An Evaluation of the Reliability of GPS-Based Transportation Data

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Abstract

GPS-based data are becoming a cornerstone for real-time transportation applications. Tracking data of vehicles from GPS receivers are however susceptible to measurement errors. The assessment of the reliability of data from GPS receiver is a neglected issue, especially in a real road network setting and in the phase after data transfer but before information identification. An evaluation method is outlined and carried out by conducting a randomized experiment. We assess the reliability of GPS-based transportation data on geographical position, speed, and elevation from three varied receivers GlobalSat BT-338X, Magellan SporTrak Pro and smart phone for three transportation modes: bicycle, car, and bus. The positional error ranging from 0±158 meters, and 74% to 100% with an error within 5 meters depending on the transportation mode and route, there is also a non-negligible risk for aberrant positioning. Speed is slightly underestimated or overestimated with errors around ±5km/h except for SporTrak Pro which had an error of -10 km/h. Elevation measurements are unreliable with errors bigger than ±100 meters.

Keywords: Transportation, GPS tracking, Reliability, Road network

1. INTRODUCTION

Global Positioning System (GPS) has emerged for civilian use in the 1990s as the space geodetic technique became accurate and affordable (Zumberge et al., 1995). GPS tracking technologies have extensively been applied in transportation studies, in particular for studying the routes of motorized vehicles (Zito et al., 1995; Quiroga and Bullock, 1998; Murakami and Wagner, 1999). Schönfelder and Antille (2002) presented an approach to collect GPS longitudinal travel behaviour data on humans and described the complexity of their daily life with the interaction between periodicity and variability. Stopher et al. (2007) demonstrated that GPS can be used successfully to supplement travel diary surveys. Kamboj and Dahiya (2011) found standard handheld GPS receiver may be used to measure sag in overhead conductor of power transmission lines along with error estimation technique LSPE. Lindsey et al. (2013) confirmed the feasibility of using GPS for route tracking to identify the specific locations where cyclists ride on a street. In environment control, for instance, Carling et al. (2013) and Jia et al. (2013) studied the induced pollutant emissions of CO2 from car movements by using a GPS tracking data of car movements.

Shen and Stopher (2014) conducted a review of GPS-based travel studies going back to late 1990s, which range from application of GPS travel surveys to methods of processing GPS data. In their review they listed representative studies using dedicated GPS receivers from 14 different countries, as well as four studies regarding smartphones. They stated that data collection based on GPS surveys is more reliable, and cheaper, than self-reported diaries, though GPS data still has some issues that require data processing methods to enhance the reliability of the data.

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Gathering information of spatial-temporal mobility by GPS is subject to critical reflections. Leduc (2008) examined recent developments in road transportation data collection and discussed the potentials in providing real-time information for routing and estimating traffic flow and volume. The author also pointed out the bottlenecks of the uncertainty in the GPS technologies still leads to the question: "How good the quality of the traffic data is?". Moreover, Van der Spek et al. (2009) concluded that GPS offers a widely useable instrument to collect invaluable spatial-temporal data on different scales and in different settings adding new layers of knowledge to urban studies, but the use of GPS-technology and deployment of GPS-receivers still offers significant challenges for future research. Besides, the enormous use of GPS tracking technologies hinges critically on the functioning of the receiver.

Nowadays, the internal system of a portable, inexpensive GPS tracking receiver is designed in a complex way due to the desire for accuracy. The U.S. National Coordination Office stated in the performance standard that "well designed GPS receivers have been achieving horizontal accuracy of 3 meters or better and vertical accuracy of 5 meters or better 95% of the time". Configuration of a GPS receiver when conducting field tracking is becoming more complicated. However, the receiver can function as an effective and reliable tool for data collection only if it does not affect the nature, quality or authenticity of the data collected (Shoval, 2008; Huang, 2013). Studies on gathering information of trips, travel modes and trip purpose have shown that accuracy varies depending on the methods, attributes and ground truth (c.f. Table2 and Table 3 in Shen and Stopher 2014). The methods reviewed in the tables either performed poorly due to the ambiguity of similar modes or were highly dependent on the "ground truth data" (Zheng et al. 2008; Chang et al. 2015). Moreover, the methods are primarily designed for information identification directly from the data rather than for data evaluation. No doubt that the application of GPS survey has opened a new era for travel data collection, the information identified from the data can be broadly applied. However, it is difficult to choose a so called "well designed" GPS receiver given that all manufactures are advertising their products to be the best. It is therefore questionable whether a GPS receiver for normal civil use can meet the standard of the U.S. National Coordination Office. The reliability of these GPS data needs to be examined before further processing for the new areas of applications.

In this study we intend to complement the existing literature by contributing to a specific issue that has little been studied, being examining the reliability of GPS data collected in a real road network setting. Especially in the validation phase after data has been transferred into computer, but before information extraction such as trip identification, mode detection, purpose imputation. This means that we will focus on questions like: What is the dynamic data reliability with varying transportation modes, road network, environmental conditions and collection settings? How well do the concurrent GPS receivers perform in tracking vehicle mobility? To what extent can the accuracy provided by the manufactures be trusted?

Following this, the assessment of the reliability of GPS tracking data needs to be scrutinized. This paper outlines a method to examine how well GPS tracking data matches the travel information of position and speed. Specially, we applied the method in a real field experiment. In the experiment, we vary the transportation mode, speed, elevation, sampling frequency, filtering level as well as the receivers. A bicycle, a car, and a bus travelling on pre-set routes with pre-set speeds are tracked by GPS receiver GlobalSat BT-338X with different collection settings. Two other receivers being Magellan SporTrak Pro and smart phones (Samsung Galaxy S5 Mini) are used to track the bicycle under same settings for comparison of performances as well as avoiding the results being receiver specific. The acquired experimental data are freely available[2] for the interest of replicability.

