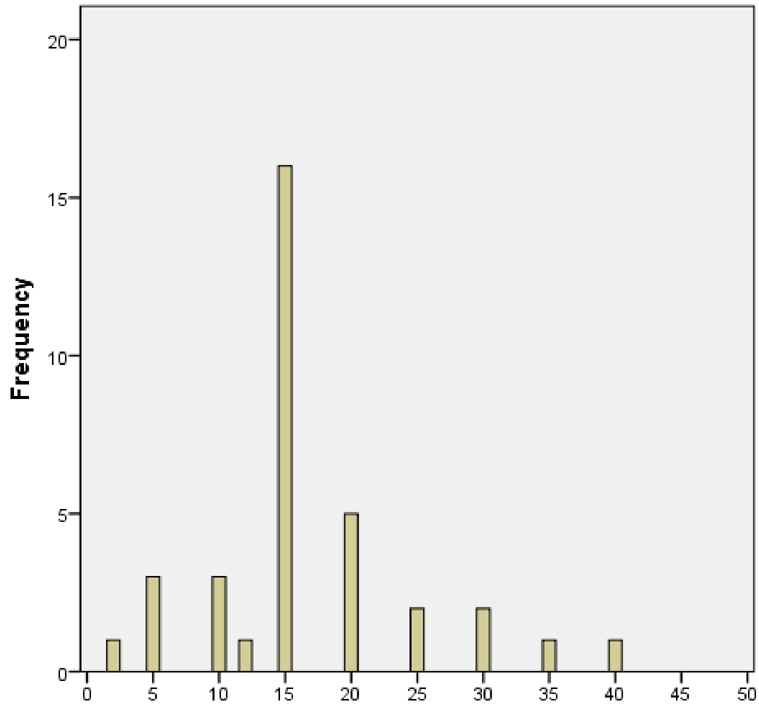


Figure 44 – Calculated travel time (in minutes)

As expected, reported travel times were largely affected by rounding, with only 2 durations items not multiple of 5.

Users were not asked to provide information on travelled distance. Trip length was derived using the routing tools described in paragraph 4.3.3. Results of this derivation process will be provided in the following paragraphs. Routing results depend on the accurately of reported addresses. Respondents were asked to report the most detailed possible addresses or recognizable points of interest. Result of location reporting quality is shown in Table 31.

USER	Locations	Correct	POI	Town / Neighborhood	Incorrect (%)
282DBC	10	5	3	2	20 %
282FFB	6	2	4	0	0 %
285898	3	2	0	1	33 %
28312F	8	2	4	2	25 %
TOT	27	11	11	5	18,5 %

Table 31 – Reported location quality

Almost 20% of provided addresses were incorrect. This error could compromise the results of distance derivation, thereby providing researchers with improper spatial data for imputation of origin and destination. The use of incorrect addresses can largely impact routing results; in addition, transport demand models require precision both in attribution of proper trip origins and destinations, and in traffic zone attribution. The possible use of GPS data to overcome or limit the effects of this problem will be addressed in the discussion of GPS data.

Travel behaviour imputation

Researchers calculated distance values through routing. The routing algorithm was able to successfully derive 96% of the travelled distances of reported trips. The only 2 trip distances that could not be derived were characterized by the same origin and destination addresses. Such trips cannot be derived using the designed method. Table 32 reports the cumulative distances per user and mode, estimated using the routing algorithm.

USER	DISTANCE	Car	PT[2]	Train	Bicycle	On-Foot
282DBC	103,3	76,5	0	0	26,8	0
282FFB	44,9	31,8	0	0	11,5	1,6
285898	32,10	32,10	0	0	0	0
28312F	192,4	8,3	6,6	166	0	8,7
TOT	372,7	148,7	6,6	166	38,3	10,3

Table 32 – Travel distance (in kilometres) by mode

Item non-response in travel diaries can be fixed through the derivation of distance information, using origins and destinations provided by users. Derivation of travel distance allowed researchers to observe variation throughout the survey period, as reported in Table 33.

USER	Tue	Wed	Thur	Fri
282DBC	17,5	24,8	40,2	20,8
282FFB	7,9	19,9	14,6	2,5
285898	5,3	12,6	9,3	4,9
28312F	2,6	7	181,4	1,4
TOT	33,3	64,3	245,5	29,6

Table 33 – Distances (in kilometres) per survey day

A high degree of day-to-day variability was observed in the distance readings, despite a low variation in performed trips (see Table 28 for reference). However, considering the survey characteristics and limited number of observations, no further analysis was carried out on this aspect during the pilot study. Further analysis was performed in the main GPS survey.

Observing the outcomes of the distance derivation process showed that the employed routing algorithm provided the same outcomes given a pair of ODs and a transport mode, resulting in zero variability in the calculated variables (distance and time). This phenomenon was not expected to affect GPS readings, therefore providing data that were characterized by higher accuracy and higher variability.

Within the chosen travel diary format, 'travel time' depended on the ability of the respondent to accurately report both trip departure and end times. A preliminary assessment of data quality showed

[2] Public transport, consisting of movements on tram, bus, metro and all services offered by the Torino metropolitan area public transport system, excluding train transport.

that trip duration values were successfully calculated for 73% of performed trips, using both self-reported data and imputation. This resulted in incomplete information on travel behaviour for a remaining 27% of overall trips.

The use of routing algorithms allowed researchers to impute the free-flow speed time of each trip, based on user-reported data and transport network characteristics. Information pertaining to transport mode choice was derived from observation of user data, using classification rules. Outcomes of this derivation are shown in Table 34.

USER	TIME	Car	PT	Train	Bicycle	On-Foot
282DBC	238	145	0	0	93	NA
282FFB	115	62	0	0	33	20
285898	69	69	0	0	0	0
28312F	319	21	56	140	0	102
TOT	741	297	56	140	126	122

Table 34 – Overall cumulated time (in minutes) spent travelling per transport mode

These outcomes demonstrated the suitability of using derivation to estimate travel time, even when travel time was not reported by users. Data completeness in self-administered travel diaries was thereby improved. However, derivation produced lower values for trip and trip segment duration, when compared to actual travel time. Table 35 shows the characteristics of derived and reported travelling time for trips with complete information by transport mode.

Transport Mode		Total	Mean	Standard Deviation
Car (15)	Reported	242	16,13	7,02
	Derived	177	11,80	6,38
Bike (9)	Reported	140	15,56	1,67
	Derived	87	9,67	3,97
Public Transport (3)	Reported	60	20	5,00
	Derived	56	18,67	4,04
On-foot (6)	Reported	115	19,17	14,97
	Derived	102	17,00	12,70
Total (33)	Reported	557	16,88	7,84
	Derived	422	12,79	7,60

Table 35 – Mean and standard deviation of reported trip duration and derived travel time

Derived travelling time is generally shorter than reported travelling time. However, when no other imputation method is possible and prompted recall interviews cannot be performed, trip duration at free-flow speed can be used as an input for derivation of travelling time. Derived travelling time can also be compared with reported data to build an indicator of time loss, or as a check value to spot possible misreported information. Further analysis on the differences among travel time derivation tools will be illustrated in the travel diary and GPS comparison section.

When travel departure and end times were provided with a high degree of completeness, surveyors were able to calculate time spent at destination, and consequentially, time spent performing reported activities. Considering time information reported by pilot survey participants, only 29% of 'time spent at destination' entries were successfully derived. Figure 45 compares the share of derived activity information to that of missing items.

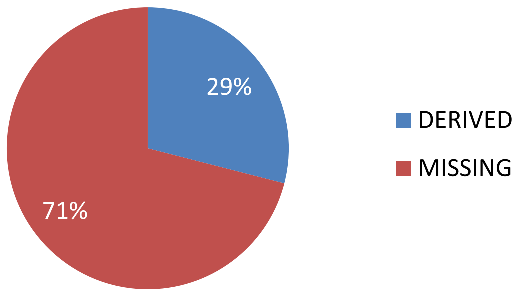


Figure 45 – Derived and missing activity duration information

'Time spent at destination' was the measure most impacted by missing information, and was consequentially the least derivable measure. A high degree of completeness and accuracy are required in 'time at origin' and destination data, to provide researchers a complete overview of travel behaviour.

Augmented travel behaviour

Using reported and derived information (based on user reported data), it was possible to reconstruct a more complete travel diary, relying solely on user data. Table 36 shows the final outcomes.

USER	Information	Total	Car	PT	Train	Bicycle	On-Foot
282DBC	Distance	103,3	76,5	0	0	26,8	NA
	Time	350	177	0	0	146	17
282FFB	Distance	44,9	31,8	0	0	0	1,6
	Time	115	62	0	0	0	20
285898	Distance	32,10	32,10	0	0	0	0
	Time	88	88	0	0	0	0
28312F	Distance	192,4	8,3	9,4	166	0	8,7
	Time	350	35	60	140	0	115
TOT	Distance	372.7	148.7	9,4	166	38.3	10,3
	Time	903	362	60	140	179	162

Table 36 – Augmented distance (kilometres) and travelled time (minutes) information by user and transport mode

Compared to the first analysis of travel diary completeness, here, 'time spent at destination' saw a similar impact, as there was no way to impute required information using the developed methods. However, the implementation of imputation methods based on routing can provide researchers with additional trip duration information, as long as information on the starts and ends of trips or single trip segments is available. Further, if researchers know both arrival time and estimated travel time, departure time can be estimated.

Additionally, the data analysis process used in the GPS pilot test allowed researchers to reconstruct estimated spatial travel patterns using only self-reported information. Figure 46 shows a travel behaviour reconstruction of one pilot survey participant. Route choice was derived using the routing tool.

Reconstruction of the travelled route provides researchers with a geographically-augmented travel diary. This spatial augmentation can help surveyors collect more information about the ways participants use space in time, improving the depth of data collection in self-administered travel surveys, as illustrated in Figure 46.

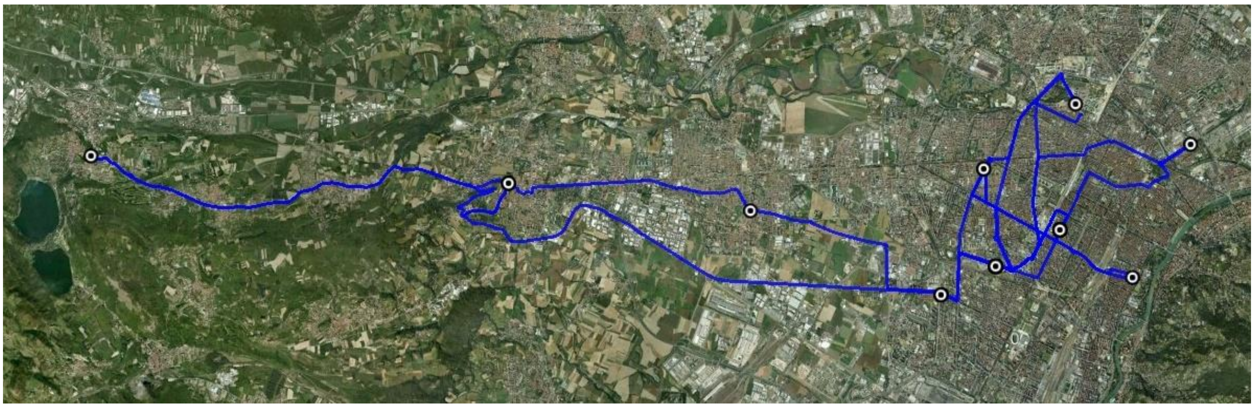


Figure 46 – Route derived from user-provided information (in blue)

Outcomes of the travel diary spatial reconstruction were compared with actual routes, as recorded by GPS devices and validated by participants after checking the maps. This comparison allowed researchers to evaluate the results of the shortest path routing and provided information on user behaviour, showing deviation of the chosen route from the shortest possible path.

GPS diary

Researchers used the pilot survey to test the designed post-processing method's ability to identify trips from raw GPS recordings and to successfully remove unreliable records from the data stream. Results will be presented in the following paragraphs.

GPS processing quality

Post-processing involved cleaning the data from incorrect and unreliable GPS recordings. Basic information about the data cleaning phase is reported in Table 37.

USER	RAW GPS DATA	CLEANED DATA	% DELETED
282DBC	874	667	23,68%
282FFB	1573	1252	20,41%
285898	1005	901	10,35%
28312F	915	776	15,19%
TOT	4367	3596	17,66%

Table 37 – Results from the GPS raw data cleaning phase

The cleaning phase resulted in vast elimination of unreliable GPS points, despite using a more conservative approach than had been used in earlier studies (Stopher, 2008; Shuessler, 2011). Approximately 82% of the overall records could be considered reliable. However, more than 20% of the total data logged by each of two different users had to be discarded.

Post-processing algorithms automatically detected potential trips and trip segments, according to stated trip parameters (see Section 4.4.2 for further details). Results from the pilot survey trip detection, using survey-specific parameters, are reported in Table 38.

USER	DETECTED TRIPS (POST PROCESSING)
282DBC	12
282FFB	14
285898	7
28312F	6
TOT	39

Table 38 – Trips detected from GPS data (automated procedure)

Researchers manually inspected the resultant detected trips, to look for erroneously-attributed trips that needed to be grouped together into a single trip (in case of an identified signal loss). This process was performed by surveyors after the first trip-derivation phase. Table 39 reports the fixes required in order to finalize trip/stage derivation after the manual check. In particular, it reports the number of segments selected for merging and number of trips that resulted (selected segments/resulting trips).

USER	SELECTED SEGMENTS	RESULTING TRIPS
282DBC	0	NA
282FFB	2	1
285898	0	NA
28312F	3	1
TOT	5	2

Table 39 – Post processing fixes (selected segments and resulting trips)

This manual inspection, and the subsequent trip modification, demonstrated that the trip-derivation algorithm can be considered reliable and useful, despite its potential for trip overreporting, as shown in Table 39 for participants 28312F and 282FFB. To use the trip-derivation algorithm with large samples, segment-merging algorithms must also be introduced.

Detection of on-foot trips based on GPS speed values identified 7 complete on-foot trips. Zero on-foot trip segments of multi-segment, multi-mode potential trips were detected. Refer to section 4.4.3 for further information on the mode-detection process used for stage-identification.

The derivation phase allowed surveyors to recreate a travel diary from GPS readings. No major data quality issues were encountered during this trip-diary reconstruction. Collected GPS tracks showed a high degree of completeness, despite some disruption in data continuity. Table 40 shows a breakdown of trips by completeness of data acquisition – including total trips/stages reported, complete trips, trips affected by cold start, and partial trips/stages.

USER	Trips/Stages	Complete	Cold start	Partial
282DBC	12	7	2	3
282FFB	13	10	2	1
285898	7	4	2	1
28312F	4	1	3	0
TOT	36	22	9	5

Table 40 – GPS-derived potential trips by degree of completeness

GPS readings allowed researchers to reconstruct travel behaviour with a high level of accuracy, using data from complete trips (or trip segments). Although GPS-observed movement affected by cold start subsequently displayed biases in time and distance information, this data still provided researchers with useful travel behaviour information. If gaps in information were consistent, trips could not be reconstructed; however, information from partial movements was still occasionally used for route reconstruction or collection of partial temporal information, such as trip ends.

Quality indicators

When GPS data collection meets researchers' quality standards, and data is continuous, GPS-derived travel information can provide surveyors with the same set of information that a travel diary can provide. The completeness and quality of the GPS-derived data, which were expected to be higher than the quality witnessed for the travel diary, are reported as follows.

Table 41 shows the number of complete trips detected throughout the survey period.

USER	Tue	Wed	Thurs	Fri
282DBC	4	3	4	1
282FFB	2	3	4	4
285898	1	3	1	2
28312F	1	0	2	1
TOT	8	9	11	8

Table 41 – GPS trips per day

The observation of GPS-derived trips and trip chains allowed researchers to recognize possible trip underreporting. Five one-trip days and one no-movement day were observed during the survey. Three probable missing trips were observed and imputed, thereby improving the total trip count by 14%. Numbers of trips recognized by GPS were compared against the number of trips listed in a travel diary, which allowed for additional recognition and evaluation of missing trips.

Distance and time information can be observed for complete trips, cold start trips, and trip stages. GPS records acquired during the pilot test provided 86% of distance and travel time information (departure, arrival and duration). Figure 47 illustrates properly-recorded information as a share of total information. Information completeness in the GPS derived travel diary ranges from 75% to 100%, depending on the user.

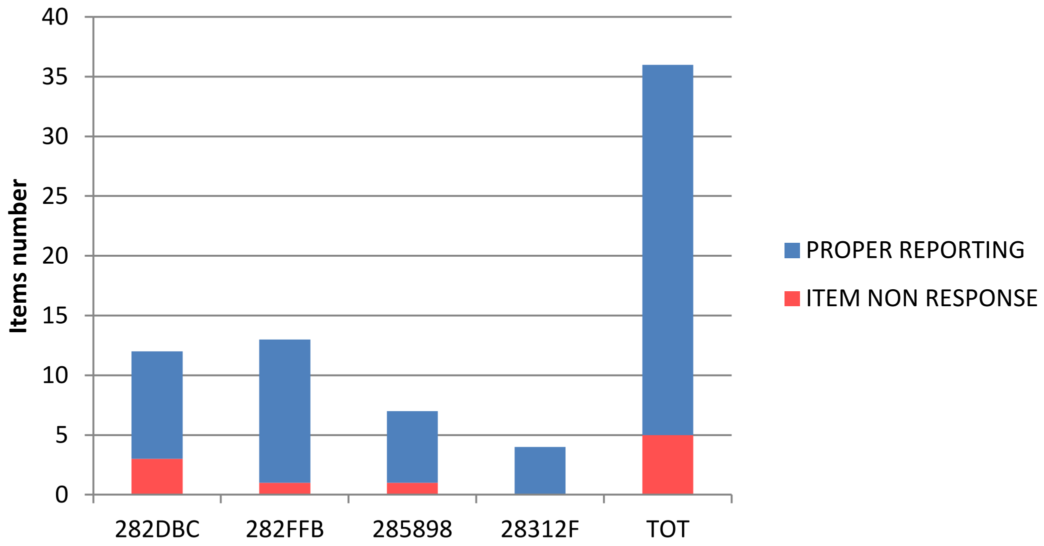


Figure 47 – Number of correctly reported information and item non-response in the GPS diary

Additionally, it was possible to record 5 arrival times derived from movements which GPS had only partially detected, due to signal loss or other malfunctions. No departure time could be derived for such potential trips and stages, largely due to GPS signal loss and cold start. Table 42 reports the total share of temporal information that GPS was able to provide.

USER	Trip starts	Trip ends
282DBC	8	12
282FFB	11	13
285898	6	7
28312F	4	4
TOT	29	36

Table 42 – Detail of trip time information in the GPS diary

The total number of time values collected and the completeness of trip chain information affected the ability of GPS to measure time spent at destination. A total of 22 activity duration values were calculated, accounting for more than 60% of total activity values.

Data collected using GPS devices were not affected by rounding and memory effect. For this reason, the resultant distribution of temporal data is characterized by a lack of strong polarization around specific values (typically multiples of 5 or 10 in the user-reported case). Figure 48 shows the frequency of time values as detected in the GPS-derived diary.

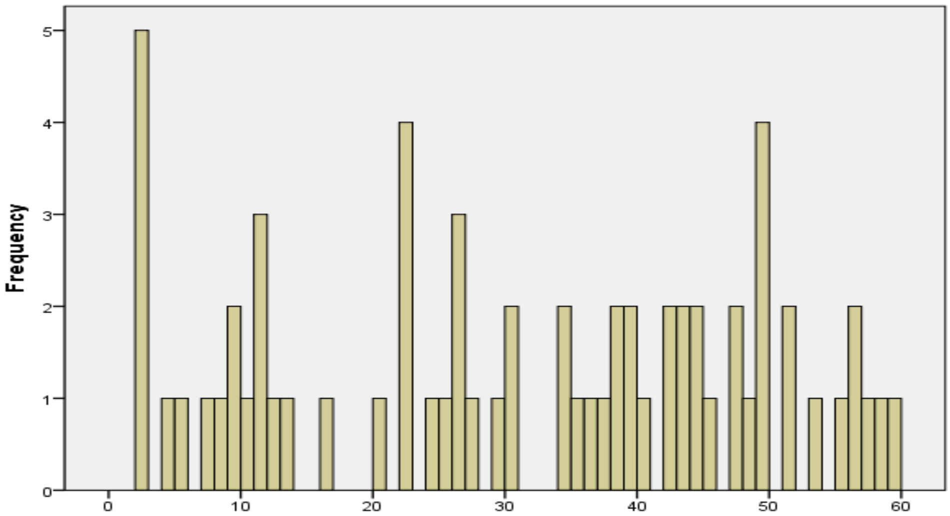


Figure 48 – GPS Time information distribution (minutes)

Data distribution demonstrated that GPS values were not affected by rounding and memory effect, and thus provided reliable temporal data on travelled time, time spent at destination, and departure and arrival times.

Trip length was observed both for complete trips and trips affected by cold start (despite a structural underestimation of the distance value in the case of cold start). For trips consisting of different stages, distance values for each stage were added together to determine the overall trip distance. GPS diaries provided researchers with trip-length information that was 86% reliable. Potential trips that were classified as partial required imputation of travel information.

Surveyors' ability to evaluate the existence of survey fatigue associated with GPS data recording was limited, due to characteristics of the survey and to limited availability of data. The mishandling and technical problems witnessed were limited and non-structural to users, specific trips, or trip segments.

Travel behaviour

Table 43 reports the GPS distance readings for the 31 reliable stages provided by GPS data, illustrated by transport mode.

USER	DISTANCE	Car	PT	Train	Bicycle	On-Foot
282DBC	45,20	39,3	0	0	4,50	1,40
282FFB	56,90	53,40	0	0	3,00	0,50
285898	25,60	25,60	0	0	0	0
28312F	10,30	7,90	0	0	0	2,40
TOT	138,00	126,20	0	0	7,50	4,30

Table 43 – GPS distances by transport mode

As previously stated, distance information obtained from GPS devices is reliable and accurate as long as data collection continuity is assured. Any disruption in the data stream results in the loss of information, or in the need for imputation. In this study, researchers identified 5 partial movements and 3 underreported trips for which no information on distance and travel time was available. In these cases, GPS data allowed researchers to impute missing information.

Time information provided by GPS is reported in Table 44, for both complete trips and trips affected by cold start. 31 travel start and end times were available to researchers, thus providing reliable travelled time information.

USER	TIME	Car	PT	Train	Bicycle	On-Foot
282DBC	117	85	0	0	7	25
282FFB	167	144	0	0	18	5
285898	126	126	0	0	0	0
28312F	52	21	0	0	0	31
TOT	462	376	0	0	25	61

Table 44 – GPS travelled time by transport mode

GPS time is as accurate as the logging interval of the GPS device. Survey-specific temporal accuracy was 10 seconds, which was even more accurate than the to-the-minute accuracy requested by surveyors.

Travel behaviour imputation

The derivation phase, which uses routing tools augmented by GPS data, provided information on time and distance to supplement the GPS-only data derivation that had occurred during the pilot phase. An explanation of the characteristics of such tools is available in Section 4.4.2.

Deriving information from partial GPS readings increased the total number of detected movements to 39. Table 45 reports the imputed travelled distance by user, sorted by transport mode.

USER	DISTANCE	Car	PT	Train	Bicycle	On-Foot
282DBC	55	39,3	0	0	14,3	1,4
282FFB	67,8	61,3	0	0	4,5	2
285898	26,8	26,8	0	0	0	0
28312F	10,9	8,3	0	0	0	2,6
TOT	160,5	135,7	0	0	18,8	6

Table 45 – GPS-based imputed distances by transport mode

Travelled time was imputed using the same tools. Table 46 shows the imputed travelled time by user.

USER	TIME	Car	PT	Train	Bicycle	On-Foot
282DBC	149	78	0	0	49	22
282FFB	173	133	0	0	19	21
285898	98	98	0	0	0	0
28312F	46	17	0	0	0	29
TOT	466	326	0	0	68	72

Table 46 – GPS-based imputed travelled time by transport mode

Augmented travel diary

Missing information on partially-detected or non-reported trips or stages - derived from the observation of the trip-chain - was imputed. Table 47 reports the distance and time information of the derived trip segments, which contributed to the calculation of information for the 39 complete GPS-detected trips.

USER	Information	Total	Car	PT	Train	Bicycle	On-Foot
282DBC	Distance	55	39.3	0	0	14,3	1,4
	Time	163	85	0	0	53	25
282FFB	Distance	66,8	61,3	0	0	3	2,5
	Time	218	164	0	0	24	30
285898	Distance	30,5	30,5	0	0	0	0
	Time	138	138	0	0	0	0
28312F	Distance	10,9	8,3	0	0	0	2,6
	Time	52	21	0	0	0	31
TOT	Distance	162,6	139	0	0	17,3	6,3
	Time	571	408	0	0	77	86

Table 47 – Augmented distance (km) and travelled time (minutes) information by user and transport mode

Derivation allowed researchers to impute 10 pieces of distance and duration information, thereby improving the data completeness of the GPS diary. The derivation process achieved an improvement of 8% in trip reporting, an overall improvement of 24% in travelled time and 17% in distance values, without seeking further feedback from respondents.

However, occurrence of missed trips and stages was expected, due to the low number of detected movements observed throughout the survey days and the lack of detection of trips on public transport. A comparison of GPS data with travel diary outcomes helped surveyors to understand the magnitude and characteristics of this underreporting.

Activity duration was impacted by underreporting, and no improvement was possible using the imputation processes developed for this study. However, the use of a specially-designed imputation method, based on existing time information and estimated trip duration, allowed the derivation of 4 additional activity duration items, thereby increasing the completeness of this measure from 61% to 72%.

GPS proved its ability to provide researchers with extensive spatial and temporal information that can be used successfully to study users' trip characteristics and travel behaviour. However, data continuity and cold start problems seemed to be the biggest threat to GPS final results. Observing trip numbers and trip chains, the final picture of the respondents' travel behaviour appeared incomplete.

The next step of the analysis, consisting of the comparison of outcomes of the two selected survey methods – traditional travel diaries and GPS devices – will be described in the following paragraphs.

GPS and travel diary

The research team compared outcomes from the two employed data collection tools. This comparison was a key step for understanding the potential of GPS implementation in travel surveys. Pilot survey data was specifically used to study the ability of GPS to detect trips, and to develop possible improvements in the implementation of such tools.

Data comparison

The first step of the planned data analysis was to evaluate the degree of correspondence among detected trip segments. 55% of overall trip stages reported in the travel diary were detected by GPS, as illustrated in Table 48.

USER	Trips	Matched	% Match
282DBC	23	12	52,17%
282FFB	11	9	81,82%
285898	8	4	50,00%
28312F	13	5	38,46%
TOT	55	30	54,55%

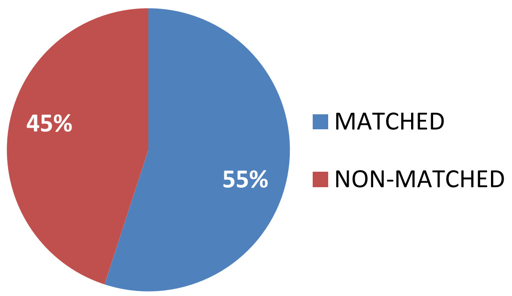


Table 48 – GPS matched and non-matched trips

Additionally, 5 new trips were exclusively detected by GPS, and 3 additional trips were added through GPS-reconstructed trip-chains. These corrections increased the number of complete trips from 55, as reported by users, to a total of 62. Table 49 illustrates the total trips per day per user resulting from the GPS-augmented diary.

USER	TOT	Tue	Wed	Thu	Fri
282DBC	23	4	7	8	4
282FFB	18	2	4	8	4
285898	8	1	3	2	2
28312F	13	1	4	6	2
TOT	62	8	18	24	12

Table 49 – GPS-augmented travel diary

While GPS was able to detect some trips not reported in the travel diary, the reverse situation was also observed; GPS-collected data was characterized by 45% underreporting of trips that had been reported by users in travel diaries, and 48% underreporting of trips accounted for with imputation-augmented travel diaries. This underreporting dramatically impacted trip detection in GPS-only travel diaries, and it was attributed to issues such as GPS signal loss and device-related problems (mishandling, forgotten device, battery issues, etc.). Figure 49 shows the contribution of mishandling to the share of missed recordings, displayed as a percentage. Information on mishandling was collected during the prompted-recall interview at the end of the survey.

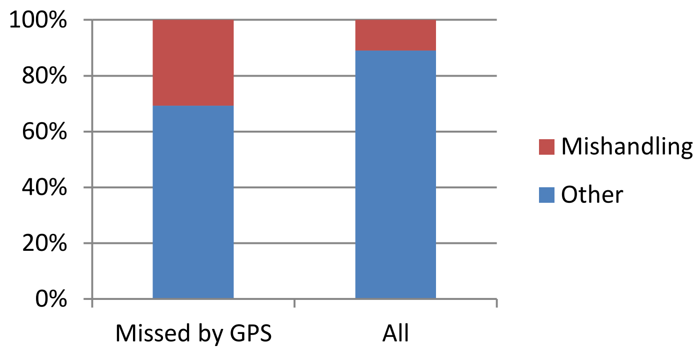


Figure 49 – Occurrence of GPS mishandling

GPS problems occurred during the fulfillment of 8 reported trips, resulting in 13% of overall trip underreporting with the GPS-only diary. In total, 34% of trips not recorded by GPS were attributed to mishandling. GPS problems also clearly impacted final results of the GPS trip detection phase; in fact, during periods free from GPS problems, resulting trip detection increased to 68% of the total trip count.

Within this period free from GPS problems, missing trips and trip segments were most frequently bicycle trips, and no detection was possible for the only trip that had been performed by public transport or train. Table 50 details GPS-diary trip/stage underreporting by transport mode.

USER	Car	PT	Train	Bicycle	On-Foot
282DBC	4 (44%)	NA	NA	5 (63%)	1 (50%)
282FFB	1 (10%)	NA	NA	3 (60%)	1 (33%)
285898	2 (25%)	NA	NA	NA	NA
28312F	0 (0%)	1 (100%)	1(100%)	NA	3 (60%)
TOT	7 (13%)	1 (100%)	1(100%)	8 (62%)	5 (50%)

Table 50 – Missed GPS trips/stages by transport mode (missed trips number and percentage)

Results showed that GPS detects car movement better than any other transport mode. Characteristics of missed and detected trip segments can be observed for further analysis. Table 51 shows the global characteristics of the group of undetected stages compared to those of the detected stages.

		DISTANCE	TIME			DISTANCE	TIME
GPS	Mean	4,19	11	**Unmatched**	Mean	3,15	10,93
	N	36			N	15	
	Median	3,7	10		Median	2	7
	Max	15,1	31		Max	16,6	32
	St_dev	3,05	6,32		St_dev	4,27	8,56

Table 51 – Statistics of reported trips versus GPS-detected trips

Though unmatched trip segments tended to be shorter, characteristics of reported movements did not differ statistically from travel behaviour that the GPS was able to successfully report. Underreporting related to GPS mishandling was not considered for this analysis.

Given GPS measurement as an accurate measure of time and distance, the degree of error of the non-GPS surveys was evaluated. Researchers compared user-provided information with GPS information from matched trip segments that contained complete travel behaviour information. The comparison groups consisted of 14 single stages for time information and 58 for distance information.

Travel modeling requires that a movement be placed within a precise time frame. Surveyors must collect precise temporal data in order to achieve this result. GPS devices provide surveyors with the highest quality of temporal information, and GPS generally outperforms respondent-provided travel diaries in terms of data quality.

Distribution of user-reported time errors, given that the GPS device provides actual times, demonstrate the efficacy of GPS in consistently improving time information and overcoming possible user misreporting due to memory and rounding effect. Figure 50 shows the frequency of measured errors, expressed as the difference between GPS data and user-reported data, categorized by absolute error range in minutes.

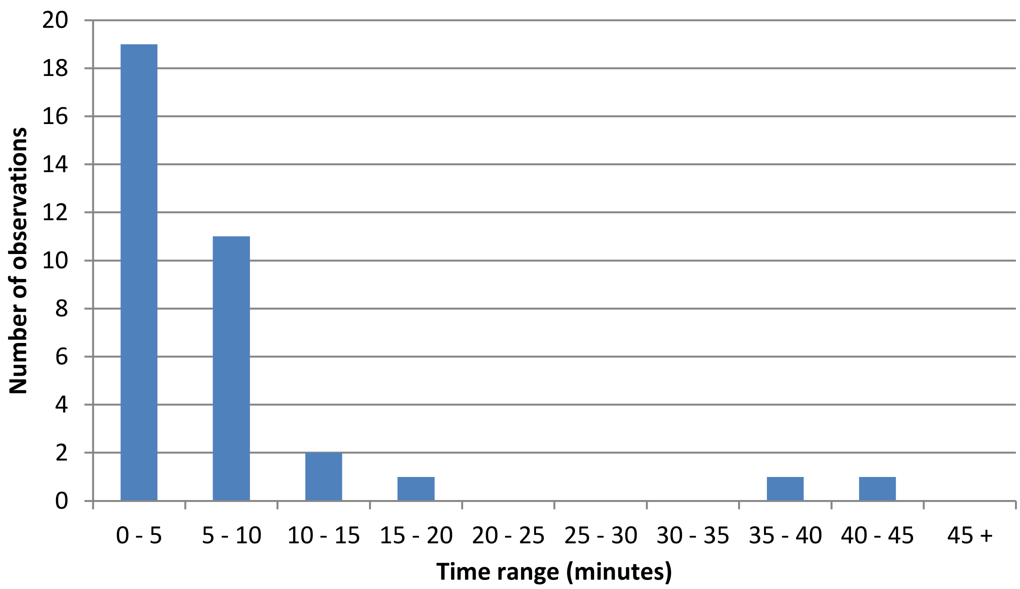


Figure 50 – Number of observations by error of user-reported times compared to GPS readings (time ranges in minutes)

In general, absolute error of time items was quantified in 5 minutes or less for 55% of user-reported entries. 68% of the remaining entries, accounting for 32% of the total reported items, witnessed an error between 5 and 10 minutes while 15% of time values included an error greater than 10 minutes.

Observation of data showed how survey participants tended to underestimate travel departure and arrival times. Figure 51 illustrates the relative difference in minutes (GPS data minus reported time) for each observation.

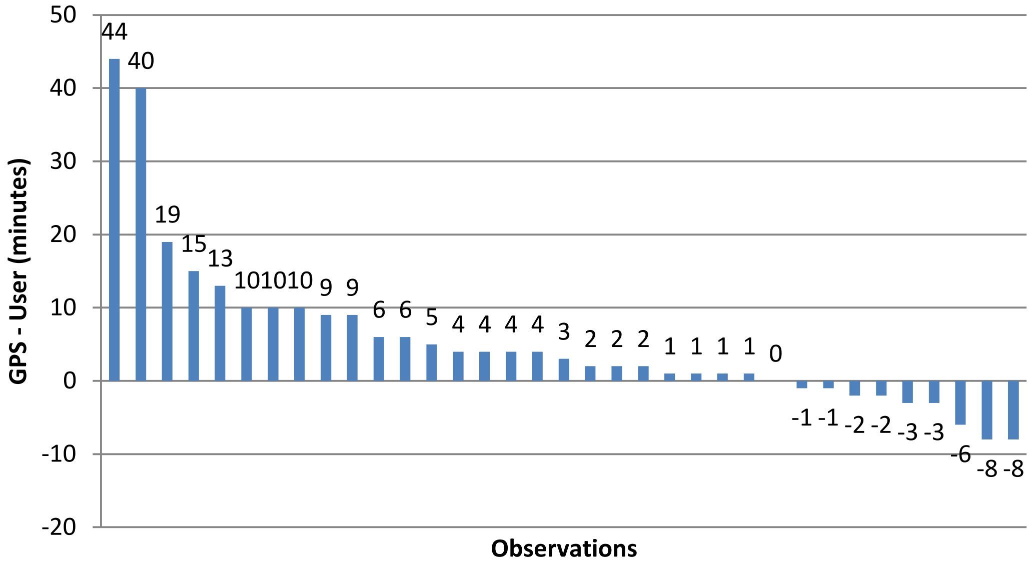


Figure 51 – Absolute error of GPS readings versus user-reported times (in minutes)

75% of user-reported data were characterized by time underestimation. Reported time values greater than GPS-measured time were reported in 25% of entries. Error was contained within a 10 minute range for 85% of observations.

Trip duration was less affected by reporting errors. Figure 52 shows the frequency of the measured stage duration error categorized by absolute error range in minutes. Two entries are characterized by an error of 40 minutes or more. The total number of observations was lower, due to the previously-described missing time and trip-end information witnessed in the travel diary.

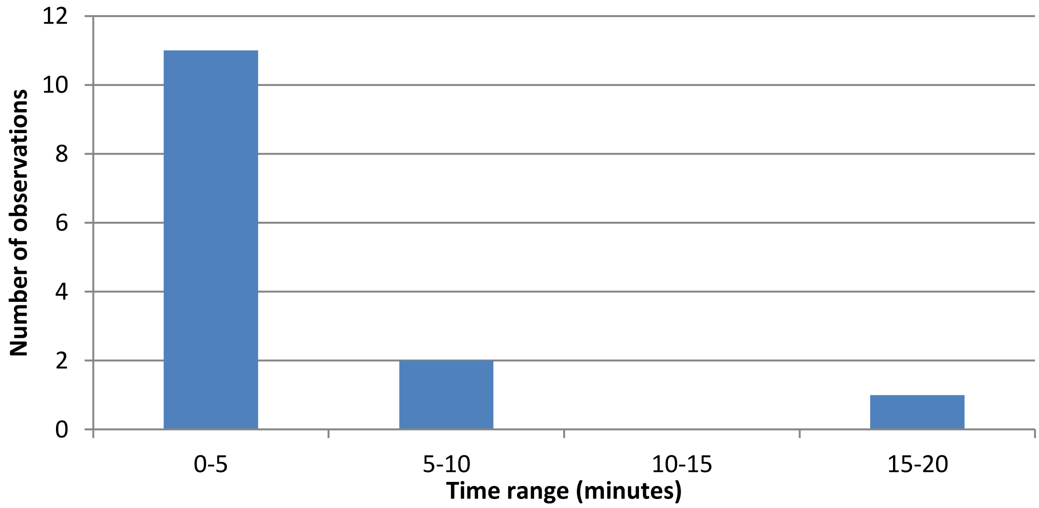


Figure 52 – Error of user-reported duration compared to GPS readings (time ranges in minutes)

Approximately 78% of reported duration information fell within 5 minutes of actual, GPS-measured travel time. Only 1 out of 14 comparable pairs of duration entries exceeded a difference of 15 minutes. The one previously-observed travel start-and-end-time error exceeding 40 minutes resulted in a trip duration in the 0-5 minute error range, which proves signs of memory effect on reporting. Single-stage errors yield a large cumulative error when a trip is considered as a whole, thereby increasing the impact of rounding effect.

Due to survey design, reported distances were unavailable. Thus, distance error was calculated by comparing distance values from routing results, based on user-reported origins and destinations, with GPS-derived travel information. Figure 53 reports the observed difference, in percentage, of the distance readings grouped by the degree of error.

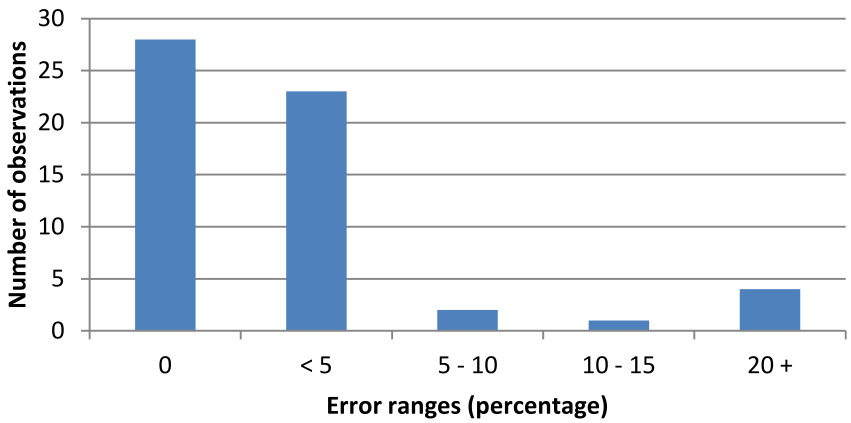


Figure 53 – Distance differences (in percentage)

Results demonstrate that shortest-path routing derived from user information matched GPS-based routing 48% of the time, and 90% of calculated distances resulted in an error below 5%. Error level thus fell in an acceptable range, even though researchers did not directly ask respondents to report distance. Further analysis on this aspect was performed during the GPS survey. As with rounding effect, distance error is compounded when single-stage errors are added to calculate complete-trip error.

Augmented travel behaviour

Results from the pilot survey demonstrate the ability of GPS to provide surveyors with useful information on respondents' travel behaviour, even in the case of incomplete trip and stage detection. The resulting GPS-augmented travel diary provided a more complete overview of travel behaviour, due to improvements in data completeness and quality, which will be discussed later. However, data from the GPS-only survey would not have allowed surveyors to reconstruct such a complete picture of daily mobility.

Complete GPS tracks were more accurate than travel diaries in determining locations, and they were used to spot misreporting and correct improper user-reported addresses. Table 52 reports the percentage of locations that were improved by GPS data. Improvement occurs every time a POI or incorrect address is transformed into a correct address.

USER	Improved	New	% Improved
282DBC	4	0	80%
282FFB	2	3	72%
285898	1	0	100%
28312F	3	0	50%
TOT	10	3	69%

Table 52 – Locations improved by GPS

Results showed that approximately 70% of the overall incorrectly reported or missing location entries were successfully improved or imputed by GPS readings. Total number of correct street level addresses almost doubled with GPS augmentation. Poor quality reporting was completely corrected for user 28312F. Use of GPS for address correction offers a crucial benefit for large scale applications, in particular for incidental trips, where inaccurate address reporting is expected to be higher.

The same approach was followed for travel temporal information and length. Table 53 shows the degree of observed improvement in the travel diary after augmentation with GPS data. Researchers used GPS readings to fix underreported temporal data and to correct the calculated distance values.

USER	**Trip Start**		**Trip End**		**Distance**	
	Improved	New	Improved	New	Improved	New
282DBC	8	0	12	0	11	1
282FFB	11	7	13	13	14	2
285898	6	0	7	6	7	0
28312F	4	0	4	0	1	0
TOT	29	7	36	19	33	3

Table 53 – Improvement of the travel diary after GPS augmentation

The use of GPS consistently improved user data, increasing the quality of reported data for 52% of collected data related to time and distance. GPS aided in the completion of missing information for 31% of considered items (62 start time, 62 arrival time and 62 distance items overall). After GPS augmentation, the number of detected trips increased by 12%, 3 new visited locations were added and 10 were improved, thereby reducing the percentage of incorrect addresses to an overall 10% – nearly halving the previous evaluation.

Surveyors used GPS positional data and routing tools to reconstruct participants' use of space. Figure 54 shows the actual routes used by one of the survey participants during the pilot survey, compared to the user-reported routing. The use of GPS as a supplementary source allowed researchers to better reconstruct routes.

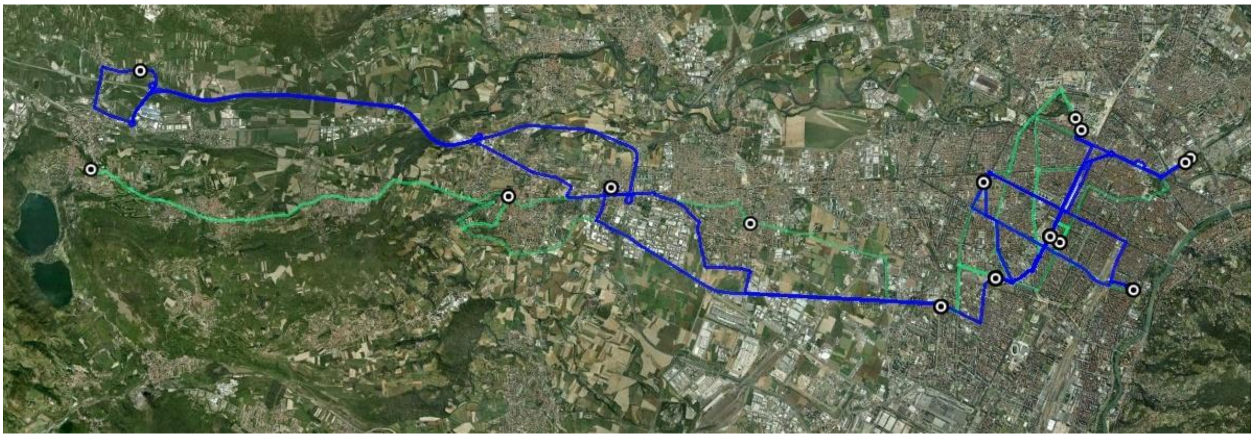


Figure 54 – Actual route (in blue) compared to the route derived from user-information (green)

The use of GPS can sensibly improve the knowledge of respondents' use of space, providing a degree of accuracy that cannot be matched by imputation with self reporting, or will require an additional burden on survey participants.

GPS-based trip information derivation

Researchers utilized user-augmented GPS data in order to study possible derivation methods for identifying transport mode and trip purpose. Results from the identification of trip purpose and transport mode will be reported below.

Purpose identification: the selected method for purpose derivation relied on previous knowledge of users' most-visited locations and the related activities performed. The pilot survey provided researchers with data to evaluate the proper number of locations required to derive an appropriate share of trip purposes. Table 54 reports the number of unique locations visited during the survey by each respondent, together with the predicted success rate of two scenarios, consisting of the top 3 and 5 most-visited locations.

USER	Unique	Top 3	Top 5
282DBC	10	12 (52%)	16 (70%)
282FFB	9	12 (67%)	13 (73%)
285898	4	7 (87%)	8 (100%)
28312F	7	8 (67%)	10 (83%)
TOT	30	39 (64%)	47 (77%)

Table 54 – Unique location and trip share in the top 3 and top 5 most-visited places

Results demonstrate that asking respondents about their most-visited places can provide surveyors with valuable purpose-derivation information, even when respondents are asked to declare only a limited number of locations, such as home, work and an additional address (gym, grocery store, children's school, etc.). In fact, the three most visited locations accounted for 64% of total trip purposes. Asking users for 5 most-visited locations resulted in an overall purpose recognition of 77%. Further analysis will be illustrated in the trip information derivation section of the 2-week survey (paragraph 4.5.2).

Transport mode detection: researchers did not proceed with mode classification using the dataset of the pilot survey. In fact, GPS data collection results did not allow researchers to perform a complete classification phase, due to a limited number of observations and detected transport modes. Nonetheless, GPS data were used to observe the discriminating factors for mode detection, and to determine the mode classification parameters for the main survey. Classification was performed for bike trips, car trips, and trips on-foot. Researchers trained the classification tree with the entire database of GPS data. GPS modes were categorized according to user-reported information. Figure 55 shows the results of this classification.

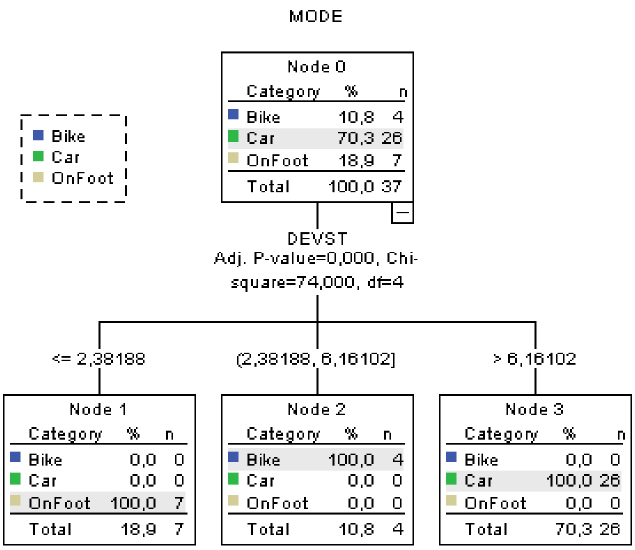


Figure 55 – Decision tree classification for GPS pilot survey data (all variables)

Despite using four different variables, it was possible to discriminate trips by car, bike and on-foot, by observing the standard deviation values of GPS-detected speeds. Results are affected by the absence of other transport modes, such as public transport and trains.

Classification rules successfully derived transport mode in GPS-only trips and stages. Researchers inspected the final outcomes of the decision tree classification in order to detect possible mis-classification. Interestingly, the results of derivation of on-foot movement using classification rules perfectly match the results of derivation using a rule-based detection algorithm, the latter of which had been employed in the trip determination phase in order to identify possible on-foot movement within the GPS data stream. The following analysis will further discuss this similarity.

A successful classification requires only speed values, as illustrated in Figure 56, whereas maximum acceleration and deceleration values are required to help distinguish public transport and train travel from trips performed with private motorized means of transport.

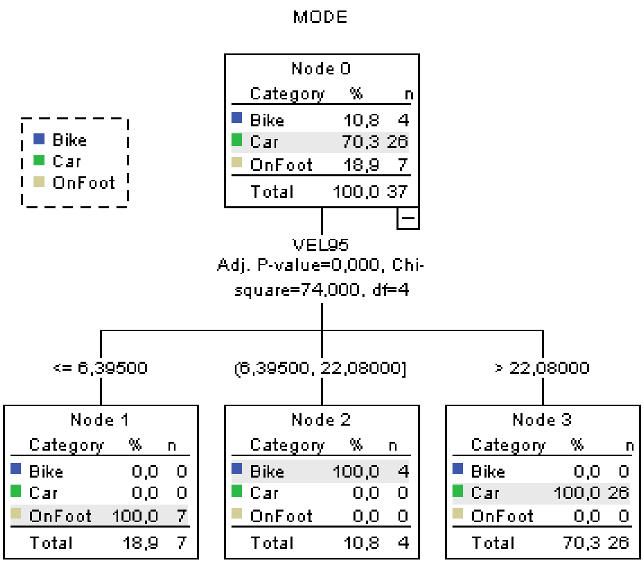


Figure 56 – Decision tree classification with speed information using pilot survey GPS data

The distinction of motorized from non-motorized means of transport and the distinction between trips on foot and by bike poses no particular problem, given the dataset of trips collected during the GPS pilot survey. However, derivation issues were expected to arise when attempting to distinguish between public transport modes and car trips. A more in-depth analysis on public versus private motorized trips will be performed in the GPS survey data analysis section.

Considerations and suggestions

Pilot survey results provided surveyors with a preliminary overview of GPS outcomes and data collection issues using the designed multi-tool method. Travel behaviour was successfully detected by using both survey tools, as confirmed by respondents during the prompted recall validation interview at the end of the survey. However, GPS-only diary tools, used on their own, were also able to provide a satisfactory picture of travel behaviour.

The user-reported travel diary exhibited consistent instances of item non-response, often related to the use of the GPS devices themselves. Without being specifically instructed to rely on GPS for temporal and spatial data collection, respondents did so anyway and were more inclined to fail to report these items in user-reported travel diaries. For this reason, researchers agreed on the need to instruct participants of the main survey to fully complete their travel diaries, even though they would be simultaneously carrying a supplementary and theoretically more precise collection tool.

GPS recordings were characterized by a lack of continuity, due to signal reception problems. For this reason, researchers suggested that the main survey include a manual inspection of GPS segments after the first trip-detection phase, to allow for the identification of possible derivation mistakes.

GPS mishandling was limited and was largely related to battery issues and forgotten devices. Respondents reported a lower battery life than was expected, resulting in more frequent recharging. Users were able to manage the problem with a full recharge of the device once per day. Nonetheless, GPS devices were unable to continuously record information at the start of each trip (cold start). For these reasons, surveyors decided to instruct participants in the main survey to recharge devices every day, and to turn on the device before trip starts, in order to minimize the effects of cold start and partial trips.

Derivation of most purpose and mode information from GPS data was possible, with limited effort. Purpose derivation was supported by information on most-visited locations, provided by the socio-economic questionnaire. Researchers determined that improvements in information derivation results could be obtained by studying proper derivation rules, using a larger dataset. In particular, methods for deriving bus and train movements were further developed in the main survey.

The GPS pilot survey allowed surveyors to identify common problems they would need to overcome during the main survey. Table 55 summarizes improved instructions that were given to participants in the main survey in order to limit the effects of problems observed during the pilot.

ISSUE	SUGGESTED INSTRUCTIONS
Trip and stage underreporting in travel diary due to the multi-tool method.	**Report every trip segment information accurately and completely even if GPS is recording information.**
Cold start issues	**Turn on the GPS device prior to trip start.**
Battery issues	**Recharge the GPS device at the end of each day.**

Table 55 – Guidelines for GPS survey instructions

4.5.2 GPS survey

The main GPS data collection benefitted from the experience of the pilot survey. Respondents were asked to put forth additional effort with travel diary reporting and to take more care in the handling of GPS devices, in order to prevent any possible data loss using the selected data collection tools. The following paragraphs will discuss the analysis of GPS survey data collected from the 8 survey participants.

Travel diary

Respondents filled out a traditional trip-diary (see ANNEX 6 for more details) designed for traditional travel surveys. Considering the results of the pilot survey, participants were specifically reminded to complete this tool as completely as possible, without relying on the possible derivation capabilities of the GPS devices, in order to provide the best possible results from reported data. Particular attention was required for temporal information, in terms of both completeness and data quality.

Quality indicators

Traditional travel surveys provided researchers with information on 228 trip stages, resulting in 190 trips. Coding and trip-chain checks allowed surveyors to spot trip underreporting and to fix missing information utilizing user-reported data. The research team identified 9 new trip segments, resulting in 9 new trips, contributing to a trip underreporting percentage of less than 5%. Observed trip underreporting was low, but missing trip information still impacted derived values, such as time at destination. There was no proof of higher underreporting related to a specific survey participant, as had been seen in the pilot study.

The overall trip segment count per user and by transport mode is reported in Table 56.

USER	Tot	Car	Moto	Taxi	PT	Train	Bicycle	On-Foot	Other
N0001	28	19	0	4	0	0	0	2	3
N0003	47	5	0	0	17	0	0	25	0
N0030	23	13	0	0	0	0	0	10	0
N0032	33	22	0	0	3	6	0	2	0
N0033	18	10	0	0	0	0	8	0	0
N0034	29	27	2	0	0	0	0	0	0
N0035	17	9	0	0	0	0	0	8	0
N0037	33	19	0	0	2	0	0	12	0
TOT	228	124	2	4	22	6	8	59	3

Table 56 – Trip segments observed and derived using the travel diary reported by transport mode

Respondents generally performed more complex trip chains, with trips comprised of multiple stages, compared to the results of the pilot survey. Participants performed movements using a wider variety of transport modes. Based on the data provided in the previous table, Figure 57 illustrates the share of employed transport modes as reported by respondents in the travel diary.

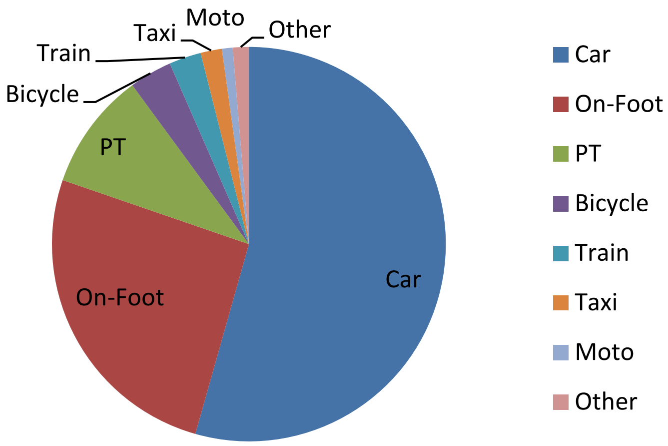


Figure 57 – Reported use of transport modes (by trip segment)

Heavy use of the personal car was evident; this was the most often used among transport mode choices.

Car stages accounted for 55% of total observed travel behaviour. Considering other transport modes reported during the survey period, on-foot movements accounted for 26% of trips, while respondents chose public transport for their mobility during 10% of trips.

Survey participants directly provided trip information using the travel diary for the first survey week. Aside from the previously-observed problem of trip underreporting, there were an insignificant number of instances of item-non response. Item non-response was observed for just four distance items in the entire travel diary, accounting for less than 2% of distance underreporting. Researchers could not collect any time or distance information for a total of 9 underreported trips, and one distance item was not reported. The overall impact of item non-response can be quantified as just 2% of all trips. Item non-response had a greater impact on departure and arrival times, as well as time spent at destination. Missing duration and distance values were subsequently derived for user-reported data or imputed through routing algorithms. Table 57 reports the impacts of underreporting and item non-response on time information.

USER	TOT items (D/A)	Departure	Arrivals	Duration	Activity time
TOTAL	456	9 (2%)	9 (2%)	9 (4%)	15 (6,5%)

Table 57 – Item non response for time information

Origin and destination addresses were available for 222 stages, with 6 stages missing location information. Missing addresses had only a minor impact on the overall completeness of location information, resulting in just 1% of total missing location information. Respondents completed a socio-economic questionnaire and provided most of the information requested on visited locations.

Nine pieces of information on transport mode were missing, along with 6 pieces of information related to trip purpose, due to detected trip underreporting. The overall share of item non-response can be quantified as just 2,5% of collected data, resulting in a very successful data collection.

The derivation of travel times and distances using routing tools, which was successfully tested in the pilot survey, depends on respondents' ability to accurately report location information. Location accuracy also impacts the assignment phase in transport modeling applications. Table 58 shows the results of the location quality assessment.

USER	Locations	Correct	POI	Town / Neighborhood	Incorrect (%)
N0001	28	6	14	8	29%
N0003	44	29	14	1	2%
N0030	22	15	5	2	9%
N0032	33	7	22	4	12%
N0033	16	14	1	1	6%
N0034	29	18	8	3	10%
N0035	17	16	1	0	0%
N0037	33	22	5	6	18%
TOTAL	222	127	70	25	11%

Table 58 – Reported location quality

Reported locations were generally correct, with a higher percentage of correct reporting in the case of habitual trips – for which addresses were reported at a house-number level 95% of the time. The lowest-quality location data were witnessed among highly-mobile users with the highest share of non-habitual trips. For example, user N0001 reported almost 30% of unreliable addresses and a 75% share of non-habitual trips.

Respondents were required to report travel behaviour in the travel diary for one survey week. Researchers were able to evaluate the existence of reporting problems, such as survey fatigue, by observing the distribution of the 190 trips throughout the survey period of one week, as shown in Table 59.

USER	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7
N0001	4	3	4	3	3	4	3
N0003	6	9	2	5	6	5	2
N0030	2	6	2	6	3	2	2
N0032	4	2	5	2	2	4	2
N0033	4	4	0	0	2	4	4
N0034	6	2	2	6	7	5	2
N0035	4	3	1	5	2	2	0
N0037	2	3	5	3	3	3	3
TOTAL	32	32	21	30	28	29	18

Table 59 – Trips reported by survey day

In addition to the presence of 3 reported no-movement days, which need to be studied in conjunction with the associated GPS data, there was no clear evidence of survey fatigue. The only exception was observed on the final day of the survey, when reporting was generally lower for most users.

Distribution of trips throughout the survey duration demonstrated how variability of reported trips depends largely upon the user. Table 60 reports the average number of trips per person and the standard deviation of the trips per user, for further analysis of this phenomenon.

USER	Mean	Median	St Dev
N0001	3,43	3	0,53
N0003	5,00	5	2,45
N0030	3,29	2	1,89
N0032	3,00	2	1,29
N0033	2,57	4	1,90
N0034	4,29	5	2,21
N0035	2,43	2	1,72
N0037	3,14	3	0,90
TOTAL	3,39	3	1,81

Table 60 – Variability of trips throughout the survey

The picture provided by the travel diary shows an average number of 3,4 trips per day, ranging from 2,4 to 5 trips. Different profiles of trips-per-day were observed. Considering the characteristics of the observed measure, the highest variability was witnessed for users with higher rates of mobility.

Travel time as reported by users was affected by rounding biases. The distribution of reported time information is illustrated in Figure 58.

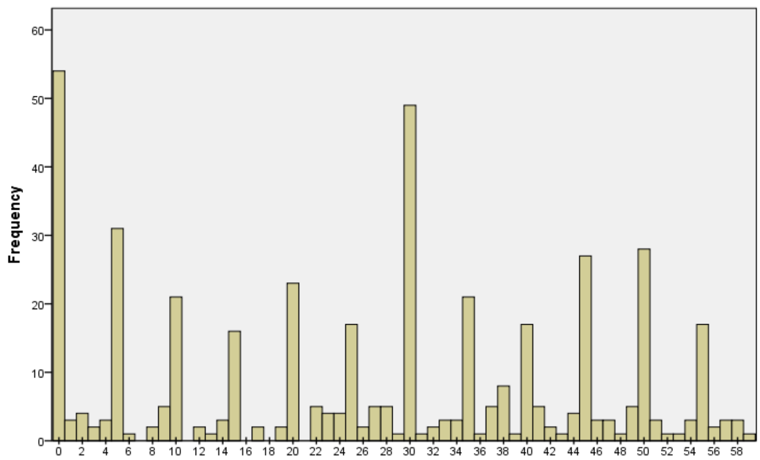


Figure 58 – Frequency of reported times (reported minutes)

Time information distribution showed a high degree of rounding effect, with the majority of time values reported as multiples of 5. This aspect was expected to affect duration information, which is derived using time information. Figure 59 shows a histogram of the frequencies of duration values of single-trip segments, calculated from user-reported information.

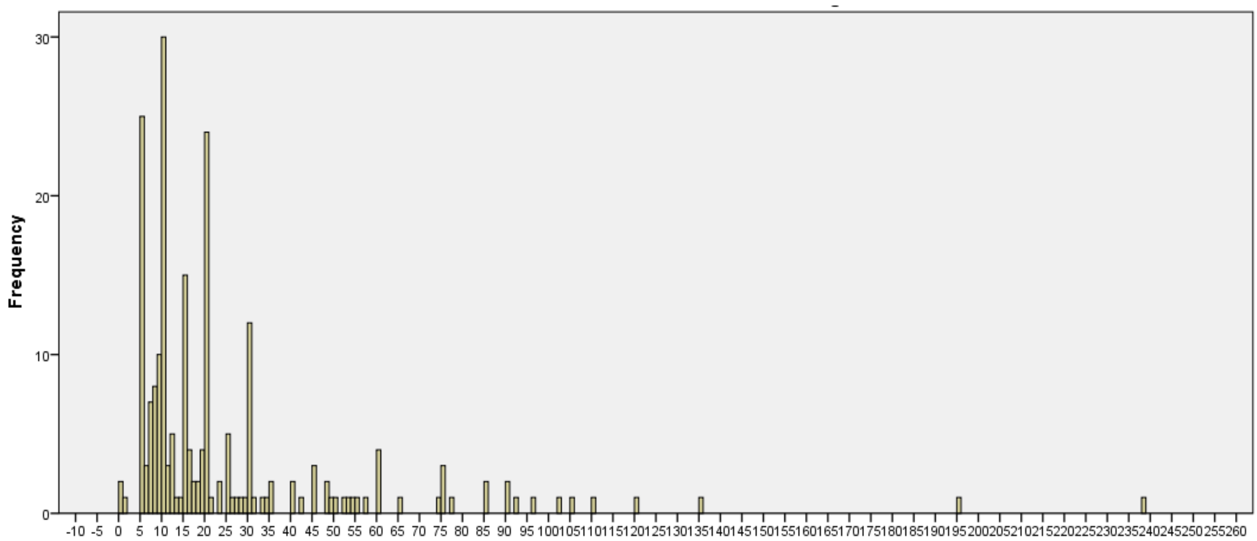


Figure 59 – Frequency of reported travel duration values (in minutes)

This chart proves the impact of rounding on duration values; in particular, for trips below 20 minutes, which were the most commonly-performed (comprising share of 68% of total reported durations). For such trip segments, duration values that were multiples of 5 were predominant over all other duration values.

Distance values can be also affected by rounding, resulting in a biased assessment of travelled kilometres. Figure 60 shows a histogram of reported distance values for each single trip stage.

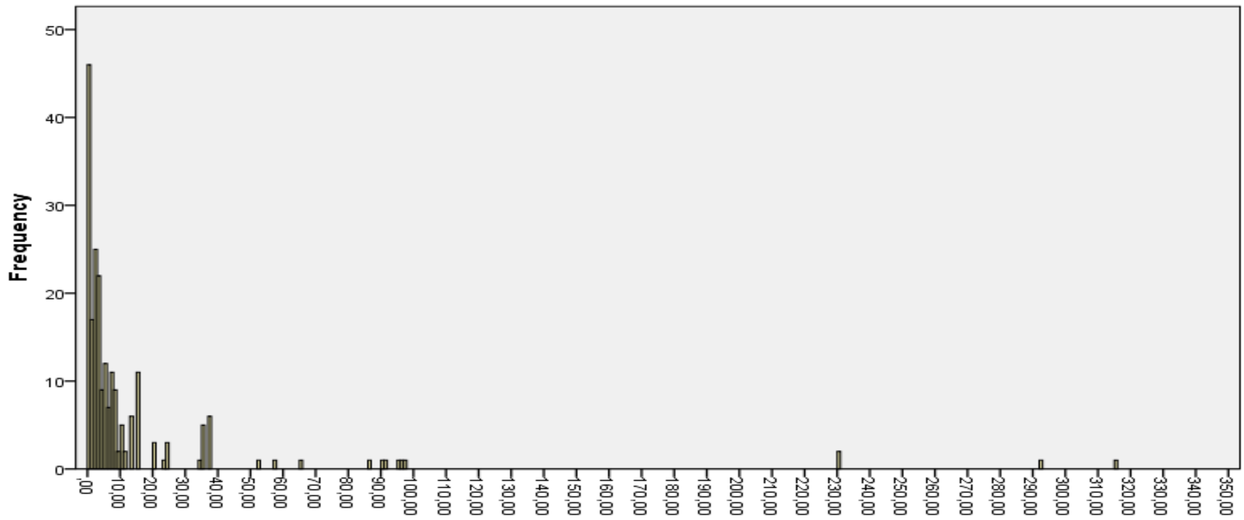


Figure 60 – Frequency of reported travel duration values (in minutes)

Declared distance tended to be reported at the kilometer level for trips of more than one kilometer, and at hundred-meter accuracy for shorter trips, as requested by surveyors in the planning phase. In fact, it was possible to witness a use of the hundred-meter accuracy for all reported trip segments within the 10-kilometer range. Accuracy lowered to the kilometer level for trip segments exceeding 10 kilometers, together with a tendency to round distances to multiples of 5 kilometers. Results do not show a prohibitive rounding effect within length information.

Travel behaviour

Respondents provided distance information for all reported trips and related stages. However, there was no way to determine distance for underreported trips detected during the travel diary check using only user-related information. Lost information was made available through derivation. Table 61 illustrates the overall reported travelled distances by user and transport mode.

USER	Car	Moto	Taxi	PT	Train	Bicycle	On-foot	Other
N0001	700,5	0	50	0	0	0	0	0
N0003	19,15	0	0	58	0	0	29,65	0
N0030	320,5	0	0	0	0	0	8,2	0
N0032	326,5	0	0	10,5	222	0	21	0
N0033	54	0	0	0	0	16	0	0
N0034	214	14	0	0	0	0	0	0
N0035	32,4	0	0	0	0	0	11,75	0
N0037	1057,5	0	0	6,5	0	0	6,6	0
TOTAL	2713,9	14	50	75	222	16	77,2	0

Table 61 – Reported travelled distance (in kilometres) by user and transport mode

As illustrated before, reported travel times were largely affected by rounding effects. This factor was expected to provide biased duration information.

Table 62 shows user-reported travel times by transport mode for the first survey week.

USER	Car	Moto	Taxi	PT	Train	Bicycle	On-Foot	Other
N0001	832	0	115	0	0	0	8	45
N0003	80	0	0	253	0	0	481	0
N0030	440	0	0	0	0	0	107	0
N0032	525	0	0	60	305	0	150	0
N0033	65	0	0	0	0	50	0	0
N0034	471	20	0	0	0	0	0	0
N0035	95	0	0	0	0	0	124	0
N0037	1052	0	0	18	0	0	85	0
TOT	3561	20	115	331	305	50	1032	45

Table 62 – Reported travel time (in minutes) by user and transport mode

Distance values did not demonstrate significant rounding effects. User-estimation error was evaluated during the later comparison of GPS and user-reported data.

Activity duration (time spent at destination) can be observed and categorized depending on declared purpose. Results from these calculations are provided in Table 63.

USER	Work	Study	Shopping	Free-time	Errand	Take/ Get a person	Home	Other
N0001	1032	0	0	100	0	0	5595	1221
N0003	200	0	73	50	170	126	7040	32
N0030	0	694	0	802	104	222	6431	0
N0032	2227	0	0	1389	0	0	2596	696
N0033	0	933	465	0	0	0	4487	100
N0034	1655	0	110	270	24	10	2545	990
N0035	1550	0	20	255	0	0	996	0
N0037	0	191	17	1501	6	0	4640	516
TOT	6664	1818	220	4832	304	358	34330	3555

Table 63 – Computed activity duration (in minutes)

Despite the presence of some unreliable data due to missing information, such as in the case of little time spent at home by user N0035, collected data can be considered complete. However, results were expected to be impacted by the rounding of time values.

Derived travel behaviour

Routing tools and other GIS tools that rely on user information can provide researchers with information on travelled distance. However, user-derived distance and time values are expected to be lower than user-reported values. Table 64 illustrates travel distances obtained with the designed imputation tools.

USER	Car	Moto	Taxi	PT	Train	Bike	On-foot	Other
N0001	639,15	0	60,6	0	0	0	0,6	2771
N0003	18,4	0	0	59,1	0	0	28,15	0
N0030	309,3	0	0	0	0	0	7,6	0
N0032	315,4	0	0	12	222	0	12	0
N0033	39,3	0	0	0	0	12,8	0	0
N0034	273,7	20	0	0	0	0	0	0
N0035	26,9	0	0	0	0	0	9	0
N0037	1041,8	0	0	4,7	0	0	5,8	0
TOTAL	2663,95	20	60,6	75,8	222	12,8	63,15	2771

Table 64 – Imputed travel distance (in kilometres) by user and transport mode

Outcomes from the imputation phase improved the overall quality of travel diary data. However, the use of information derived from shortest path algorithms, which rely on reported origin and destination locations, was expected to result in underestimation of imputed values, thereby adding a source of error to survey outcomes. Applicability of such algorithms is thereby limited, both for distance and time determination. The degree of error produced by algorithmic estimation will be discussed in the paragraph comparing GPS and travel diaries.

Augmented travel diary

Users provided fairly complete distance reporting, which researchers improved with limited imputation efforts. Imputation added to the data up to 2% of total distance travelled by all participants. Estimation of this correction value did not take into account travel by plane, included in the "Other" category.

The observed degree of improvement was low, largely because user reporting had been so complete. Additionally, most imputed trips had to be calculated manually, because the routing tool is unable to provide distances travelled by plane. GPS is also incapable of providing information on these types of trips.

Variability of distance values was assessed by observing the overall distance data of the improved travel diary per day by user. Table 65 reports the results of travel diary augmentation. Airplane trip distances were omitted in this analysis in order provide comparable data among users (only user N0001 reported such trips).

USER	Mon	Tue	Wed	Thu	Fri	St Dev Week	Sat	Sun	St Dev W-E	St Dev TOT
N0001	8,00	29,00	69,58	255,00	252,50	121,56	74,00	74,00	0,00	102,07
N0003	9,60	16,90	12,10	24,30	24,20	6,76	1,75	19,15	12,30	8,20
N0030	1,40	2,40	1,40	15,00	9,00	6,02	160,50	139,00	15,20	70,67
N0032	111,00	111,00	22,60	111,00	188,50	58,73	7,00	58,00	36,06	62,47
N0033	0,00	4,00	8,00	18,00	8,00	6,69	32,00	0,00	22,63	11,49
N0034	43,00	51,30	40,00	26,00	74,60	17,93	10,00	10,00	0,00	23,24
N0035	22,40	4,00	4,00	0,00	4,55	8,81	5,20	4,00	0,85	7,29
N0037	192,00	12,50	8,40	194,00	7,00	100,64	630,00	26,70	426,60	226,81

Table 65 – Variation of travelled distance (in kilometres) throughout the survey period

Observed day-to-day variability of distance values was significant for most participants, with high standard deviation values during week days. Variability during weekends was, as expected, lower for most users, except for respondent N0037, who also reported the most variable travelled distance. In general, a shorter-duration survey would have provided only a partial picture of the weekly travel pattern. Dispersion indicators were lower only in cases of lower observed mobility, observed with 3 respondents.

As illustrated during analysis of user-reported data quality, reported travel times were affected by rounding effects, which resulted in biased duration information. However, the completeness of reported data allowed surveyors to reconstruct the temporal dimension of survey participants' travel behaviour. Imputation of missing data was carried out using the time required to perform travel at free flow speed. Table 66 shows reported travel times augmented by imputed information.

USER	Car	Moto	Taxi	PT	Train	Bike	On-foot	Other
N0001	832	0	115	0	0	0	8	265
N0003	80	0	0	288	0	0	481	0
N0030	440	0	0	0	0	0	107	0
N0032	572	0	0	60	305	0	150	0
N0033	65	0	0	0	0	50	0	0
N0034	485	20	0	0	0	0	0	0
N0035	95	0	0	0	0	0	124	0
N0037	1052	0	0	18	0	0	85	0
TOTAL	3631	20	115	36	305	50	979	265

Table 66 – Reported and imputed travel time (in minutes) by user and mode

Imputed time information was expected to be lower than actual time spent travelling, as observed in the pilot survey data analysis. However, in the main study, the use of imputed time data increased the overall travel duration value by 8%. Data from all means of transport were considered.

The availability of a more complete dataset allowed surveyors to better observe the variability of the travelled time of each respondent throughout the week, as shown in Table 67.

USER	Mon	Tue	Wed	Thu	Fri	St Dev Week	Sat	Sun	St Dev W-E	St Dev TOT
N0001	47	173	107	240	288	97,37	145	230	60,10	83,59
N0003	155	106	76	136	246	64,53	50	80	21,21	65,80
N0030	15	35	20	81	46	26,29	207	143	45,25	71,97
N0032	193	193	94	171	203	44,50	13	220	146,37	74,79
N0033	0,00	12	25	30	23	12,02	25	0,00	17,68	12,47
N0034	76	124	95	40	154	43,79	20	20	0,00	52,15
N0035	99	15	15	0,00	75	43,45	52	25	19,09	36,34
N0037	204	39	35	195	51	86,71	523	108	293,45	173,02

Table 67 – Variation of travel duration values throughout the first survey week

As expected from the observation of variation among distance values, the day-to-day variability of travelled time observed throughout the survey period was significant. Such variability, expressed by standard deviation, ranged from 12 to 97 minutes, with higher maximum values observed on weekend days. Observing total variability, dispersion of travel times varied from a fairly stable standard deviation of 12 minutes (for user N0033) to an extremely variable standard deviation of 173 minutes (for user N0037), corresponding to that user's very complex travel behaviour pattern. As expected, weekday variability and weekend variability were vastly different. In general, a high value of day-to-day variability in travel times was witnessed for most survey participants. Standard deviation values greater or equal than 45 minutes were observed for 75% of participants during weekdays.

Distance values showed clear variability patterns during the week. Figure 61 illustrates variability among travelled distances for the 8 respondents.

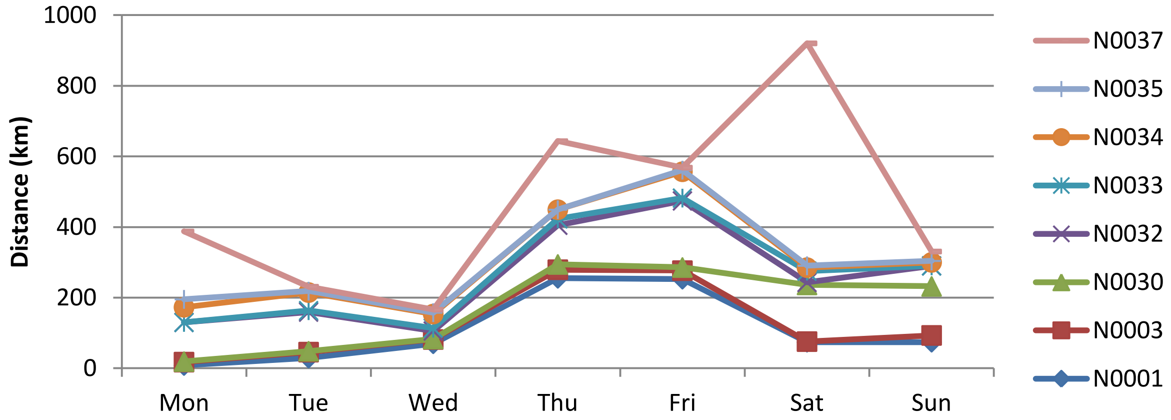


Figure 61 – Travelled distance (in kilometres) by respondent and day of the week

As expected, multi-day surveys provided a significantly more complete picture of travel behaviour. Observed travelled distance varied throughout the week, with a peak observed on Thursday and Friday for all respondents.

Further demonstrating the effects of variability on travel behaviour, Figure 62 illustrates the absolute time values of the least- and most-mobile respondents throughout the survey duration.

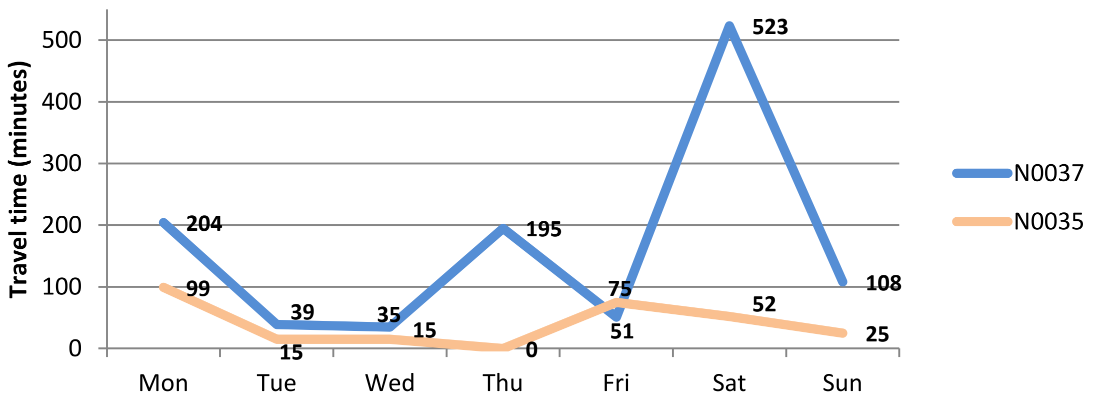


Figure 62 – Travel time (in minutes) of most and least mobile respondent

Observation of changes in travel time proved the existence of travel trends (peaks and low-mobility days), and of differences between weekdays and weekends. These trends were observed among even the least-mobile users within the sample.

GPS diary

Researchers used the designed and previously-tested post-processing method to remove unreliable records from the two survey weeks' raw GPS data, and to identify potential trips. Post-processing outcomes benefitted from the previous experience of the pilot survey. Results from the first week were compared with travel diary data in order to evaluate the accuracy and completeness of the derivation.

GPS processing quality

The post-processing phase was necessary in order to remove incorrect and unreliable GPS recordings from the data. Basic information about the data cleaning phase is reported in Table 68.

USER	RAW GPS DATA	CLEANED DATA	% DELETED
N0001	4238	3732	11,94%
N0003	1863	1071	42,51%
N0030	5217	4363	16,37%
N0032	4902	4482	8,57%
N0033	1882	1566	16,79%
N0034	6941	5888	15,17%
N0035	1126	595	47,16%
N0037	2255	1887	16,32%
TOT	28424	23584	17,03%

Table 68 – Results from the GPS cleaning and filtering phase

While the overall amount of deleted data was comparable to the result observed in the pilot survey, values of more than 40% of records discarded were witnessed for 2 users. Researchers expected these deletions to impact data completeness.

Post-processing algorithms detected potential trips using the methodology described in Section 4.4.2. Results from the trip-detection phase of the pilot survey are reported in Table 69.

USER	GPS Trips	USER	GPS Trips
N0001	26	N0033	29
N0003	17	N0034	45
N0030	41	N0035	17
N0032	37	N0037	24
TOTAL IDENTIFIED TRIPS			236

Table 69 – Trips identified using GPS data (automated procedure)

Surveyors identified relevant data collection problems after the manual check of the trip derivation phase. Several possible trips had to be merged into single, complete trips, as they had been falsely separated due to frequent signal loss, especially in the more densely-built areas of the city of Torino. The impact of signal loss was significantly higher in the outcomes of the main survey than in the outcomes of the pilot survey. Final outcomes of the manual check and the finalized number of trips or stages detected by GPS are shown in Table 70.

USER	SELECTED SEGMENTS	RESULTING TRIPS
N0001	8	3
N0003	6	3
N0030	10	4
N0032	3	1
N0033	13	6
N0034	6	2
N0035	8	3
N0037	3	1
TOT	57	23

Table 70 – Post processing fixes (selected segments and resulting trips)

The overall number of potential trips that were erroneously derived and needed to be merged was significant. Results of the manual check and analysis showed that disruption of GPS data in 57 segments led to the definition of 23 complete, merged trips. Researchers expected this disruption in observed positioning data to have a significant impact on trip completeness and GPS data quality; in particular, travel distance was expected to be significantly lower for GPS trips consisting of multiple separated segments.

Quality indicators

Surveyors evaluated trip completeness by observing the number of complete potential trips and potential trips affected by cold start. This 'cold start' delay in data collection can be generally estimated at 500 meters or 2/3 minutes of recording, depending on the transport mode. Figure 63 shows the overall share of reliable trips or trip segments compared to partially-detected movements, while Table 71 illustrates the overall quality of the 202 detected trips or trip stages.

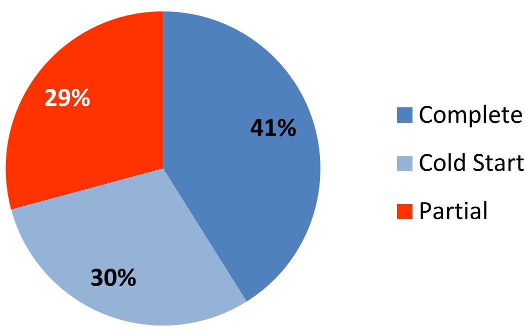


Figure 63 – GPS trip data quality

Potential trips characterized by partial information account for 30% of all detected trips. Table 71 illustrates the different degrees of completeness observed among users.

USER	Trips/Stages	Complete	Cold start	Partial
N0001	21	6	10	5
N0003	14	5	2	7
N0030	35	16	7	12
N0032	35	14	12	9
N0033	22	10	7	5
N0034	41	20	11	10
N0035	12	6	5	1
N0037	22	6	6	10

Table 71 – GPS-derived trips by degree of completeness

Researchers obtained the total number of trips by distinguishing trips and trip segments based on derived and user-reported information. The following reported results on trip identification anticipate the data analysis results that will successively be provided. The number of identified trips was lower than expected for a personal travel survey with the defined characteristics. Further analysis of the nature of trip/stage underreporting was carried out during the GPS and travel diary comparison. The opportunity to observe travel behaviour for 2 consecutive weeks allowed researchers to compare the number of trips each week, and thus to spot possible differences or data collection issues. Table 72 and Table 73 show the outcomes of trip identification for the first and second survey week, respectively.

USER	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	TOT
N0001	4	2	1	5	1	1	1	15
N0003	3	6	0	0	0	2	0	11
N0030	0	6	2	6	3	2	2	21
N0032	3	2	5	4	3	2	4	23
N0033	3	3	0	0	0	3	0	9
N0034	2	6	2	4	5	1	2	22
N0035	1	0	1	1	2	0	0	5
N0037	0	2	0	1	3	1	1	8
TOTAL	16	27	11	21	17	12	10	114

Table 72 – GPS derived trips per survey day - First week

The average trip-per-day count seen in the first GPS survey week was 2,4, with a maximum observed value of 3,3. The high number of no-movement days or single-trip days for one specific user was evidence of data collection problems. No GPS underreporting was identified during the first week. However, researchers had expected high underreporting values during the comparison of identified trips with user reported trips, considering the low number of trips per day, and data disruption.

USER	DAY8	DAY9	DAY10	DAY11	DAY12	DAY13	DAY14	TOT
N0001	1	3	1	0	1	0	0	6
N0003	0	0	0	0	0	0	3	3
N0030	0	1	1	5	1	2	4	14
N0032	2	0	0	4	2	2	2	12
N0033	2	1	3	0	3	4	0	13
N0034	5	3	0	1	2	2	6	19
N0035	0	3	0	0	2	0	2	7
N0037	3	5	0	5	1	0	0	14
TOTAL	13	16	5	15	12	10	17	88

Table 73 – GPS derived trips per survey day - Second week

As expected, the number of reported trips dropped during the second survey week, as did the number of no-movement days (22). The average number of trips per day was 1,6, while the maximum value was 2,7. Data suggested the occurrence of survey fatigue in the GPS-only travel survey. While most GPS devices recorded fewer trip segments and complete trips than during the first week, only one user recorded an increased number of trips during the second week. Additionally, 18 missing trips were detected by using identified trip chains, resulting in a high degree of underreporting.

Surveyors initially attributed GPS survey underreporting to GPS mishandling, technical problems and actual no-movement days. Analysis of the GPS functionality diary (see ANNEX 7 for more details) provided researchers with more information on the nature of observed underreporting. Table 74 reports the outcomes from the coded GPS functionality diary.

USER	DAY8	DAY9	DAY10	DAY11	DAY12	DAY13	DAY14
N0001	24	24	24	24	24	24	24
N0003	24	5	24	0	0	24	9
N0030	15	24	24	24	24	24	24
N0032	24	N/A	N/A	24	24	24	24
N0033	24	24	24	12	24	24	12
N0034	15	24	0	24	24	24	24
N0035	0	17	0	0	24	24	24
N0037	24	18	15	15	24	24	N/A

Table 74 – GPS functionality diary – Hours of device operation

Users reported 3 no-moving days in the second survey week. One user forgot to carry or failed to turn on the GPS device for 6 days, while other respondents reported problems that prevented data collection for the entire survey day on 10 different occasions. GPS-related problems were mainly related to forgotten devices and battery depletion. As a result of these data collection issues, devices were reported as fully functioning just 66% of the time throughout the overall duration of the GPS-only part of the survey. Further analysis of this underreporting was performed during the comparison of data from the first week with user-reported information.

Due to data collection problems, GPS data failed to provide a complete overview of the travel behaviour of respondents. Total underreporting, estimated from GPS data observation, was quantified in 18 trips, concentrated in the second survey week. However, additional underreporting due to GPS device problems likely impacted the first week as well.

Incomplete information from the GPS-only survey was used to augment the travel diary, but GPS data on their own were not able to provide a complete overview of travel behaviour. For this reason, GPS data from the Torino GPS survey were mainly used to augment user-reported data collected during the first survey week.

In general, item non-response depends on the quality of the GPS-recorded trip segments and resulting complete trips. As seen in the pilot survey, completely-detected movements provided all the spatial and temporal information required, while partial movements were generally helpful in determining only travel end or travelled route, and only in cases where the central part of a trip was recorded.

The low quality of collected data resulted in a 21% overall item non-response, varying largely among users. An evaluation of the impact of item non-response of time information on data quality is provided in Figure 64.

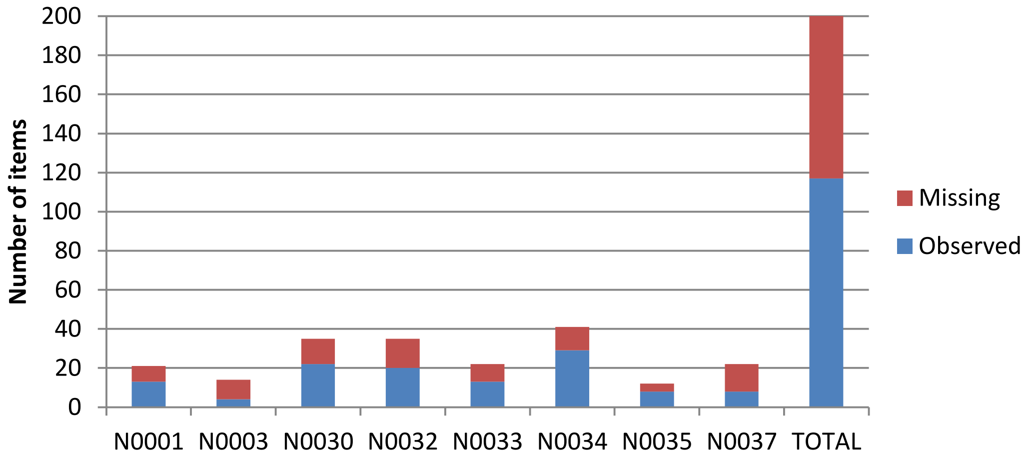


Figure 64 – Number of corrected trip start and arrival times in the GPS diary

GPS data was characterized by a high degree of incomplete time information. Further, the quality of data collection degraded as the survey went on, displaying evidence of survey fatigue. Overall missing time information during the first week was quantified as less than 15%, while the second week witnessed a 28% share of missing time entries, increasing to 38% if item non-response is considered in addition to trip non-response.

The impact of the lack of time information on travel duration and 'time spent at destination' was high. 33% of trip duration information was missing. Again, differences between the first and second weeks were evident, with a share of missing duration values of 29% and 39%, respectively. Surveyors were unable to calculate ‘time spent at destination’ for 58% of GPS trips and trip segments throughout the whole survey.

Missing distance information caused by partial recording of GPS trips comprised 30% of the overall distance values.

Considering the scarce quality of data collected during the second week, and in order to allow for better data comparability, researchers specifically studied GPS recordings of the first week in isolation. However, the entire dataset was used for trip and purpose identification, and for observation of trip-to-trip variability.

Despite a high degree of item non-response, GPS provided surveyors with reliable temporal data, unaffected by rounding and memory effect. Figure 65 shows the distribution of accurate GPS arrival and departure times for the first week of the GPS survey.

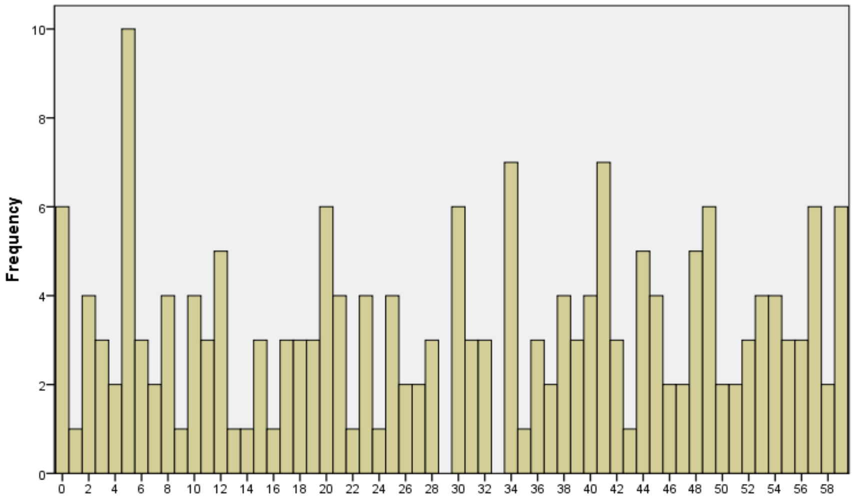


Figure 65 – Frequency of GPS times (minutes)

Observation of time items confirmed that GPS recordings were unaffected by rounding or memory effects, as was previously observed in the GPS pilot.

Similarly, it was possible to observe the distribution of duration values, calculated from single temporal item values, as illustrated in Figure 66.

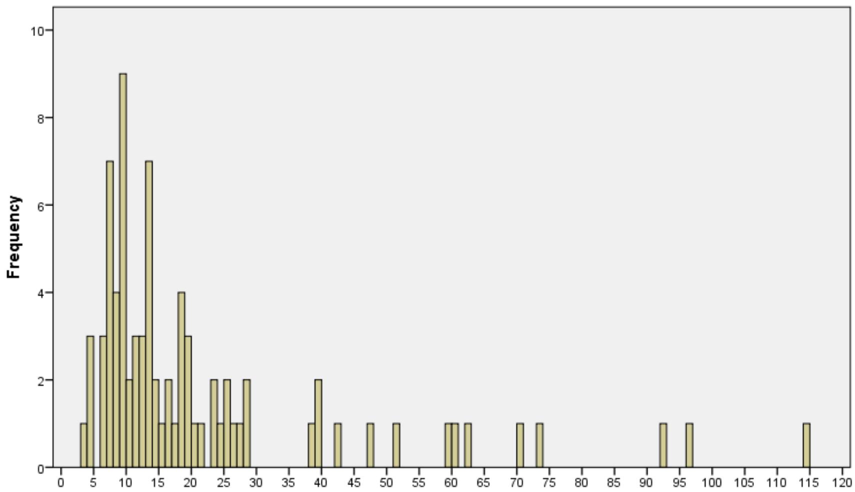


Figure 66 – Frequency of GPS duration (minutes)

The distribution of duration values showed no concentration of values around particular numbers outside the expected concentration of trips in the range from 5 to 15 minute range, which constitutes the largest share of performed trips.

GPS distance data were another important source of information for travel diary augmentation. Characteristics of the GPS-detected distance entries are reported in Figure 67.

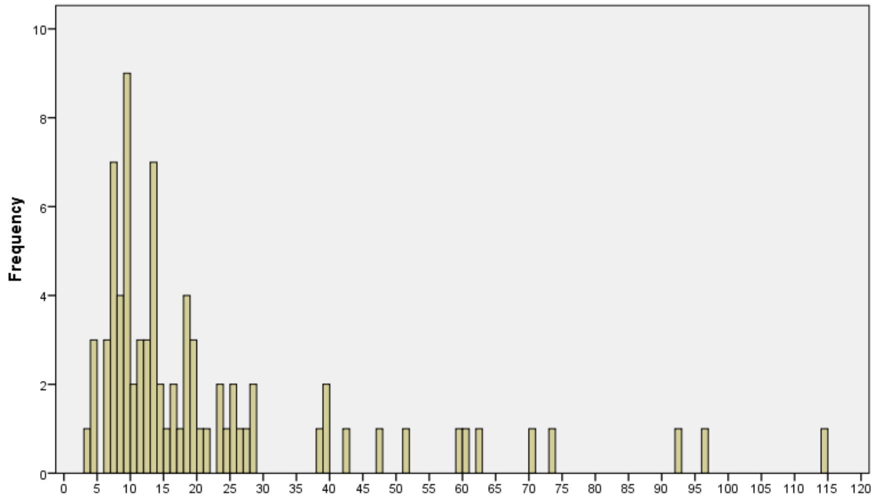


Figure 67 – Frequency of GPS distances (kilometres)

Trips and trip stages recorded by GPS were for the most part below 15 kilometres, with a peak in the 5-10 km segment. Short trips (<5 km) were rarely collected by the device. Data were characterized by hundred-meter accuracy at all distances. GPS can easily provide more accurate values if required by survey needs.

Travel behaviour

GPS data allowed researchers to reconstruct distances and travelled times. Devices collected a total of 932 km and 29 hours of travelled time. Total travelled distances and times per user and as average value per day are shown in Table 75.

USER	Trips	Distance	Time	Km/day	Min/day
N0001	15	400,5	485	57,21	69,29
N0003	11	8,3	78	1,19	11,14
N0030	21	61,8	208	8,83	29,71
N0032	22	256,5	543	36,64	77,57
N0033	9	15,60	48	2,23	6,86
N0034	22	152	310	21,71	44,29
N0035	4	2,3	24	0,33	3,43
N0037	8	35,1	41	5,01	5,86

Table 75 – Trips, distances (in kilometres) and times (in minutes) of the first survey week

Researchers expected, and witnessed low overall values of distance and travelled times for most respondents, when compared with user-reported times. However, it was still possible to observe the distribution of trips and trip information among transport modes, as reported in Table 76. Transport modes were sorted based on user-reported data and derivation, which will be explained later in this chapter.

	Car	Moto	Taxi	PT	Train	Bicycle	On-foot
Trips	75	2	1	8	0	5	20
Distance	850,5	22	15,8	7	0	6,1	30,7
Time	1235	57	18	49	0	35	343

Table 76 – Overall travelled distance and travel time by transport mode

The research team observed a predominance of recorded travel by car, followed by on-foot movements. Other transport modes seemed more difficult to detect during the GPS travel survey; for example, there was no evidence of train use.

Travel behaviour imputation

Anticipating the transport mode classification that will be explained in the trip information derivation paragraph, GPS provided researchers with routing from origin to destination, using the actual travelled route. This accurate routing provided surveyors with more precise imputation information on distance and travel time in the case of partial GPS recordings, compared to conventional shortest-path routing. Even when accurate data were available, the use of shortest travel time and exact distance provided researchers with information for building indicators of time loss and extra travelled distance. A description of such indicators is provided in paragraph 4.4.2.

Table 77 shows an overview of the routed distance and time for trips and trip segments where this tool could be employed.

	Car	Moto	Taxi	PT	Train	Bicycle	On-foot
Trips	73	2	1	7	3	5	20
Distance	1855	22,7	17,8	33	90	6,7	26,5
Time	2037	46	23	158	141	31	330

Table 77 – Derived distance and time for the first week of the GPS survey

Analysis of the overall data showed a great improvement in both distance and time values through use of partial data to reconstruct trip information. This derivation helped researchers to largely overcome the problem of information missed by the GPS device, in cases when GPS data collection guaranteed the detection of partial trip chains. Long-lasting gaps in data recording, which leave no traces of trips and stages, necessarily result in loss of information. As expected, imputation largely improved data on partial trips, while it contributed only a small degree of distance correction for trips and stages affected by cold start.

As expected, derived time values were lower than actual times, due to the use of free-flow speed. Such an effect was previously witnessed from the outcomes of shortest path routing during the GPS pilot survey. However, derivation tools provided researchers with a close estimation of the real time value, by basing estimations on an actual travelled route.

Augmented travel diary

Using information derived from routing, and information observed from GPS–recorded, complete movements, it was possible to reconstruct an augmented diary based on GPS-only data. Table 78 reports the total value of the augmented distance by user and transport mode. Car trip distances were largely imputed after this phase.

USER	Car	Moto	Taxi	PT	Train	Bike	On-foot
N0001	597,3	0	17,8	0	0	0	2,8
N0003	0	0	0	33,8	0	0	1,6
N0030	292,9	0	0	0	0	0	6,3
N0032	232,6	0	0	0	90	0	24,6
N0033	14,7	0	0	0	0	6,8	0
N0034	150,3	22	0	0	0	0	0
N0035	7,20	0	0	0	0	0	0,7
N0037	215,5	0	0	0	0	0	0,3
TOTAL	1510,5	22	17,8	33,8	90	6,8	36,3

Table 78 – GPS and derived distance (in kilometres) by transport mode

The overall distance value was improved by 84% with the contribution of imputed distances.

Table 79 illustrates values of the augmented travelled time per transport mode and user.

USER	Car	Moto	Taxi	PT	Train	Bike	On-foot
N0001	571	0	18	0	0	0	36
N0003	0	0	0	175	0	0	29
N0030	359	0	0	0	0	0	83
N0032	329	0	0	0	141	0	228
N0033	20	0	0	0	0	35	0
N0034	290	57	0	0	0	0	0
N0035	21	0	0	0	0	0	9
N0037	216	0	0	0	0	0	1
TOTAL	1806	57	18	175	141	35	386

Table 79 – GPS and derived travelled time by transport mode

Time values were successfully derived using routing tools, even in the case of partial data. However, considering the high share of underreporting and the underestimation of the routing tool outcomes, the overall value was expected to be significantly lower than the actual measure observed for the detected trips. This phenomenon might be expected whenever imputation is employed on a large scale.

Surveyors assessed the possible impact of the underestimation of time and distance values on the imputation phase. Figure 68 shows the difference of travel time values between complete GPS trip segments and the same imputed trips.

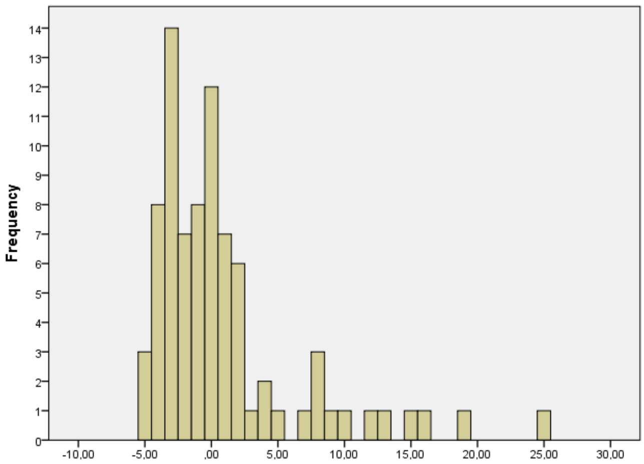


Figure 68 – Frequency of travel time errors, in minutes, of derived time versus GPS time

Observed time differences between GPS-time and derived time were as high as 25 minutes. Imputed values that were lower than GPS values never exceeded 5 minutes' difference, and differences were largely related to cold starts. Time difference increases over longer travelled distances. GPS and imputed time values are comparable for stages shorter than 5 kilometres. However, the single-stage temporal error accumulates in the case of trips consisting of multiple trip segments.

Researchers further evaluated the overall derivation performance of the imputed information by observing the way time and distance values differ from GPS as travelled distance increases. Figure 69 shows the absolute error (in kilometres and minutes) as observed by travelled distance.

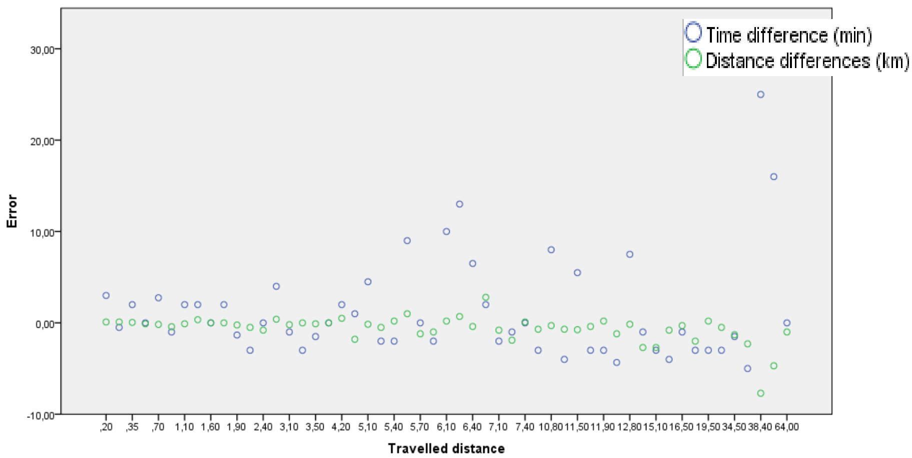


Figure 69 – Absolute error (in minutes and kilometres) of GPS values versus imputed values by travelled distance

Data demonstrated that GPS time tended to differ more from free-flow speed time as travelled distance grew, due to the impact of delays on travel time. Imputed distance data, by contrast, were reliable, even if overreporting of such measures was witnessed for trips over 30 km. The research team attributed this trend to gaps in GPS recordings, which resulted in shorter observed distances.

Despite the possibility of using imputation tools to complete partial data, the low number of detected trips was identified as a major issue. A comparison of user-reported and GPS-augmented data clarified the magnitude and characteristics of this problem.

Travel behaviour indicators

The differences between GPS information and information derived from GPS-based routing can provide researchers with valuable indicators of time and distance loss. Understanding the differences between travelled time and theoretical travel time is an indicator of time loss itself. This trend can be measured cumulatively in order to derive time loss during a survey day or an entire week, or to understand the share of time loss per single trip or stage, per specific users' trips, or per specific type of trip –, such as car trip time loss versus time loss on public transport (given the scheduled departure and arrival times).

Despite the lack of complete data, the GPS survey dataset provided surveyors with some general information on time loss. Table 80 illustrates the time lost per trip segment per mean of transport for the 35 trip segments that demonstrated a positive time error.

Mode	Stages	Time loss (min)	Time lost per trip
Car	21	162,00	7,71
Moto	2	15,00	7,50
Public Transport	3	12,00	4,00
Bicycle	2	8,00	4,00
On-foot	7	25,00	3,57
TOTAL	35	222,00	6,34

Table 80 – Estimated time loss (in minutes) by transport mode

More than 6 minutes of extra time per stage were observed throughout the survey. 43% of the stages for which time a loss indicator was available were characterized by extra travelled time. Trip segments below 5 kilometers saw time loss in 50% of occurrences, with an average extra travelled time of approximately 3 minutes.

Another valuable measure is the different time loss value observed among users. Figure 70 shows the differences in extra time per trip per user as observed for car trips.

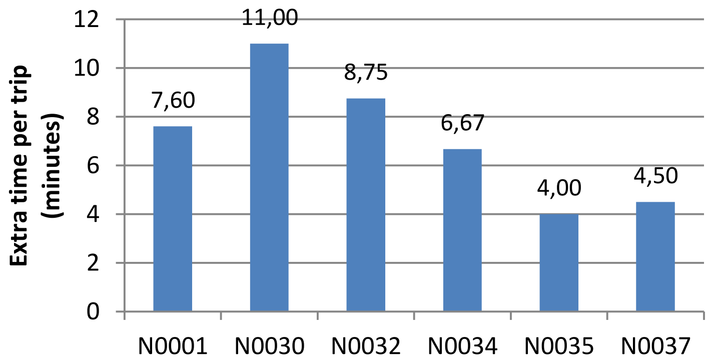


Figure 70 – Estimated extra time per trip travelled by car per user

Survey results provided only a partial picture of travel behaviour, but still demonstrated the potential for use of high-quality GPS temporal data for the study of travel behaviour. Such measures can help researchers determine individuals' travel behaviour, and can assist in assessment of the impact of routing choices on users' daily time budgets.

Similarly, distance data can be used to compare the extra travelled distance to the shortest path distance derived from GPS-collected origins and destinations. The percentage of extra travelled distance can provide researchers with a route choice indicator, which can describe users' propensity for choosing the shortest path to fulfil their movement needs with a selected transport mode.

Table 81 reports the results of the comparison of extra travelled distance as a percentage, per transport mode. Results are shown for car trips and categorized by trip distance ranges, to evaluate the impact of distance on extra travel.

Mode	Distance range	Stages	Extra dist (km)	Extra %
Car	ALL	27	66,7	10%
	Below 10 km	10	21,60	50%
	From 10 to 20 km	8	7,6	8%
	More than 20 km	9	39,5	7%

Table 81 – Extra distance travelled compared to the shortest path by car

41% of the overall comparable car trips were longer than their shortest possible option. Considering car trips only, it was possible to observe large differences for shorter movements, while longer car trips showed a lower share of extra travelled distance.

Observation of user data can help researchers to understand user-specific differences in travel behaviour, within the context of general survey trends. Table 82 reports the results of the calculation of extra distance travelled by car per user.

User	Stages	Extra dist (km)	Extra %
N0001	5	23,10	15%
N0030	5	18,30	34%
N0032	8	18,40	30%
N0033	1	0,30	6%
N0034	3	1,30	6%
N0037	5	5,30	10%

Table 82 – Extra distance travelled compared to the shortest path by car per user

Results show how the measure largely varied among users. However, data incompleteness prevented surveyors from determining certain travel trends. Further investigation into these trends should be pursued.

GPS and travel diaries

GPS detected 152 trip segments during the first week, contributing to the derivation of 112 trips. The reported and imputed number of trip stages for the same survey period was 244, which comprised a total of 190 trips. Figure 71 shows the share of travel diary trip segments matched by GPS versus unmatched trips.

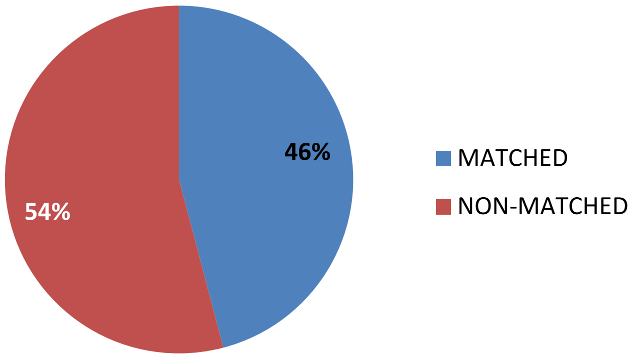
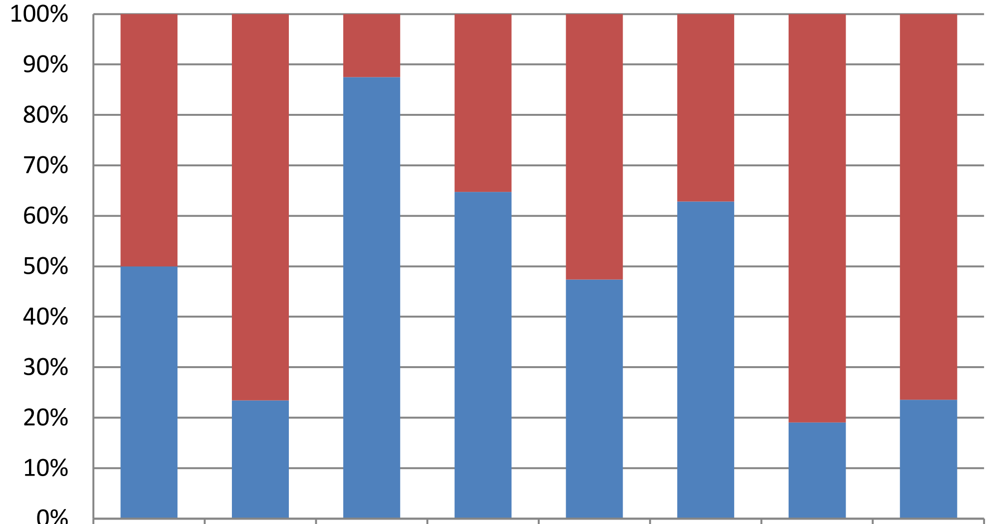


Figure 71 – Matched trips (Travel diary versus GPS)

Results show that GPS devices were able to capture 46% of the overall user reported movements. Results were significantly lower than pilot survey outcomes, despite the GPS handling suggestions that were provided to users. The percentage of matched movement varied among survey participants, as illustrated in Figure 72.



	N0001	N0003	N0030	N0032	N0033	N0034	N0035	N0037
Non-matched	15	36	3	12	10	13	17	26
Matched	15	11	21	22	9	22	4	8

Figure 72 – GPS matched and non-matched trips per user

Trip and stage matching was unsatisfactory, with only three devices (device N0030, N0032 and N0034) successfully improving upon average results observed during the pilot survey. The overall matching rate for the total number of reported trip segments was 49%.

Use of different transport modes was expected to influence the feasibility of GPS trip detection. Table 83 illustrates the number of matched movements by means of transport.

Mode	Stages	Matched	% Match
Car + moto	135	75	55,56%
Taxi	4	1	25,00%
Public Transport	22	8	36,36%
Train	9	5	55,56%
Bicycle	6	3	50,00%
On-foot	65	20	30,77%

Table 83 – GPS Matched trips per transport mode

Movements performed with private motorized modes (car and motorcycle), together with train trips, witnessed the highest detection rate. However, all GPS-identified train trips were always at least partially collected. Travelling by bicycle was detected 50% of the time, while on-foot movement and use of public transport, including taxi, posed the highest threat to GPS data collection.

The ability of GPS to easily record positioning data depends on the features of an area. More densely-built zones prevent GPS from receiving clear satellite signals. In the GPS survey, it was possible to observe the varying success of GPS detection based on the area where movements were performed. Table 84 illustrates the percentage of successfully-detected trip segments that started and ended within Torino city limits.

Mode	Stages	Matched	% Match
Car + moto	40	14	35,00%
Public Transport	20	7	35,00%
On-foot	58	15	25,86%
TOTAL	118	37	31,36%

Table 84 – GPS Matched trip stages per transport mode (Torino area)

Stages performed inside the city of Torino witnessed a very low matching rate, significantly below the overall detection rates. Table 85 shows the distances of such trip segments, assessing the degree to which distance can influence GPS data collection.

Distance	Stages	Matched	% Match
Below 1 km	30	13	43,33%
From 1 to 5 km	78	17	21,79%
From 5 to 10 km	9	3	33,33%
Above 10 km	2	2	100,00%

Table 85 – Matched trip stages by travel distance (Torino area)

Short-distance movements inside the Torino city limits were the most difficult to record by the GPS devices employed in the survey. Movements between 1 and 5 km were the least easily detected. Interestingly, the highest rate of detection of short-distance travel was witnessed for movements below 1 kilometre. However, trips below 5 kilometres typically represent the highest percentage of reported travels in urban environments, and the low detection-percentage of movements of this length can largely impact the results of a GPS-only survey.

Researchers also evaluated the results of GPS trip-detection for stages performed completely outside the Torino city limits. Table 86 illustrates the matching percentage of such trip segments by transport mode.

Mode	Stages	Matched	% Match
Car	61	36	59,02%
Taxi	1	0	0,00%
Public transport	1	0	0,00%
Bicycle	9	5	55,56%
On-foot	6	5	83,33%
TOTAL	82	46	56,10%

Table 86 – GPS Matched trip stages per transport mode (outside Torino)

Despite accounting for a smaller share of movements, detection rate sensitivity increased for movements outside Torino. Results from the identification of car trips and on-foot trips via GPS data saw significant improvement. Trip segments using public transport and taxis were not detected, but were also rarely reported for trips outside the Torino city boundaries. Further study of the detection of such modes should be pursued.

Considering GPS characteristics and previous analyses, the GPS travel-detection rate was expected to be lower for shorter trips. Table 87 illustrates how travelled distance influences successful GPS trip-detection.

Distance	Stages	Matched	% Match
Below 5 km	30	13	43,33%
From 5 to 10 km	24	12	50,00%
From 10 to 50 km	22	18	43,33%
More than 50 km	3	3	100,00%

Table 87 – Matched trip stages by travel distance (outside Torino)

Travelled distances outside the city of Torino tended to be longer. The detection rate of GPS versus user-reported trips was higher for all distance ranges, although a detection rate higher than 50% was observed for the 3 trips over 50 km.

Results of the observation of GPS trip and stage underreporting characteristics generally showed higher misreporting for movements within the Torino city limits – especially for movements from 1 to 5 kilometres, which represent an important share of user-reported travel behaviour. Considering the lack of a GPS functionality diary, there is no available information on the share of non-reported trips that can be attributed to problems with GPS.

Researchers also observed the differences between characteristics of detected trip segments and characteristics of undetected trips. Table 88 describes the different characteristics using descriptive statistics of time and distance values.

		DISTANCE (km)	TIME (min)			DISTANCE (km)	TIME (min)
GPS	Mean	17,84	23,38	**Unmatched**	Mean	8,30	19,43
	N	114			N	127	
	Median	5,5	13		Median	2	10
	Max	305	140		Max	292	195
	St_dev	42,86	25.39		St_dev	28,43	24,22

Table 88 – Statistics of reported trip stages versus GPS detected

Means of the two groups differed significantly, both for distance and time values, according to statistical tests. Unmatched trip segments were shorter than the trip segments observed from GPS data. Results, together with previous analysis on detected movements by transport mode, confirmed that shorter travels with non-motorized transport modes, such as on-foot and bicycle movements, were more difficult to detect.

Data comparison

Surveyors collected and derived data from four different sources:

- respondents
- user-based derivation
- GPS information
- GPS-based derivation

Comparing measures collected by the different sources, and noting the differences between those measures and the actual GPS-recorded travel times and distances, it is possible to assess degree to which GPS units can provide an accurate and complete picture of travel behaviour. Reference values include GPS time information regarding the duration of trips and trip stages, and GPS-based derived distance, including travelled distance.

Analysis of the means and variance of the 4 groups, consisting of 64 comparable time and distance observations, did not identify any relevant statistical differences among groups. However, greater differences between groups were evidenced when researchers compared GPS-collected time and distance values against user-reported data.

Table 89 shows the results of the comparison of travelled distances by data source. Average value and overall variance of the distance value are reported.

DATA SOURCE	NUMBER	TOT	AVERAGE	VARIANCE
REPORTED	64	973,1	15,20469	909,6482
SHORTEST PATH	64	914,6	14,29063	790,8704
GPS	64	911,4	14,24071	735,4063
GPS-BASED ROUTING	64	930,45	14,53828	800,9747

Table 89 – Comparison of travelled distance (in kilometres) among employed tools

Reported travel distance saw the highest total distance and highest variance among all observed groups. The GPS group logged the shortest cumulative distance, probably due to the effects of GPS collection gaps, such as cold starts. Such collection gaps plagued 40% of observed trips within the GPS group. Comparing reported distance with the results of GPS-routing, assuming the actual distance as a reference value, researchers noted a 0,7 km overestimation of distance per trip. This difference lowers to 0,5 for trips of less than 10 km, which represented 75% of the observations.

Table 90 reports data on the comparison of duration of observed movements in minutes, by group.

DATA SOURCE	NUMBER	TOT	AVERAGE	VARIANCE
REPORTED	64	1794	28,03125	1033,269
SHORTEST PATH	64	1417	22,14063	543,6466
GPS	64	1511	23,60938	542,2418
GPS-BASED ROUTING	64	1537	24,01563	621,349

Table 90 – Comparison of duration (in minutes) among employed tools

The group of reported travel times still shows the highest total value of minutes spent travelling. Comparing the cumulative value of travel time reported by users with the GPS travel time (with GPS travel time assumed to be the closest measure to the actual time value), an average 4,4 minute difference per observation was witnessed. This value did not change for movements shorter than 10 km.

The comparison of reported travel behaviour with actual travel information proved the tendency for users to overestimate both travel distance and travel time.

The previous analysis took into consideration the cumulative measures of distance and travel duration. Evaluation of differences can be performed on single items, both reported and derived, in order to shed light on the differences of reported versus observed data. In contrast to the previous evaluation phase, which considered only complete trips, the following assessment will use all reliable single items from both survey tools.

Following the framework adopted for the pilot survey, Figure 73 shows the number of observations by measured errors, categorized into time ranges.

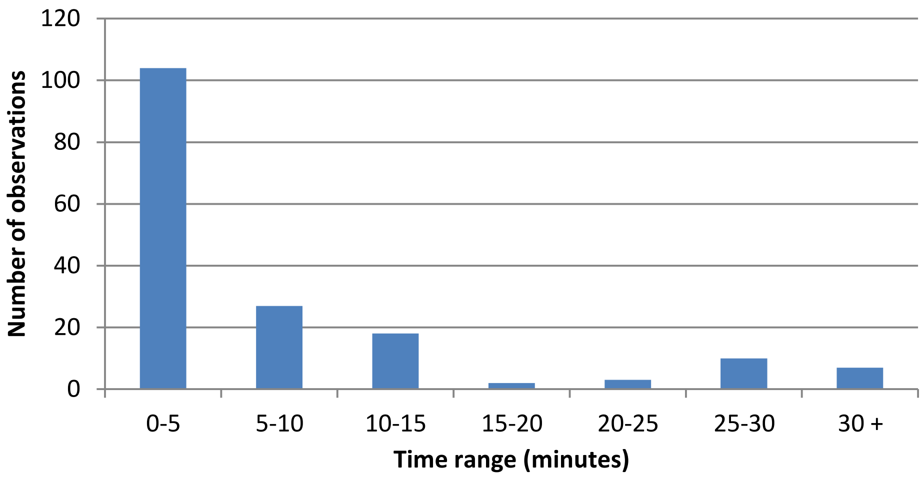


Figure 73 – Number of observations by error of user-reported times compared to GPS readings (time ranges in minutes)

60% of user-reported time information witnessed an error lower than 5 minutes, within the range of rounding effect. Approximately 10% of the total information matched GPS data. A limited number of user-reported time information carried a difference of more than 15 minutes. Such large errors can compromise the association of the related trip to the correct actual time-frame.

As previously stated, the general trend of reported data shows the tendency to overestimate travelled time. Observation of time items showed a tendency to report trip start and end times earlier than the actual times. This trend was observed for all users, with differing abilities among users to report correct times, as illustrated in the chart in Figure 74.

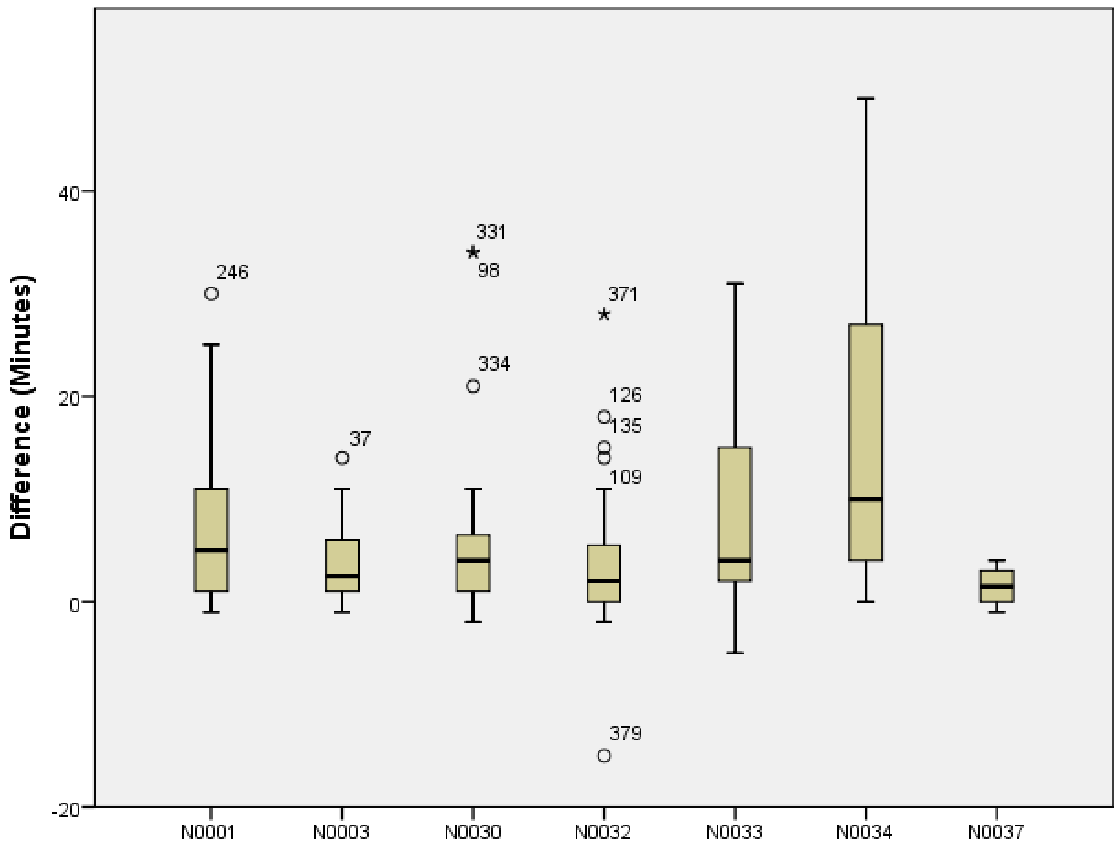


Figure 74 – Box-plot chart of the differences (in minutes) of GPS readings versus reported trip starts and stops

The study of reported time information shows how users tended to declare travel start and ends with an average advance of 7 minutes, ranging from 2 to 10 minutes, referring to the single user's median values (median being a more robust measure of central location, considering the observed outliers). Additional analysis on this phenomenon might be planned in future passive travel surveys.

Augmented travel behaviour

Despite data collection problems that plagued the GPS-only survey, the concurrent use of two survey tools allowed surveyors to augment user-reported data with passively-observed travel behaviour. The availability of a more complete dataset allowed surveyors to better observe the variability of the travelled time of each respondent throughout the week.

GPS-detected trips, not reported by users, were successfully added to the augmented diary, thereby reducing overall trip underreporting. The integration of such trips into the dataset of trip diary data provided researchers with an improved overview of trips performed during the survey. Table 91 shows the final number of complete trips included in the GPS-augmented travel diary. Data refer only to the first week of the GPS survey, when data was being collected concurrently by both GPS and traditional survey tools.

USER	TRIPS	TD_ONLY	GPS_ONLY
N0001	26	15	2
N0003	35	35	0
N0030	24	3	1
N0032	20	12	1
N0033	18	10	1
N0034	35	13	4
N0035	21	17	2
N0037	23	26	1
TOTAL	202	131	12

Table 91 – GPS augmented travel diary trips and data sources

The use of GPS improved the number of trips by 6%, to a total of 202, and the number of trip segments by 16 units, contributing to a total of 244 stages and increasing total stages by 7%.

Information on distance, time and related measures was updated in order to impute missing items and improve reported data, integrating GPS and GPS-derived data. GPS-observed time and GPS-based distance (calculated by routing tools) were considered as actual/correct values and were preferred over user-reported data.

Table 92 reports information about distances travelled by transport mode, as compiled in the GPS-augmented travel diary.

USER	Mon	Tue	Wed	Thu	Fri	St Dev Week	Sat	Sun	St Dev W-E	St Dev TOT
N0001	5,95	1070,10	72,20	1098,10	1104,80	576,79	71,20	72,40	0,85	554,12
N0003	8,80	11,00	11,60	25,00	24,35	7,86	1,20	18,40	12,16	8,68
N0030	1,20	2,40	1,20	15,30	6,70	6,00	151,80	137,70	9,97	68,31
N0032	109,00	105,20	28,50	105,00	122,10	37,25	7,10	58,00	35,99	45,16
N0033	0	3,80	7,60	16,00	5,40	5,96	18,90	0,00	13,36	7,45
N0034	45,40	79,60	47,40	27,90	74,10	21,53	26,80	6,50	14,35	26,29
N0035	21,70	4,80	4,80	0	4,60	8,37	5,60	4,40	0,85	6,93
N0037	191,40	10,80	8,00	183,10	10,50	97,26	617,20	25,30	418,54	221,97

Table 92 – Variation in travelled distance (in kilometres) throughout the first survey week

Table 93 shows the overall time spent travelling by survey day, as reported in the GPS-augmented travel diary.

USER	Mon	Tue	Wed	Thu	Fri	St Dev Week	Sat	Sun	St Dev W-E	St Dev TOT
N0001	47	235	142	420	313	145	112	212	71	127
N0003	155	112	70	145	255	69	50	80	21	70
N0030	18	31	20	97	25	33	201	141	42	72
N0032	205	211	59	192	145	63	9	287	197	96
N0033	0	12	28	30	25	13	23	0	16	13
N0034	86	128	122	33	141	44	116	21	67	48
N0035	100	18	20	0	75	43	52	26	18	36
N0037	206	37	35	199	53	88	478	115	257	158

Table 93 – Variation in trip duration values (in minutes) throughout the first survey week

The augmented time and distance values saw improved accuracy, thereby resulting in shorter trip durations and travelled times, and limiting the impact of overestimation by survey participants. The overall picture of travel behaviour was more complete and item non-response was further lowered, as compared to results from the self-administered travel diaries.

As a result of this improvement in data completeness and quality, it was possible to better reconstruct time spent at destination. Activity duration was reported by user-declared purpose. Results from the calculation, based on GPS and reported data, are provided in Table 94.

USER	Work	Study	Shopping	Free-time	Errand	Take/ Get a person	Home	Other
N0001	667	0	0	117	0	0	5508	1254
N0003	205	0	73	50	162	132	7018	32
N0030	0	692	0	800	252	223	6424	0
N0032	2207	0	0	1655	0	0	3293	699
N0033	0	925	0	432	0	0	4529	96
N0034	1659	0	122	427	82	5	4479	1174
N0035	1961	0	1306	255	0	0	3289	0
N0037	0	191	17	1500	6	0	4640	549
Total	6699	1808	1518	5236	502	360	39180	3804

Table 94 – Computed activity duration (in minutes)

The main travel behaviour indicators benefitted from GPS-augmentation, gaining more reliable information and more precise time items. GPS-augmentation also allowed researchers to associate respondents' trips and trip stages to a more suitable time-frame, thereby potentially improving data quality for modelling purposes.

GPS data was also used to successfully amend incorrect or imprecise addresses provided by users. In fact, the GPS-based address database provided surveyors with 96% of the addresses of the 108 unique locations visited. This contributed to the correction of 7 of the 8 incorrectly-reported addresses (resulting in 25 incorrect items in the travel diary) and of 13 of the 14 points of interest (POI) addresses (present in the information of 70 trip stages). The final share of incorrectly-reported addresses was lowered to 2%, significantly better than the 11% observed in the traditional travel diary. Table 95 summarizes the overall number of improved addresses.

	Locations	Correct	POI	Town / Neighborhood	Incorrect (%)
UNIQUE	56	54	2	1	2%
TOTAL	222	215	4	3	2%

Table 95 – Augmented location quality

The improvement of the address quality was clear. This achievement allowed researchers to place in the correct geographic position the origins and destination of 98% of the observed movements and of the unique locations. Additionally, researchers detected 27 unique locations during the second week, adding more information to each user's travel behaviour dataset.

GPS-based trip information derivation

Surveyors used raw GPS data, supplemented with user-provided data, to derive information on transport mode and trip purpose, and to understand the potential of such data to provide information on habits and attitudes.

Transport mode detection: the pilot survey transport mode classification phase had proven the possibility of easily discriminating among car, bike and on-foot trips. Surveyors extracted 4 variables from GPS trips: 95^{th} percentile of speed, 95^{th} percentile of maximum acceleration and deceleration, and standard deviation of speed values. The challenge of the GPS survey is to try to derive public transport modes and train using the classification process, to assess if the decision tree classification approach can be successfully implemented.

Classification rules employed in the pilot survey were applied to the main survey dataset. The objective of the first stage of transport mode detection was to assess the ability of the classification rules to discriminate among non-motorized (on-foot and bike) and motorized transport modes. Further modal discrimination was not possible, because of the limited dataset that was used to train the learning-algorithm used in the pilot survey. This dataset consisted only of trips on-foot, by bike and by car.

The use of the detection rules of the pilot survey based on the values of the standard deviation of recorded speed, allowed researchers to properly link transport modes to 185 valid trip segments without any training of the classification tree. Table 96 reports the results of the derivation.

	Observations	**Detected**	**Correct (%)**
On-Foot	36	36	100%
Bicycle	6	6	100%
Motorized	143	143	100%

Table 96 – Transport mode derivation success of GPS survey trips using the GPS pilot classification rules

Derivation success depended on the ease of discriminating motorized movements from movements on foot and by bike. Distinction between different motorized travel modes was expected to be more challenging. Another aspect influencing the success of the first stage of transport mode identification was the small number of non-motorized trips, as compared to motorized trips. Condition 4.8 exemplifies the selection rules adopted for the successful classification of motorized and non-motorized trips.

```
/* Node 1 */.
IF (DEVST NOT MISSING AND(DEVST <= 2.4))
THEN
Node = 1
Prediction = 'OnFoot'
Probability = 1.000000

/* Node 2 */.
IF (DEVST NOT MISSING AND(DEVST > 2.4 AND DEVST <= 6.2))
THEN
Node = 2
Prediction = 'Bike'
Probability = 1.000000

/* Node 3 */.
IF (DEVST IS MISSING  OR (DEVST > 6.2))
THEN
Node = 3
Prediction = 'Motorized'
Probability = 1.000000
```

Condition 4.8

Once motorized trips were isolated, it was possible to use a training set of GPS trips representing the various motorized modes; in particular, car, tram, bus and train trips. The original data analysis plan consisted of the creation of a training set using observations from the first 3 survey days. However, data issues limited the number of available observations for motorized trips other than by car. Composition of the final training set of the motorized poll is reported in Table 97.

Transport mode	Number
Car	117
Motorcycle	1
Bus	11
Tram	8
Train	6
Total	143

Table 97 – Detected motorized trips for decision tree classification

The research team was only able to run the classification rule algorithm on the entire dataset in order to observe possible derivation rules for future experiences. Researchers focused on possible rules to use in discriminating among different public transport modes, such as train, bus and tram. Understanding differences in of speed, acceleration and speed variability can supplement future studies and can offer different strategies for trip derivation.

Decision tree rules extracted from the public transport group showed how discrimination among such varied transport modes is feasible, though not as straightforward as separating motorized from non-motorized modes. Figure 75 shows the identified classification rules (see ANNEX 11 for full-sized picture).

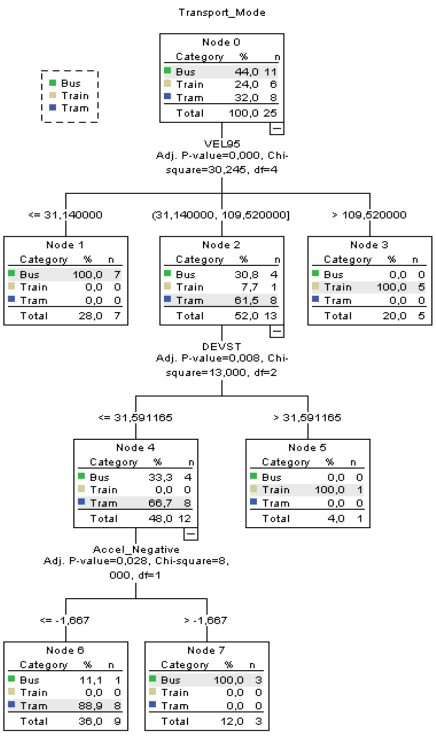


Figure 75 – Classification rules for identification of the various modes of public transport

Classification rules used 3 of the 4 extracted variables. In particular, speed, standard deviation of speed and 95th percentile of deceleration were employed in this classification.

The CHAID growing method created 7 nodes and produced an overall detection rate of 96%. Final results of the classification of transport modes are reported in Table 98.

Observed	Predicted			
	Bus	Train	Tram	Correct %
Bus	10	0	1	90,9%
Train	0	6	0	100,0%
Tram	0	0	8	100,0%
Overall %	40,0%	24,0%	36,0%	96,0%

Table 98 – Results of identification of transport mode using decision trees

Lower and higher travel speed ranges were associated with bus and train travel, respectively. The sole use of speed as a classifying characteristic successfully identified 5 out of 6 train movements. Adding standard deviation of speed allowed researchers to identify the last remaining train trip. It was necessary to add the deceleration value to the classification in order to distinguish between bus and tram travel. In fact, the deceleration observed in tram movement seemed higher than the typical deceleration of buses.

The next step for completion of the study of the possible rules for transport mode classification was to discriminate car trips from public transport trips. Researchers expected this identification to be challenging, considering the large number of observed car movements versus the limited share of public transport trips. In particular, it was necessary to avoid overfitting the classification rules; i.e., shaping them specifically to discriminate only between car trips and public transport trips, so that they could not be used in other studies.

Rule extraction failed to provide concrete and generalizable rules for the discrimination of private from public transport modes. Some general rules observed included the certain attribution of trips with maximum speed values between 50 and 105 km to private car trips, and the possibility of detecting train trips in the over-105 km group when low maximum acceleration values (< 1.7 m/s) are observed. Any further attempts to improve detection percentages led to overfitting and failed to provide valid rules.

The transport mode detection phase allowed researchers to study how the extracted variables were able to characterize most transport modes. Limited availability of information on public transport movement adversely affected overall results. Further data collection will be needed in order to better evaluate classification rules.

Purpose determination: on a socio-economic questionnaire, survey participants declared their home and work addresses, as well as the addresses of often-used services, such as post offices, pharmacies, family doctors, grocery stores, bus and metro stops. (See ANNEX 5 for the translation of the socio-economic questionnaire). The number of purposes derived from requested purpose information dictated the success rate of the employed method. Previous analysis performed during the GPS pilot survey had provided some preliminary data on the potential use of this method.

Users visited 108 unique locations during the first survey week. The number of unique locations visited in each survey day is shown in Table 99.

USER	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	TOT
N0001	3	4	2	2	1	3	1	16
N0003	3	9	0	2	2	2	2	20
N0030	2	2	6	0	3	0	0	13
N0032	4	1	3	4	0	2	0	14
N0033	3	2	0	0	1	0	0	6
N0034	5	3	1	1	3	2	0	15
N0035	3	1	0	3	0	0	0	7
N0037	3	3	4	1	2	3	1	17
TOTAL	26	25	16	13	12	12	4	108

Table 99 – Unique locations visited per survey day per user

The number of uniquely identified locations ranged from 6 to 20 and was related to the number of overall trips. Of the 108 locations, 56 comprised the more relevant trip ends, which actively contribute to trip purpose derivation. Remaining unique locations were associated with bus stops, parking lots and metro stations, which are all related to trip stages. Figure 76 illustrates the relationship between the total number of performed trips and unique locations by user.

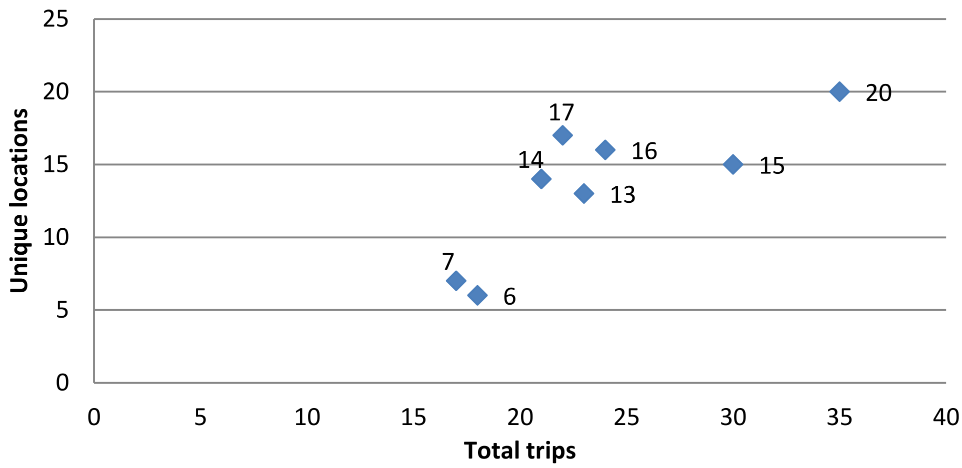


Figure 76 – Unique location versus total performed trips

This figure illustrates how the number of unique locations increased with the number of total trips. Each unique location was characterised by a specific purpose (or several purposes). However, the percentage of performed trips related to declared most-visited locations – and thus, the ability of trip data to describe trip purpose – did not follow the same directly proportional trend. Table 100 reports the percentage of derived purposes that can be explained by knowing the activities associated with the 3 and 5 most-visited addresses as declared by users (Top 3 and Top 5 scenario). Stage-related locations were not considered in this analysis.

USER	Top 3	% of Purposes	Top 5	% of Purposes
N0001	13	54%	18	75%
N0003	24	69%	26	74%
N0030	13	57%	15	65%
N0032	16	76%	21	100%
N0033	13	72%	15	83%
N0034	21	70%	25	83%
N0035	16	88%	18	100%
N0037	14	64%	18	82%
TOTAL	130	68%	156	82%

Table 100 – Number of trips and percentage of explained activities related to top 3 and 5 most-visited locations by user

Using the proposed method, successful purpose derivation depends on the ability of surveyors to collect trip purposes associated with the most commonly-visited locations, which represent the greatest share of overall visited destinations. After this first phase, researchers evaluated the number of locations in the questionnaire visited during the survey period, as well as the number of related trip purposes detected. Collected information allowed surveyors to derive a fair percentage of the overall activities at given locations, allowing researchers to augment GPS data without a need for further user interaction. Table 101 reports the share per user of activities explained by pre-declared most-visited locations.

USER	Unique locations questionnaire	Trip purposes questionnaire	% of Purposes
N0001	3	7	29%
N0003	4	25	71%
N0030	3	11	48%
N0032	4	19	90%
N0033	3	12	67%
N0034	4	17	57%
N0035	3	15	88%
N0037	.3	14	64%
TOTAL	24	120	63%

Table 101 – Number of trips and percentage of explained activities related to locations provided by user

The use of questionnaire data allowed researchers to derive 63% of trip purposes, with percentages that varied from 29% to 90%. The number of unique locations visited varied from 3 to 4. However, not all reported information included most-visited locations, which resulted in a lower derivation rate than in the Top 3 scenario – even with 4 identified locations. Researchers decided to improve results through the identification of points of interest, such as train stations, airports, or shopping malls, attributing the label "home" to any location where an overnight stay was detected. Results of this augmentation are reported in Table 102.

USER	Extra Unique location (augmented)	Extra trip purposes after augmentation	% of Purposes
N0001	3	7	58%
N0003	0	0	71%
N0030	2	4	65%
N0032	0	0	90%
N0033	0	0	67%
N0034	0	0	57%
N0035	0	0	88%
N0037	1	1	68%
TOTAL	6	12	69%

Table 102 – Number of trips and percentage of explained activities after augmentation of user information

Overall purpose derivation with augmentation reached 69%, which was comparable with the success rate observed for the Top 3 scenario. The lowest derivation values were around 58%.

Unavailable options for most-visited location were related to parent visits, relative visits and friend visits, which were the cause of a significant number of trips taken by participants during the survey. These trips generated the lowest purpose derivation rates. Vacation-related locations were another source of valuable purpose information, accounting for a significant number of trips during the weekend. In general, asking users about their home and work addresses and closest services provided researchers with a partial picture of activities performed during the survey week. Augmentation helped to bring percentages to a level comparable with other GPS experiences (Lu et al., 2012, McGowen and McNally, 2007; Wolf et al., 2001), without inclusion of land-use information or use of machine-learning algorithms. However, results were still not satisfactory in the case of highly mobile respondents.

Improvement of the employed purpose derivation method relies on the collection of information on users' most-visited places. Observation suggests that some of these locations cannot be directly collected from respondents in a socio-economic questionnaire (e.g. friends' addresses). Possible ways to overcome this problem include asking participants directly to state the places that they expect to visit during the survey period, or showing the GPS-derived locations and asking respondents for further information through a prompted-recall interview.

Possibilities of using land-use information for purpose derivation in the Torino area are limited. In fact, as reported in the data analysis plan, the coexistence of multiple purposes in the same location, or survey participants performing more than one activity in a single location, results in a challenging purpose derivation.

Derivation of questionnaire information: researchers used questionnaire data to derive trip purpose, and to collect the necessary data on the socio-economic status of each respondent. The questionnaire was designed to inspect travel habits and attitudes and to collect information on vehicle and transit pass ownership. After having analysed the potential of GPS implementation through a literature review and from the results of the travel surveys, researchers could evaluate the appropriateness of the use of GPS data in reconstructing information provided by users.

GPS tracking allows researchers to continuously record travel behaviour for the whole survey duration, providing information on distances, times, locations, routes, etc. Time spent for specific activities throughout the week can be observed directly from GPS-derived data with a high temporal accuracy. Additionally, the spatial dimension of GPS data can allow researchers to calculate travel habit indicators, such as time loss and extra distance, which can subsequently describe certain traits of users' travel behaviour. The possibility of observing speed profiles with a second-by-second time-frame can be used to understand driving, riding or walking behaviour depending on transport mode. This information, if supplemented by a specifically-designed interview, provides researchers with data for studying travel attitudes.

Besides specific information on demographics and ownership, GPS-only surveys are theoretically capable of providing most of the information that researchers had asked respondents directly. However, collecting information directly from respondents can add additional value to a GPS survey, by allowing researchers to assess the accordance of GPS data with user declared habits, and to understand reasons for possible disagreement (i.e. incorrect data or problems related to user perception). The comparison of GPS-collected data with user-provided data can provide valuable information to help researchers study user perceptions.

4.5.3 Supplementary data collection test

Following the methodology that had been designed acknowledging GPS data collection problems, researchers carried out supplementary tests specifically designed to test data collection in non-ideal data collection environments. In particular, the research team decided to carry out a supplemental data collection in the Torino city centre.

The first GPS data collection test was performed in January 2011, in order to evaluate signal reception, under all potential troublesome conditions of a more sensitive GPS device and a standard GPS receiver with conservative data-collection settings. The test site was the core of the city centre of Torino, and data collection was performed simultaneously using both devices, following a predefined route.

The first device employed was a high-sensitivity Ublox 6 module connected to an external antenna. Researchers set the same quality standard, in terms of satellites and HDOP (with speed discrimination), used in the post-processing phase of the GPS travel survey in order to collect data with comparable quality standards. Satellite lock was verified prior to the test start in order to prevent any cold start problems. Results of the test are shown in Figure 77.

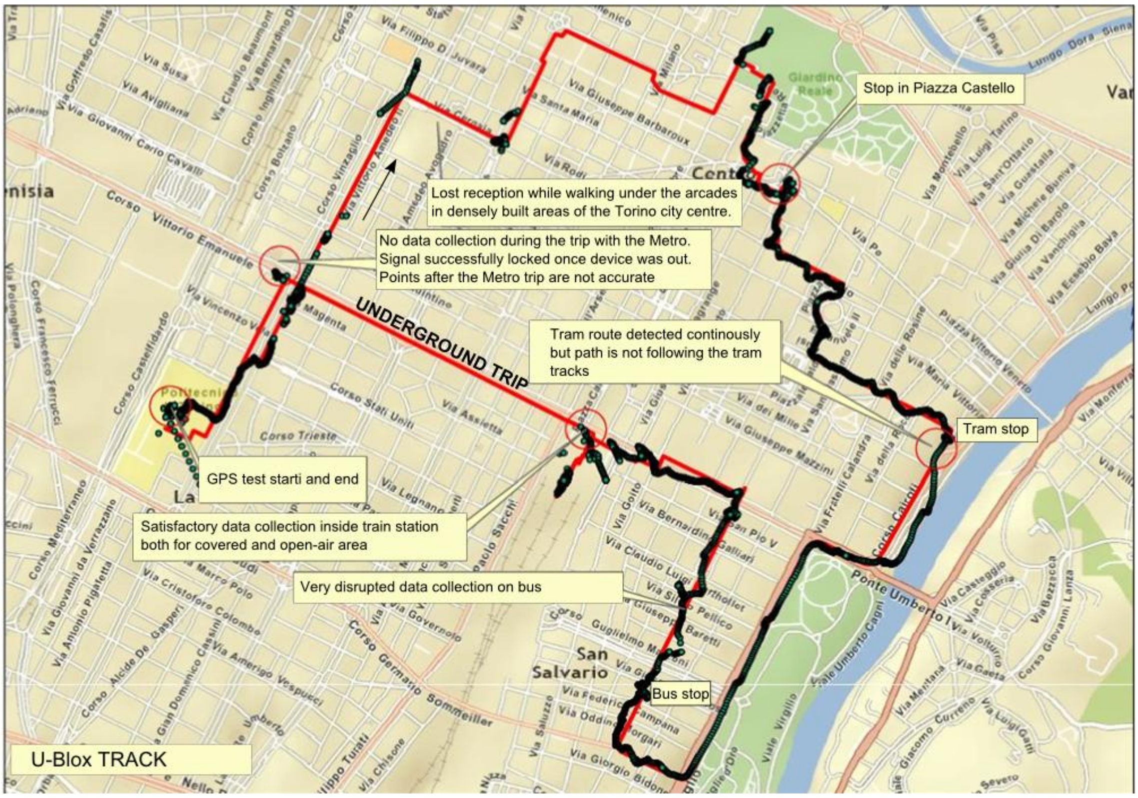


Figure 77 – Ublox data recording during data collection test (black dots) compared to the actual travelled route (red line)

Data collection problems occurred in the city centre, even with the use of an updated GPS device. Trips on foot in the most densely-built area of the city could not be easily detected. Short trips on foot after a momentary data loss due to a Metro trip resulted in unreliable data collection once satellite signal was restored. However, a better detection of public transport movements was witnessed, with differences noted between tram and bus trips. Some indoor movement was detected during a stop in the city center (Piazza Castello) and at the train station.

Solutions must be found in order to overcome the structural biases of GPS devices, as observed in the Torino survey and in successive data collection tests. If suitable solutions cannot be found, passive data collection based on GPS technology may be deemed impractical for use in personal tracking in the Torino city centre. Applications would, in this case, be limited to in-vehicle GPS use, which is less affected by data recording issues in densely-built areas.

One possible solution is to prefer data continuity over reliability, intervening later with aberrant point detection and map-matching tools. This tactic allows surveyors to collect the maximum allowable number of GPS positions, time, and distance recordings. Surveyors tested this data collection scenario using a Garmin GPSMAP 60Cx equipped with a SirfStarIII chipset. The device was set to collect all possible recordings, ignoring data accuracy, in concert with the UBlox test. Satellite lock and proper data recording were verified prior to the test start. Results of this test are provided in Figure 78.

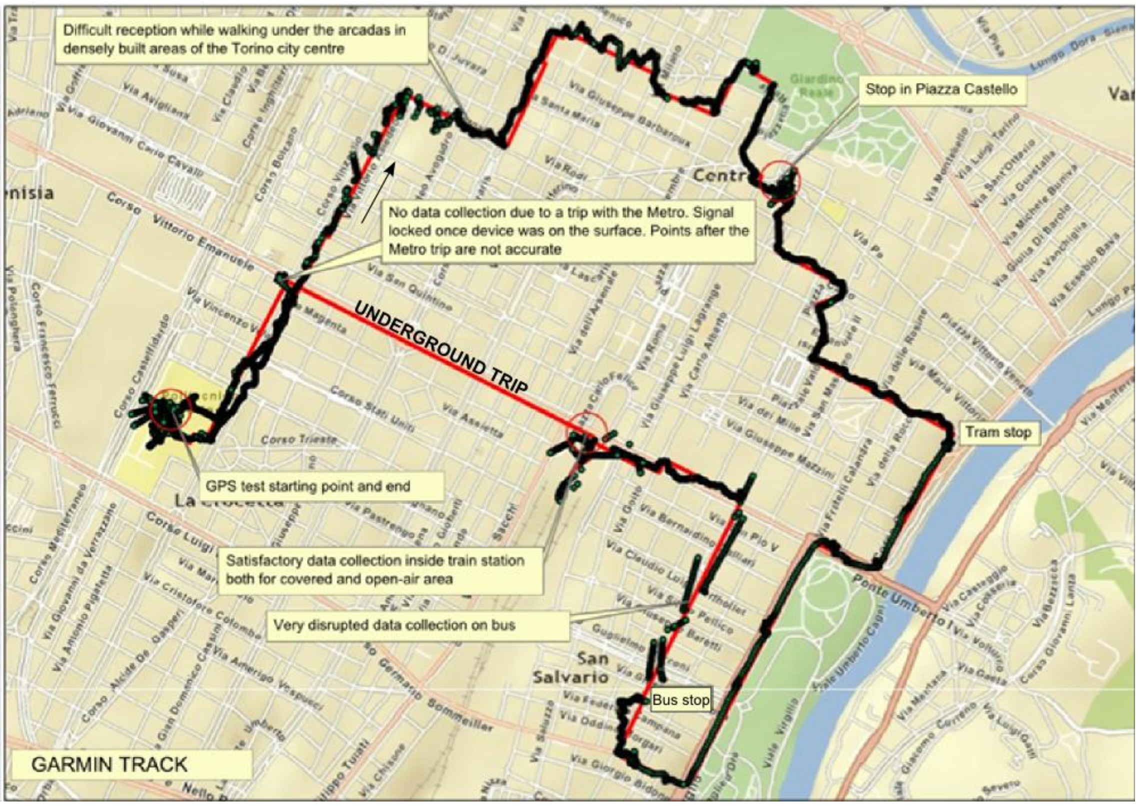


Figure 78 – Garmin data recording during data collection test (black dots) compared to the actual travelled route (red line)

Use of these selected settings allowed surveyors to obtain information on the entire route, even highlighting inaccurate data collection during most of the trip. Data collection on the bus was more challenging than on the tram, as can be seen in the UBlox tracks in Figure 77. Indoor movements were detected with these higher settings. Data collection after data loss (underground trip by metro) resulted in unreliable data.

Despite the vast improvements in devices’ performances in terms of speed of satellite signal lock and receivers’ sensitivity, possible data disruption in densely-built environments can still result in data loss. Possible solutions include augmentation of GPS receivers with supplementary data sources. GPS can be successfully supplemented by additional motion sensor, assisted satellite information via network, or the possibility of the concurrent use of additional positioning methods.

Current-market Smartphones represent one device that can easily integrate all previously mentioned data-collection methods. The reliability and continuity of data collected by such devices might be tested in a travel survey scenario.

The research team at Politecnico di Torino carried out a specialized test using a tracking application installed on a LG Optimus L3 Smartphone. The application was set to continuously record positional data through GPS and to collect location information, exchanging data with the 3G network whenever satellite positioning was not possible. The test collected positional data from one respondent in the Torino city centre for a 15-day period in September 2012. Figure 79 illustrates the final result.

Figure 79 – 15 day Smartphone data collection in the city centre of Torino

The Smartphone application provided the research team with continuous data collection under all conditions, both indoors and outdoors. No cold start issues were witnessed; further, data loss was limited and did not result in partial trip recording. Data quality degraded in the case of indoor environments and urban canyons, but usable data was still collected in these situations. Trips on public transport modes were successfully detected at a cost of low-quality positional data. However, the Torino pilot and GPS survey outcomes proved the possibility of reconstructing complete travel information even from partial or low-quality data.

The use of devices that record lower-quality data in order to guarantee continuity will result in higher positional errors. These errors must be addressed with a specifically-designed post-processing method.

DISCUSSIONS AND CONCLUSIONS

By observing the outcomes of the GPS survey, the Torino research team was able to evaluate the potential of GPS data collection for implementation in larger surveys. In particular, researchers isolated the travel behaviour data that can be derived from traditional travel diaries, the data that can only be derived using GPS technology, and the data that can be derived through the concurrent use of both tools.

Through travel diaries, respondents provided researchers with a high level of data completeness regarding trip origins, destination, length, and times. These data were the basis for the reconstruction of travel behaviour throughout the survey days. GPS readings augmented the evaluation of reporting quality, resulting in the identification of rounding and memory effect of time and distance, and of overreporting in both time and distance values. GPS data detected extra trips (i.e., trips not reported in travel diaries) and generally improved the completeness of travel diary entries. However, data obtained from respondents' self-reporting do not differ largely from the corresponding data obtained through GPS readings, whereas GPS surveys witnessed a high degree of missing information when compared against user-reported information.

Faced with the outcomes of the Torino GPS survey, utilizing solely GPS in travel surveys might have painted for researchers an incomplete picture of participants' true travel behaviour, due to problems such as frequent signal loss, mishandling and battery issues. Despite the fact that self-administered travel diaries provided less accurate data than GPS, such diaries actually out-performed GPS-derived travel behaviour data, in terms of data completeness, throughout the whole survey week. During the second week of the study, GPS data was collected without support from user-reported information. Absent these self-reporting diaries, the second-week data provided surveyors with an incomplete picture of users' travel behaviour.

Researchers witnessed high variability in both distance and travel time measurements. Thus, a sampling of only 2 or 3 days might have led surveyors to misrepresent the travel behaviour of survey participants, underlining the need to design longer surveys.

A longer survey period can result in survey fatigue, due to the increasing burden placed on a respondent as the survey goes on. The use of GPS is recognized as a successful method for countering this phenomenon, thereby allowing accurate recording of trip data over the course of a multi-day survey. However, a different trend was witnessed during the Torino GPS survey. Respondents did not show any data reporting problems that can be attributed to fatigue. On the contrary, GPS-only survey outcomes witnessed a drop in data collection for most users, when compared against GPS data recorded in the first week. Survey fatigue was, therefore, observed in the GPS-only survey. The concurrent use of traditional and passive methods seemed beneficial for both tools. Further studies must be performed in order to evaluate survey fatigue as it relates to GPS-only surveys.

Data collection issues can be attributed to mishandling or technical problems with the device, as well as to the loss of satellite signals. Data collection gaps attributed to signal loss or poor reception are caused by characteristics of the GPS device, as well as the context or setting in which the device is used.

Researchers expected to see the greatest problems in signal reception in the most densely-built areas of Torino, where signal is degraded and multi-path effect is more relevant (see section 3.1.2 for additional information on GPS error sources). Surveyors used devices previously employed in a GPS survey within the activities of the French NTS in 2008. French surveyors had reported only minor problems with data collection; however, the dense urban fabric of the Torino central areas seemed to largely influence data collection, thereby compromising survey results.

At present, GPS and GNSS devices available on the market are increasingly accurate and capable of detecting satellite signals under the most difficult circumstances. Lower weight and smaller size limit the burden on respondents, while battery strength and high storage capacity facilitate a long duration, continuous, high-quality data collection. Additional movement sensors, such as accelerometers, can successfully supplement data mode derivation and save battery by switching off the device when no movement is detected. Currently-available high-sensitivity receivers can collect data indoors, distinguishing very weak and disturbed signals. Additionally, the number of available satellites will eventually increase, as will the quality of their signals (see section 3.1.3 for more details on future GNSS improvements).

Detection of satellite signals under non-ideal conditions can still result in unreliable data, as witnessed in the supplementary GPS data collection test carried out by the research team in the city centre of Torino. Despite technological advances in GPS devices and the resulting advances in data collection accuracy and continuity, mishandling and technical issues can still occur in GPS-only surveys, preventing proper information reporting and constituting a GPS device-specific bias.

One possible approach for limiting disruption in data collection is the simultaneous use of multiple positional data sources, such as GPS implemented with network-based information or GSM and WiFi positioning. For example, current-market Smartphones integrate these positioning tools and can therefore be used as data collection tools for survey purposes. Using personal devices for surveying can potentially limit mishandling and forgotten/lost devices, problems that are common in GPS-only surveys that rely on devices not owned by, or familiar to the study participants.

Major implementation problems present with Smartphone technology include privacy issues (i.e., users are unable to turn off data collection) and increased battery consumption, due to a high positioning frequency and the extended use of GPS receiver. Increasing survey costs must be considered if researchers must provide survey participants with such devices (purchasing costs, deployment, retrieval, loss, damages, etc.). In addition, relying solely on existing Smartphone owners to participate in surveys can result in sampling biases. Future studies must address these concerns.

When data collection problems and device mishandling are limited, the accuracy of GPS cannot be matched by respondents using traditional survey tools. Passive recording of positional data prevents memory effects that plague traditional survey tools – in particular, for short incidental trips – which can in turn result in underreporting.

Researchers can successfully define trip, stage and tour-derivation rules to post-process raw GPS data, thereby preventing possible user misreporting due to misinterpretation. These rules can be changed in a later moment on the same dataset. The survey area can be modified without the loss information, for example, by including trips that took place outside the original survey limits that were still recorded by the GPS (Bricka et al, 2003).

In addition to allowing researchers to ascertain basic travel behaviour information, such as origins, destinations, travelled distances and travel time, collecting continuous and accurate positioning data for long periods of time allows surveyors to study respondents' spatial habits, using spatial probability density tools such as kernel density estimation. Spatial density analysis illustrates the way each respondent uses spaces and locations, augmenting basic travel behaviour information with an additional spatial dimension. Figure 80 shows the results of such a tool on the Torino 15-day test with the Smartphone application.

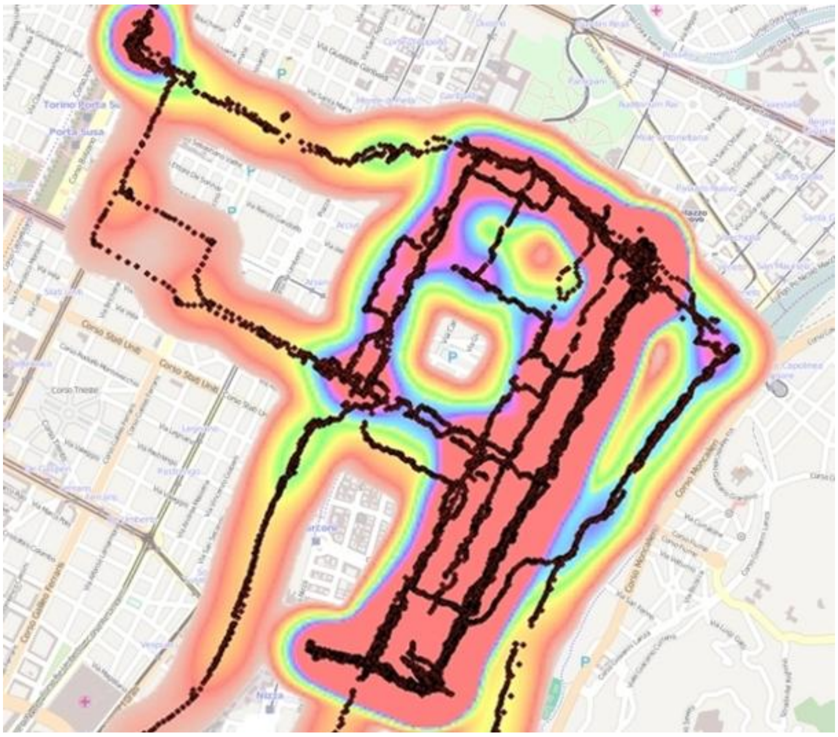


Figure 80 – Kernel density estimation for the 15-day Smartphone data collection

Results of the density probability estimation of GPS data illustrate the use of space throughout the survey period, highlighting the areas the respondent was more likely to visit. In this specific case study, the user concentrated his activities according to a main axis connecting home to work. Most of the stops observed during the test were concentrated along this axis. A secondary axis can be witnessed along two of the major streets of the Torino city centre (Via Roma and Via Po) and was related to shopping/leisure activities. A particular concentration of location points is identified for the Torino Porta Susa train station. Different densities can be applied to different days of the week or times of the day, in order to study various probability distributions.

Outcomes of this analysis demonstrate the possibilities of using GPS data to transcend the traditional approach to household and personal travel surveys. Positioning data allows surveyors to carry out additional spatial and temporal analysis.

Additionally, GPS data can potentially be used to study the following:

- use of space, calculating the surface and morphology of users' territories using home range estimation methods;
- driving behaviour, observing speed profiles related to private vehicle use;
- slow mobility, distinguishing among different types of on-foot experiences (Boffi et al., 2003)
- route choices, observing how individuals choose routes depending on attitudes and available alternatives.

Some of the main strengths of GPS travel surveys are reported in Table 103.

STRENGTHS	DESCRIPTION
Mature technology	GPS surveys have been used in the transport field for more than 25 years.
Data quality	GPS units provide accurate and rich data on time, distance and position in space. No memory or rounding problems.
Clear definition of survey units	Survey area, trip/stage and activity identification rules are clearly defined by surveyors, with no chance of misinterpretation of survey instructions.
Potential for supplementary travel and spatial behaviour analysis	GPS data allow researchers to study more aspects of user habits and preferences while using the same dataset.

Table 103 – GPS survey strengths

Despite the acknowledged strengths of a GPS survey, some survey-specific structural biases must be successfully addressed. In particular, GPS data are structurally different from information obtained through traditional travel surveys. For this reason, the use of a GPS-only survey can potentially lead to outcomes that cannot be compared with previous survey results, thereby interrupting the survey time-series. In the case of the Torino GPS travel survey, despite observing the same users for the same survey period, most user-reported data are of a higher quality than GPS-derived data.

Post-processing methods also affect survey results. Surveys that use different post-processing or different parameters within the same post-processing method can provide different outcomes. The wide variety of device characteristics, trip detection, trip purpose and transport mode derivation methods can result in incomparable data. Data comparability will be assured by post-processing harmonization.

Additionally, GPS-based surveys are characterised by specific recruitment biases, as summarized in section 2.2.2. In particular, privacy issues, technology divide and willingness to participate of some population groups can largely affect GPS travel surveys (Bricka, 2008, Stopher and Greaves, 2008).

The GPS device is a survey tool that has been proven appropriate for integration into a larger survey effort. Survey-specific problems remain, such as rising survey costs, difficulties in contacting individuals, and the increasing difficulty of convincing individuals to participate in travel surveys.

Table 104 summarizes the drawbacks identified during the state-of-the-art check and field tests.

DRAWBACKS	DESCRIPTION
Survey comparability (GPS vs traditional)	Surveys carried out with different tools can provide incomparable results.
Survey comparability (GPS vs GPS)	Different post-processing methods and derivation parameters can provide incomparable results.
Device specific biases (user side)	Data loss occurs due to forgotten device, depleted battery, device switched off, broken device.
Device specific biases (device side)	Signal loss can occur in densely-built areas, indoors, with certain public transport modes and as a consequence of cold start, resulting in data collection disruption.
Recruitment biases	Technology is not accepted by all population groups.
Survey specific biases	Problems related to recruitment, survey costs and general tendency for individuals not to participate in surveys still remain.

Table 104 – GPS survey drawbacks

GPS and passive data collection tools show great potential in providing surveyors with high-quality spatial and temporal data. However, both device-specific and survey-specific biases remain to be carefully evaluated.

The concurrent use of a GPS device and a travel diary allowed researchers to create a GPS-augmented travel diary that can supplement self-reported data with a more accurate spatial and temporal dimension. Survey outcomes demonstrate the need for GPS data collection continuity, which will guarantee the success of GPS-based travel surveys. Keys for future success include ease in the use of GPS devices, as well as the capacity for such tools to record data under challenging environments for signal reception, such the central and most densely-built areas of Torino.

Results show that, even with potential for improvement in data collection, a degree of user-reported data collection is desirable, in order to evaluate and guarantee data completeness and derivation success. Using a degree of self-reporting also allows survey results to be compared with the results of previous traditional travel surveys. Post-processing methods are incapable of deriving all necessary information, and the use of prompted recall studies has proven to have a positive impact on survey results.

User-reported information must be collected via travel diaries. Despite placing a higher burden on survey participants, user involvement prevents data loss resulting from GPS collection gaps and provides valuable information for researchers to use in improving trip and purpose-derivation algorithms.

Traditional survey tools include simplified diaries or memory joggers to reduce the burden of a multi-day multi-instrumental survey. Outcomes from the GPS surveys in Torino proved the possibility of augmenting user-reported travel information even when it was incomplete, and showed a higher degree of user involvement in the survey effort when participants were directly asked for information.

The use of a prompted-recall interview after data collection can be included for validation reasons. The use of such an interview at the end of each day can potentially influence participants' behaviour, by inadvertently revealing the results of the survey. However, asking respondents for feedback at the end of the survey can also lead to a higher memory effect.

Survey-specific recruitment biases are witnessed in GPS-based travel surveys. The use of such tools does not guarantee higher representativeness within samples. However, the possibility of longer surveys and smaller samples (given a defined survey error estimation) does guarantee researchers lower costs and higher-quality data. The use of multi-instrumental survey methods and specific survey tool sets for specific population groups (e.g. traditional tools for elderly persons and new tools for large households) can guarantee a greater degree of representativeness (Bricka, 2011).

Rapid technological developments and the general acceptance of positioning technologies will help researchers to overcome actual biases, and to modify methods of spatial data collection of spatial data in a way that reduces surveyor control. Positioning technologies will improve in reliability and evolve to be more pervasive in individuals' lives. Smartphone penetration is expected to increase, thereby gradually reducing the technology divide. The possibility of tracking survey respondents using applications on their personal devices will result in a smaller sample bias for future experiences, due to the increasingly generalized acceptance of such technologies. Use of Smartphone technology in travel studies will guarantee even lower implementation costs (only application development will be needed), but technology biases related to future market penetration of the devices should be studied.

New opportunities for the study of travel behaviour will arise from various emerging data sources, such as social networks and datasets of major information technology companies. Additionally, growth of platforms for sharing volunteered geographic information, where user-generated content aids in the completion of large shared projects in the mapping field, will offer new avenues for the study of human movement. Researchers might evaluate the future possibility of relying on individuals' sharing their travel data, either voluntarily or indirectly, outside the experience of officially being involved in a survey effort. Travel behaviour data obtained outside a survey, however, poses its own challenges, as it could be uncontrolled and unstructured. Data obtained in such a fashion must be managed more heavily than survey data in order to obtain usable results.

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Annexes

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Annex 1 – NAVSTAR GPS CHARACTERISTICS

The Navigation Satellite Timing and Ranging Global Positioning System (NAVSTAR-GPS), currently the most commonly used satellite-based navigation system, was developed and is operated by the U.S. Department of Defence (US Air Force). The U.S. Department of Defence approved the system architecture in 1973 and the system was declared fully operational in April 1995. Originally designed for military purposes only, it is now used more by civilians than by the military.

GPS is used to provide accurate positioning, navigation and timing services on a worldwide scale through the use of satellite signals, which are available at no cost, with a GPS/GNSS receiver (Parkinson, 1996; National Research Council US, 1996).

The system consists of three segments: a space segment, a control segment, and a user segment.

Space Segment

The GPS space segment consists of a constellation of satellites transmitting radio signals to users. A constellation of 24 GPS satellites is ensured, 95% of the time. The Air Force maintains 31 operational GPS satellites, plus 3-4 previously decommissioned satellites that can be reactivated if needed. Figure 81 illustrates the NAVSTAR satellite constellation.

Figure 81 – GPS space segment

Satellites are arranged into six equally-spaced orbits, with each orbit containing at least 4 satellite slots. The orbital planes have an inclination angle of 55 degrees relative to the earth's equator and the orbit altitude is approximately 20.200 km (Medium Earth Orbit). Each satellite circles the Earth two times per day. This setting is designed to ensure the view of at least four satellites, more often six to eight (Barzaghi, 2004), at any time from any point of the planet.

According to the original GPS design, each satellite broadcasts two carrier signals (L1 and L2). Signals are then modulated into ranging codes such as:

- Coarse Acquisition or Clear Access (C/A) code, available for free civilian use;
- Precision or Precise (P) code, specifically designed for military applications. To prevent unauthorized access to the P code, a Y code is generated using an encryption sequence. The P(Y) code can be decrypted only using authorized devices.
- Navigation Data (D) code contains information on satellite constellation position, signal starting time, and correction factors. The D code is modulated on top of the C/A and the P code.

C/A modulates L1 carrier only while P code modulates both L1 and L2. Navigation information related to the D code is encoded in both L1 and L2 signals.

To allow receivers to distinguish GPS satellite signals characterized by the same frequency, each satellite transmits a unique deterministic sequence called pseudorandom noise (PRN), which does not correlate with any other satellite's PRN code.

GPS satellite signal characteristics are illustrated in Figure 82.

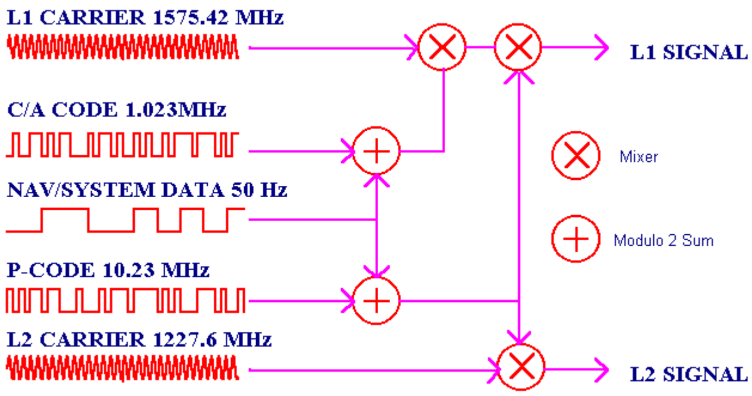


Figure 82 – GPS signal characteristics

Different generations of satellites are currently forming the GPS constellation, and replacement programs of older satellites are on-going. While older satellites were generally designed with a lifespan of 7 years, newer generations are designed to provide users with better signals and to last until 15 years (GPS Block III under development). (www.gps.gov/systems/gps/space/)

The last GPS constellation expansion, dated June 2011, increased the number of satellites to 27 by empowering some of the orbits with extra satellite slots, thereby improving the signal coverage in most parts of the world. (U.S. Air Force)

Control Segment

A global network of ground facilities monitors the functionality of the GPS satellite constellation (Figure 83). This ground control segment is designed to perform analyses, and it send commands and data to the GPS space segment.

Currently, the control segment consists of several stations and antennae installed throughout the world, covering different latitudes and longitudes. In particular, the operational control segment includes:

- a master control station (MCS), to assess proper satellite operations and control the GPS constellation in order to guarantee system accuracy. In case of satellite failure, the MCS can reposition satellites to maintain the system performance;
- a backup of the master control station;
- sixteen monitoring stations, to track satellite information, collect atmospheric data, and send the information to the Master Control Station. Six stations are controlled by the U.S. Air Force and 10 by the National Geospatial-Intelligence Agency (NGA)
- twelve command and control antennae used to communicate with GPS satellites for command and control purposes. Four GPS-dedicated antennae are positioned together with U.S. Air Force

monitoring stations, while the system uses the eight antennae of the Air Force Satellite Control Network (AFSCN) remote tracking stations.

http://www.gps.gov/systems/gps/control/

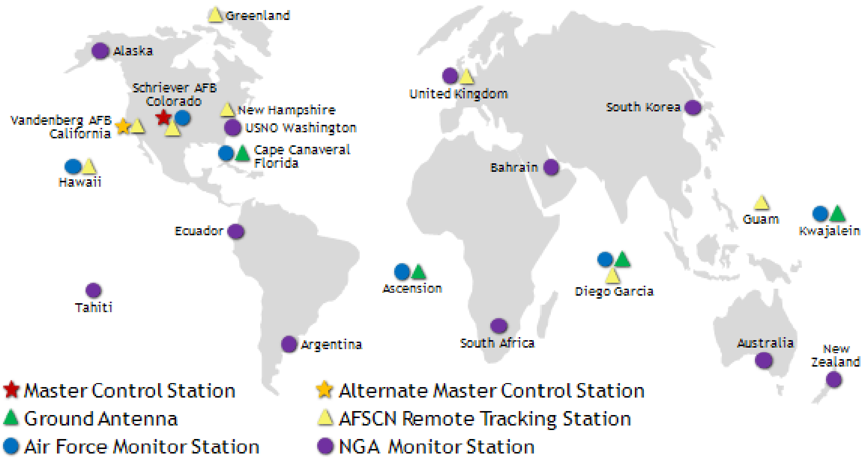


Figure 83 – GPS ground segment (GPS.gov, 2012)

User Segment

The GPS user segment consists of the specific L-band radio receiver/processors and antennae which receive GPS signals, thereby allowing users to access the secure GPS Precise Positioning Service for military purposes, or the free Standard Positioning Service. GPS services are accessible using a specific GPS/GNSS receiver.

Besides specific GPS receivers, several personal products, such as cell phones, watches, computers, etc. embed GPS and GNSS capabilities. The 2012 GNSS Market Report estimates 600 million of GNSS-enabled devices shipped in 2012, with further growth anticipated in the future. In fact, the European GNSS Agency estimates that global shipments will exceed 1 billion units before 2020, driven by growth in emerging economies.

Different manufacturers provide different GPS device solutions. Both analytical tools (i.e., signal tracking, positioning and filtering algorithms) and outputs (i.e., provided output format and related information) can vary according to the product vendor.

Devices differ by receivers' sensitivity, number of satellite/device signal correlators – referred as channels – and the time necessary for the first satellite fix, depending on the device's ability to predict satellite positions (cold, warm and hot start). Size, weight and battery life vary among different GPS device solutions. Storage capacity is another important feature of the receivers, in particular for tracking applications. (Gps.gov ; Navipedia.net).

Annex 2 – ADDITIONAL GLOBAL NAVIGATION SATELLITE SYSTEMS

Besides the widely used NAVSTAR GPS, several navigation satellite systems are active or under development. These will contribute to the next generation of GNSS services, which will allow users to benefit from the use of different satellite constellations. The various Global Navigation Systems are illustrated below.

GLONASS

GLONASS is a satellite navigation system operated for the Russian government by the Russian Aerospace Defense Forces. Restored in 2011 after more of a decade of funding problems, it consists of 24 operational satellites orbiting in 4 different orbital planes with 64.8 degree inclination. Each orbital plane hosts 6 operational satellites slots plus additional spare satellites.

http://new.glonass-iac.ru/en/CUSGLONASS/index.php
http://www.glonass-ianc.rsa.ru/en/guide/
http://www.spaceandtech.com/spacedata/constellations/glonass_consum.shtml

GALILEO

Galileo is a global navigation satellite system under development by the European Union (EU) and the European Space Agency (ESA). Galileo aims to provide a high-precision positioning system to European nations, independent from other operational navigation systems.

Once fully operational, it will consist of 30 operational satellites revolving around Earth in 3 orbital planes of 56° inclination. According to ESA, the constellation setting will provide a better coverage at high latitudes than GPS, thanks to the deployment and inclination of the satellites. This solution will guarantee better positioning estimation at higher latitudes and has potentially beneficial applications for northern Europe.

http://ec.europa.eu/enterprise/policies/satnav/galileo/why/index_en.htm
http://www.gsa.europa.eu/galileo-0
http://www.gsa.europa.eu/galileo/programme
http://en.wikipedia.org/wiki/Galileo_(satellite_navigation)

COMPASS

The Chinese global positioning system will consist of a constellation of 35 satellites, 30 non-geostationary satellites (27 in medium earth orbit and 3 in inclined geosynchronous orbit) and 5 geostationary orbit satellites for backward compatibility with the existing local positioning system BeiDou-1.

Compass will provide two levels of service: a free service available globally for general use and a licensed service for Chinese government and military users. The civilian service will provide users with an accuracy of 10 meters, while the licensed service will have a higher degree of accuracy.

Annex 3 – GPS DEVICE SPECIFICATIONS

ROYALTEK RBT3000 Specifications

General Features

Frequency:	L1, 1575.42 MHz
C/A:	1.023 Mhz chip rate
Channels:	12 Channels all-in-view tracking
DGPS Source:	SBAS (WAAS/EGNOS)
Antenna Type:	Built-in antenna (external antennal optional)
Accuracy:	DGPS: None
Position:	10 meters RMS, 25 meters CEP, without SA
Velocity:	0.1 meters/second, without SA
Time:	1 microsecond synchronised to GPS time
Acquisition Time:	Open Sky, Stationary
Reacquisition:	0.1 seconds, average
Cold Start:	<45 seconds, average
Warm Start:	<38 seconds, average
Hot Start:	<8 seconds, average

Dynamic Conditions:

Altitude:	<18,000 meter
Velocity:	<515 meter/second
Acceleration:	<4g
Interface:	
Connection:	Bluetooth (Class 3) Serial Port
Protocol:	Default: NMEA-0183 (v2.20)-GGA, GLL, GSA, GSV, RMC, VTG
Power:	Built-in rechargeable battery and DC input charging protection circuit
Operation Time:	10 hours after full charge, in continuous operation mode with BT & GPS
Device Size:	108.3mm (Long), 52.86mm (Width), 23.85mm (Height)
Data-logger:	Capacity for storing 30,000 records

Environmental:

Operating Temperature:	-20 to +60 degrees Celcius
Relative Humidity:	5% to 95%, non-condensing

Annex 4 – NMEA-0183 PROTOCOL

NMEA-0183 sentences provided by the RoyalTek GPS device are shown below. Parameters included in the original NMEA-0183 structure not recorded by the device are omitted from the sentence description.

NMEA-0183 sentences – GGA, RMC, GLL, VTG, GSA

SENTENCE EXAMPLE
GGA $GPGGA,183601.772,4503.2787,N,00738.8513,E,1,04,13.8,278.8,M,,M,,*7D
RMC $GPRMC,183601.772,A,4503.2787,N,00738.8513,E,8.076753,290.130524,230310,,*06
GLL $GPGLL,4503.2787,N,00738.8513,E,183601.772,A*30
VTG $GPVTG,290.130524,T,,M,8.076753,N,14.957863,K*61
GSA $GPGSA,A,3,,,,,,,,,,,,,39.7,34.3,,*39

GGA – Global Positioning System fixed data

EXAMPLE
$GPGGA,134441.070,4504.6584,N,00731.1050,E,1,03,17.1,0.0,M,,M,,*7D

Name	Unit	Description
UTC Time	hhmmss.sss	Time
Latitude	ddmm.mmmm	
N/S Indicator	Code	N=north or S=south
Longitude	dddmm.mmmm	
E/W Indicator	Code	E=east or W=west
Position Fix Indicator	Code	Used Fix
Satellites Used	Num	Range 0 to 12
HDOP	Num	Horizontal Dilution of Precision
Altitude	Meters	MLS Altitude
Units	Code	M=meters

RMC – Recommended minimum specific GNSS data

EXAMPLE
$GPRMC,161110.275,A,4504.0617,N,00739.6852,E,0.000000,0.000000,220310,,*06

Name	Unit	Description
UTC Time	hhmmss.sss	Time
Status	Code	A=active or V=Void
Latitude	ddmm.mmmm	
N/S Indicator	Code	N=north or S=south
Longitude	dddmm.mmmm	
E/W Indicator	Code	E=east or W=west
Speed Over Ground	Knots	
Course Over Ground	Degrees	
Date	ddmmyy	

GLL – Geographic position – Latitude/Longitude

EXAMPLE
$GPGLL,4503.7024,N,00739.9174,E,144135.837,A*3B

Name	Unit	Description
Latitude	hhmmss.sss	Time
N/S Indicator	Code	N=north or S=south
Longitude	ddmm.mmmm	
E/W Indicator	Code	E=east or W=west
UTC Time	dddmm.mmmm	

VTG – Course over ground and ground speed

EXAMPLE
$GPVTG,246.806610,T,,M,24.309736,N,45.020775,K*51

Name	Unit	Description
Course	Degrees	Heading
Reference	Code	T=True
Reference	Code	M = Magnetic
Speed	Knots	Horizontal speed
Units	Code	N = Knots
Speed	Code	Horizontal speed in Km/h

GSA – GNSS DOP and active satellites

EXAMPLE
$GPGSA,A,3,,,,,,,,,,,,,8.0,3.4,,*3F

Name	Unit	Description
Mode 1	Code	A = Allowed to switch from 2D to 3D
Mode 2	Code	3 = 3+ satellites used for 3D positioning
PDOP	Num	Position Dilution of Precision
HDOP	Num	Horizontal Dilution of Precision

Unique Positional and Navigation Information provided by the GPS device

Name	Unit	Description
Date	ddmmyy	Date
UTC Time	hhmmss.sss	Time
Latitude	ddmm.mmmm	Latitude
Longitude	dddmm.mmmm	Longitude
Altitude	Meters	MLS Altitude
Speed	Meters/Knots	Horizontal Speed
Course	Degrees	Heading
Satellites Used	Num	Range 0 to 12
PDOP	Num	Position Dilution of Precision
HDOP	Num	Horizontal Dilution of Precision

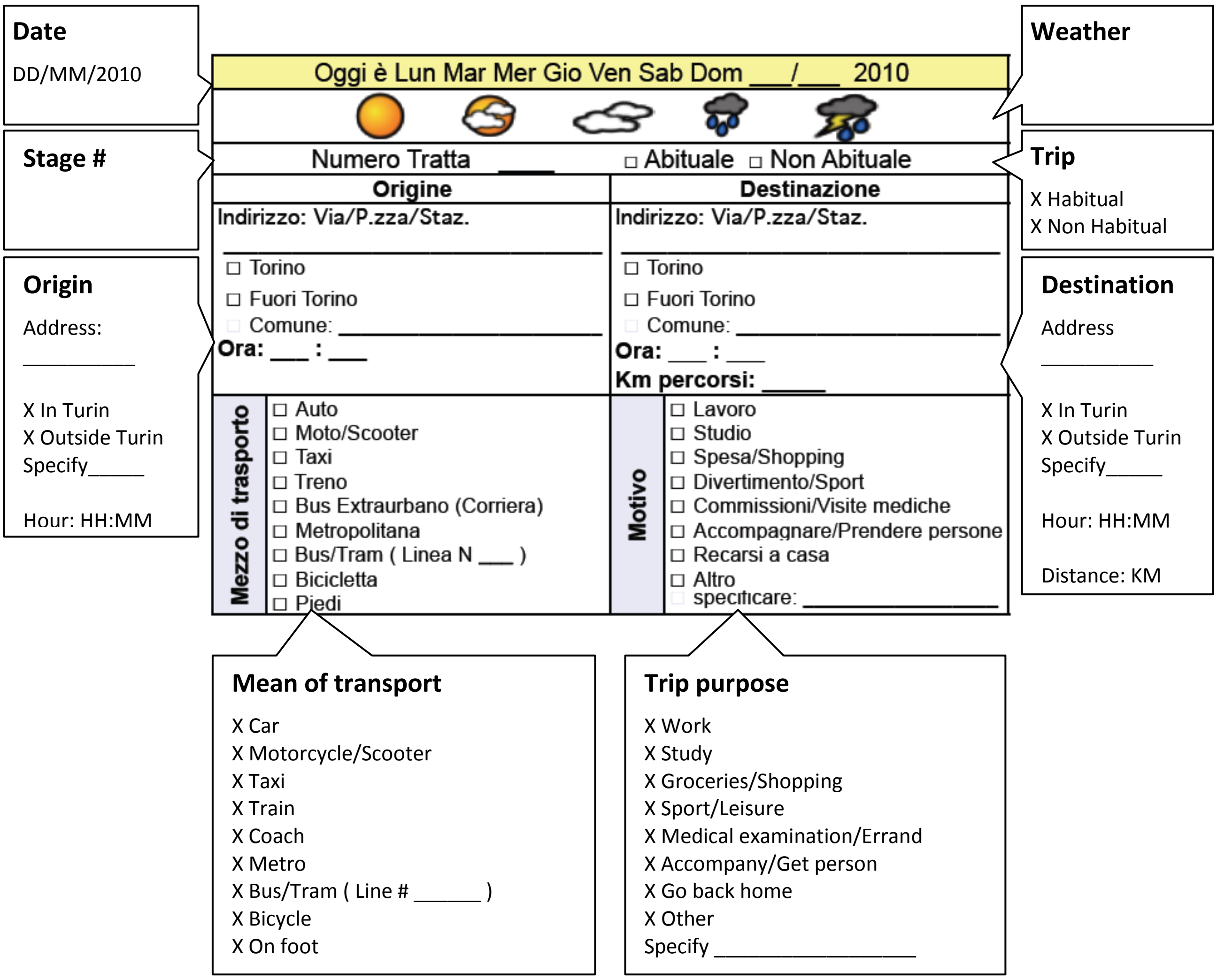
Annex 5 – SOCIO-ECONOMIC QUESTIONNAIRE

The research team provided users with a socio-economic questionnaire supplemented with questions about travel habits and attitudes. An English translation of the trip- and activity-related questions of the socio-economic questionnaire is provided below. The order of the questions is modified from the original version.

TRANSPORT MODE USE AND TRAVEL CHOICES	
1	How many days a week do you use a private motorized mean of transport (car/motorcycle)?
1.1	as a driver?
1.2	as a passenger?
2	Do you use public transport?
3	Do you own a public transport pass?
3.1	Which kind (annual, weekly, seasonal)?
4	How many days of the week do you use the bicycle for your mobility?
5	How many days of the week do you perform entirely on-foot trips?
6	What is the mean of transport you mostly use for your most frequent trip?
7	What is the maximum acceptable travel time for your most frequent trip (one way)?
8	Do you usually prefer choosing the shortest route to your destinations?
ACTIVITIES AND SERVICES	
9	Are your family travel needs influencing your daily mobility?
10	How many hours a week you dedicate to leisure and meeting friends?
11	How many hours a week you dedicate to sports/physical activities?
12	How many hours a week you dedicate to shopping?
13	Considering your work place (or study place):
13.1	How long does it take you to walk there from home (if feasible)?
13.2	If not on-foot, what transport mode do you use?
13.3	How long does it take you to complete the trip with that transport mode?
14	Accessibility of commonly used services (distance, travelling time and accessibility degree)
14.1	Grocery store
14.2	Pharmacy
14.3	Family doctor
14.4	Post office
14.5	Park
14.6	Public Library
14.7	Sport center, gym, soccer field, etc.
14.8	Public transport stop (closest and mostly used bus, tram or metro stop)
14.9	Train station
DEMOGRAPHIC INFORMATION	
15	Gender
16	Age
17	Education
18	Income group
19	Marital status
20	Number of family members (and basic demographic information)
21	Home Address
22	Employment
23	Work address (or prevalent work address)
24	Working hours (from – to)
25	Wife/husband employment
26	Wife/husband working hours (from – to)
27	Wife/husband work address
TRANSPORT MODE USE / OWNERSHIP	
28	How many people in your family have a driving license?
29	How many people in your family have a public transport pass?
30	Car/Motorcycle ownership (list vehicles and characteristics)
31	Bicycle ownership

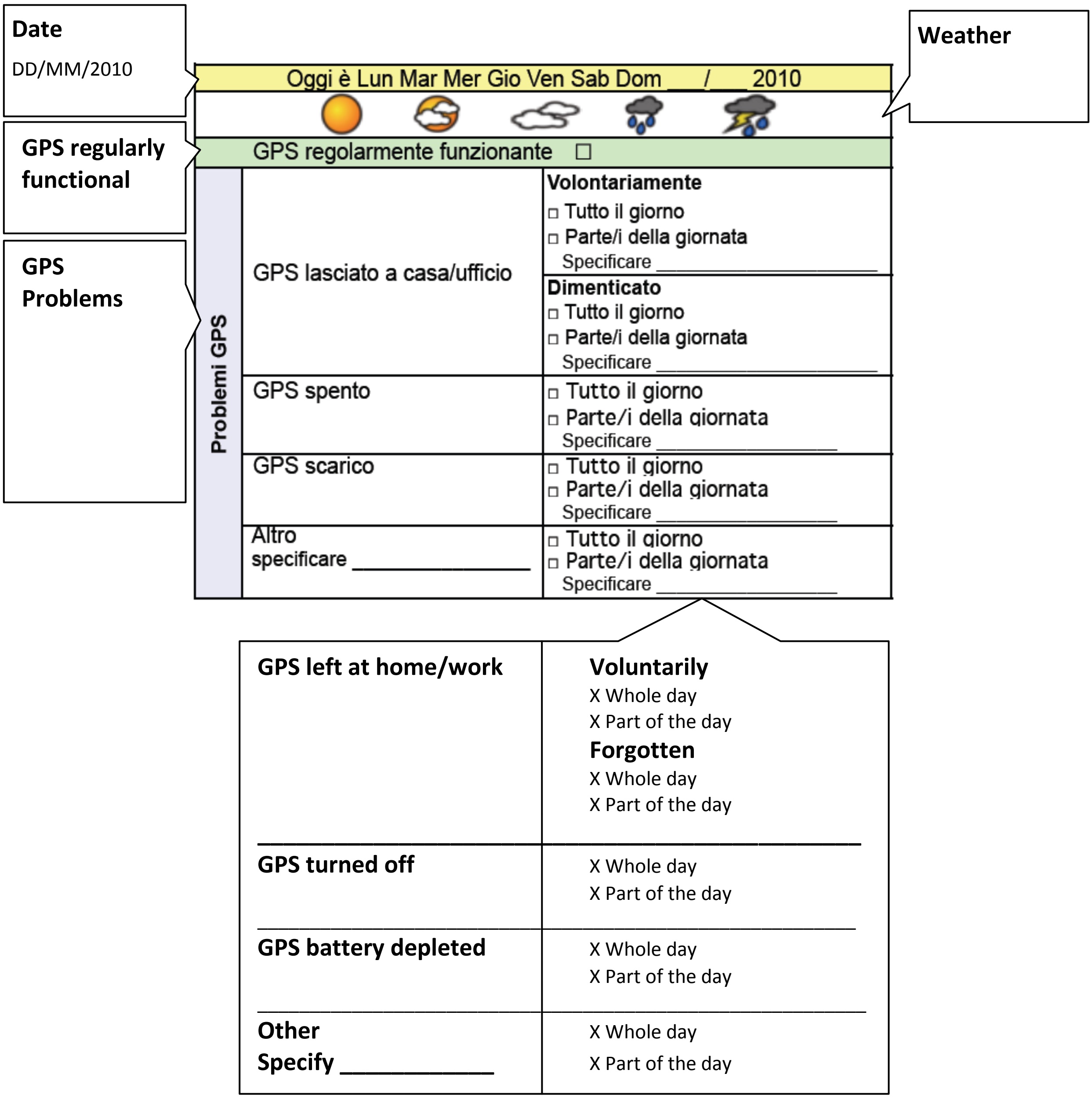
Annex 6 – TRAVEL DIARY

A traditional travel diary was used to collect trip information from survey participants. Researchers used a travel diary format specifically designed for a traditional paper and pencil self-administered interview. This tool was used in previous personal travel surveys.



Annex 7 – GPS DIARY

Surveyors asked respondents to report possible problems with the GPS during the second survey week, in order for the research team to distinguish data collection gaps due to GPS mishandling or device problems from GPS signal loss.



Annex 8 – GPS PILOT DATA COLLECTION

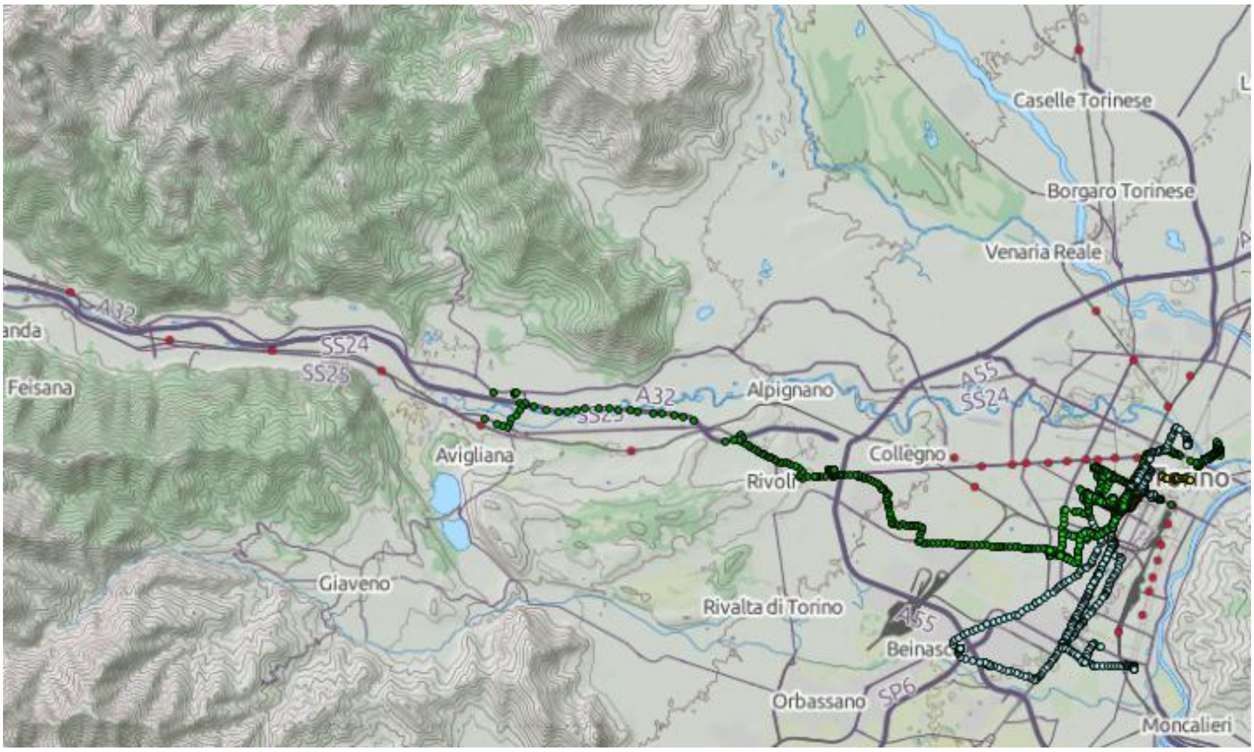


Figure 84 – GPS pilot-survey - Overall data collection

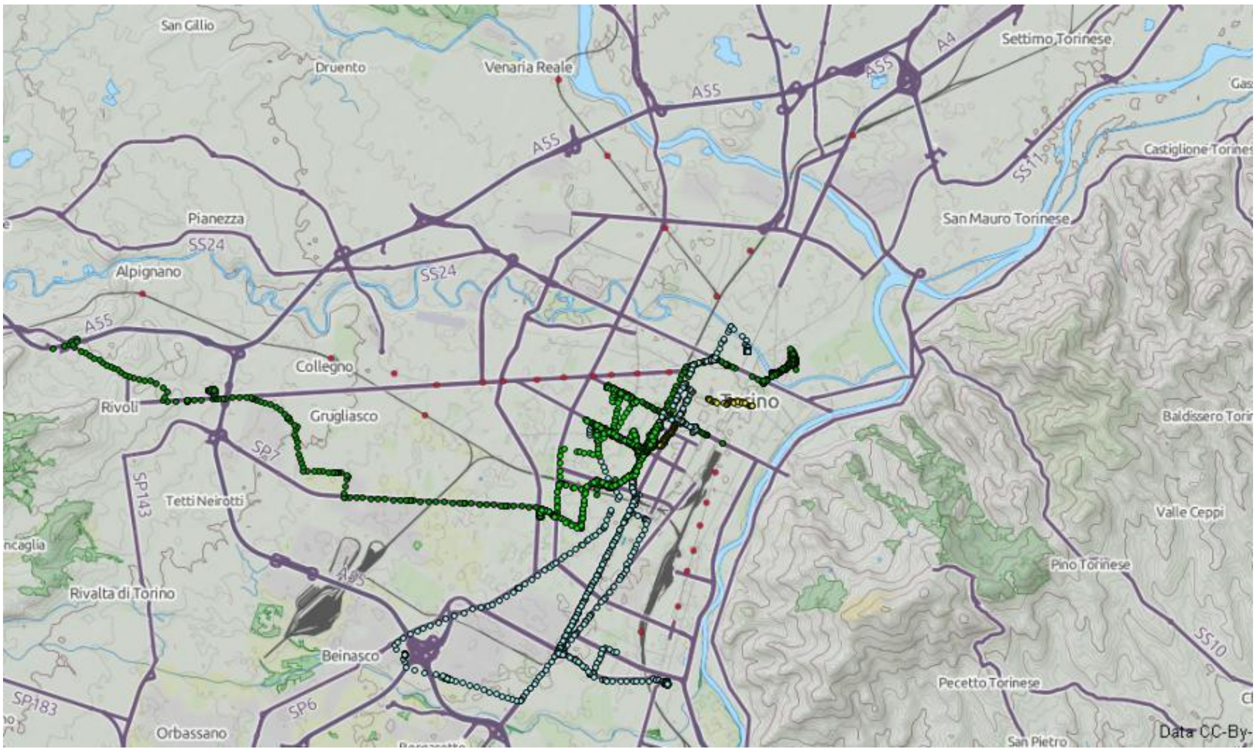


Figure 85 – GPS pilot survey - Data collection in Torino

Annex 9 – GPS SURVEY DATA COLLECTION

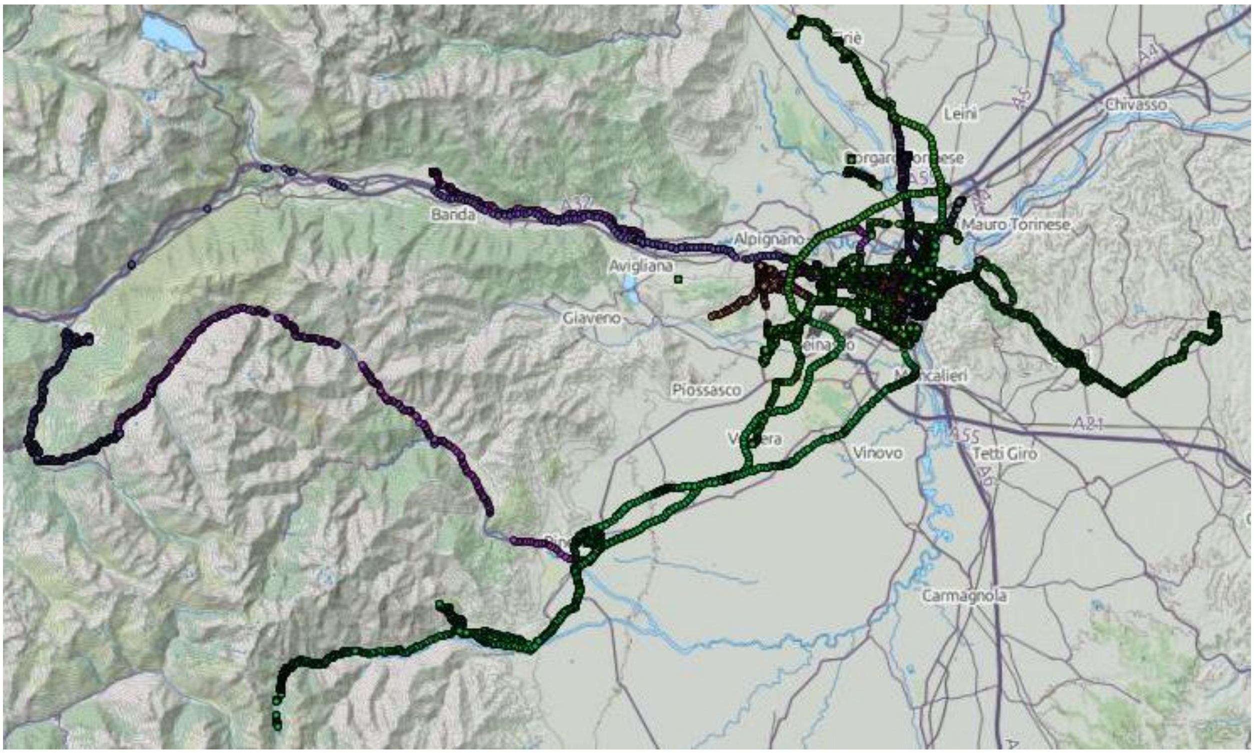


Figure 86 – GPS survey - Overall data collection

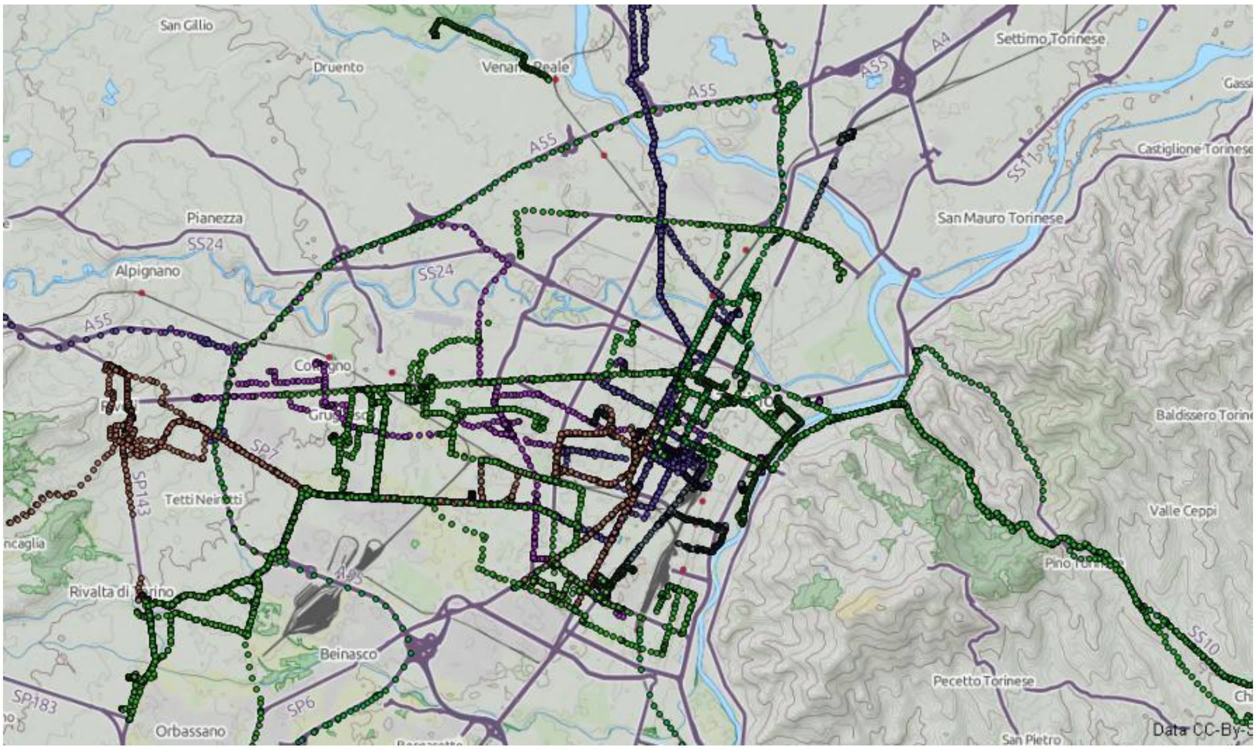
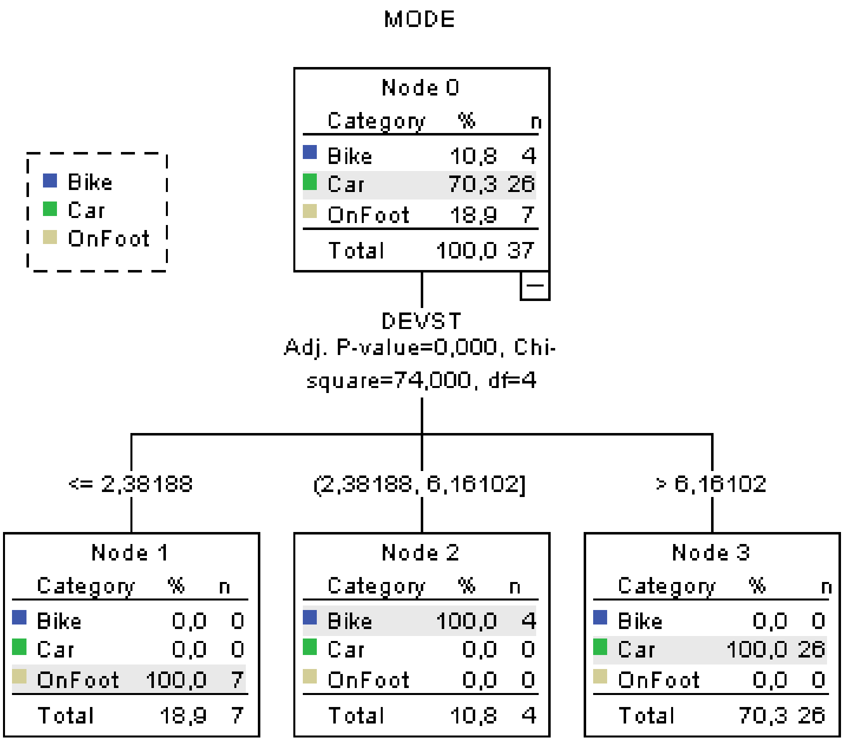


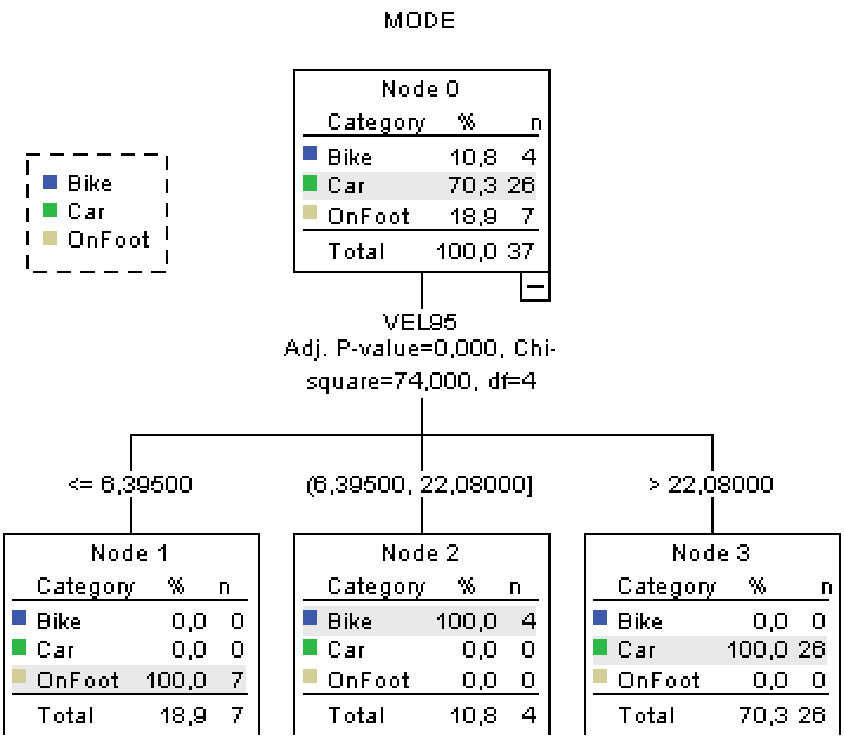
Figure 87 – GPS Survey - Data collection in Torino

Annex 10 – TRANSPORT MODE IDENTIFICATION – GPS PILOT

The study of the transport mode detection in the GPS pilot allowed researchers to determine classification rules to discriminate motorized from non-motorized movements. In particular, the method is able to distinguish between car, bicycle and stages on foot relying on the value of the variability of the observed speed, as shown in the decision tree scheme illustrated below.



The same results can be achieved using only the value of the 95th percentile of the speed values, thus providing researchers with a classification using limited information. Results are shown below.



Annex 11 – TRANSPORT MODE IDENTIFICATION – GPS SURVEY

The GPS survey benefitted from the experience of the GPS pilot survey in determining trips performed with motorized transport modes, non motorized transport modes and on-foot. However, the scarcity of public transport data compared with car movements did not allow researchers to detect certain transport modes among motorized modes. Nonetheless, the decision tree illustrated below demonstrates the possibility of discriminating among train, bus and tram trips.