Section 2 provides a review of researches related to examining the reliability of GPS tracking. Section 3 presents the experimental design and the data collection process. Section 4 gives the experimental results. Section 5 ends the paper with a concluding discussion of the findings.

2. LITERATURE REVIEW

A thorough search for literatures relevant to the use of GPS-based transportation data was conducted in a former related work (Zhao et al., 2014). There is a vast body of studies reporting on applications of GPS with a brief

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[2] http://users.du.se/~xzh/

discussion about the reliability of the data. The discussions contained in these studies do not add any new knowledge to the data reliability and we therefore turn to studies with reliability as the primary concern.

Obviously the quality of the hardware and the surroundings where the GPS is being used may affect the reliability of the receiver. The starting point is that a GPS receiver requires a clear sight with at least four satellites to determine spatial positions. In urban environments, buildings may partly block satellite signals, forcing the GPS receiver to work with a poor geometric constellation of satellites, thereby reducing the accuracy of the positional estimates. Multipath propagation of the radio signal due to reflection in the surroundings may further lead to decreased positional accuracy without notification by the GPS receiver, thereby reducing the integrity of the navigation solution. The accuracy may be enhanced by advanced hardware chipsets, dual-frequency receivers, carrier-phase measurements supported by augmentation systems (e.g. SBASs, WAAS, EGNOS and MSAS), even combination of the global navigation satellite system (GPS, GLONASS, BeiDou and Galileo, Li et al, 2015). It is possible to have a real-time positional accuracy within decimetres under required conditions; however, those kinds of receivers are too expensive for normal use like in car tracking systems. Moreover, the required conditions do not only call for sophisticated GPS receivers, sensors, vehicles, and map information, but also put requirements on trajectory dynamics and surrounding environment (Skog and Handel, 2009, Li et al. 2015).

Dead Reckoning (DR) system and map matching algorithms integrated with differential GPS (DGPS) are examples of commonly used hybrid systems for enhancing the positioning of vehicles on land (Zhao et al., 2014). The DR system can smooth the error of the GPS and provide continuous positioning even in times when the GPS is unavailable (Meng, et al., 2004). Map-matching has been predominantly applied in post-processing GPS data (e.g., Marchal et al., 2005; Schüssler and Axhausen, 2009a, 2009b). In essence, map matching is to use a digital map of the road network to impose constraints on the GPS navigation and tracking recordings (Skog and Handel, 2009). It has become a popular solution to remedy the inherent error of the GPS when an underlying network is available. Quddus et al. (2007) reviewed the currently existing map-matching algorithms and their limitations. Stopher et al. (2013) proposed adding map editing to manually fix certain data errors besides fixing the cold/warm start issue (Chen et al. 2010).

Stopher and Speisser (2011) conducted tests for five transportation modes under various circumstances and found that the tested GPS devices are accurate enough to be useful as a substitute for self-report surveys. However, they only checked one type of GPS device (BTT08) and neglected the examination of speed. The reviewed studies in Zhao et al., 2014 most relevant to our study are those attempting to assess the reliability of GPS data by comparing them to known conditions. These studies aim to evaluate the reliability of GPS receiver, but are typically not conducted as experiments. They examine one transportation mode, one environment, one aspect of tracked information, or one configuration of the receiver, the importance of road network is neglected as well. Those studies are also examining the static accuracy using small samples without controlling for external conditions. Studies that examined the reliability of GPS receivers on sport events, animal activities are not reviewed in detail considering there is no road network restriction and the standard for reliability is different from transportation research. A notable exception is the recent work of Schipperijn et al. (2014). They tested the dynamic accuracy of Qstarz Q1000XT portable GPS receiver for the use in public health applications under varying real-world environmental conditions, for four modes of transportation at three levels of sampling frequency. They found that not even a half of the positional recordings were within 2.5 meters of the actual positions with the proportions varying by travel mode and area. Montini et al. (2015) compared the travel diaries generated from smartphones and dedicated GPS devices but with a focus on the performances of sampling frequency, route and activities detection. As claimed by Schipperijn et al. (2014), mobile objects in free-living studies are likely to move dynamically. It is therefore vital to know the dynamic accuracy for various travel modes in changing surroundings. However, Schipperijn et al. (2014) only studied the influence on positional accuracy by changing the sampling frequency of the GPS receiver but neglecting other factors possibly affecting the accuracy.

To conclude, despite the increasing popularity of GPS in active living research, missing data and errors are still the main challenges for GPS studies (Shen and Stopher, 2014). The reliability of current GPS receivers employing different configurations and how they are affected by a variety of conditions for tracking various types of vehicles on real road networks is limited.

3. EXPERIMENTAL DESIGN AND DATA COLLECTION

Vehicles are restricted by an underlying road network when travelling, various transportation modes are therefore necessary in representing common users travelling on different levels of a road network (c.f. Schipperijn et al. 2014). To examine how well GPS tracking data of vehicles matches an actual route travelled, we therefore consider bicycle, car, and bus being the dominating modes in private transportations; the mode of pedestrian is omitted because bicycles travel on the same level of a road network. In the experiment, the vehicles travel on pre-set routes of known geographical position and elevation with speeds decided in advance. Their mobility is being tracked simultaneously by the GPS receivers when they are travelling.

For the experiments, a standard and integrated GPS receiver that could be broadly used in different vehicles under various circumstances is preferable. Other important features in selecting the receiver are that the receiver is user friendly, easy to operate and has a durable battery. GlobalSat BT-338X, Magellan SporTrak Pro and smart phone (Samsung Galaxy S5 Mini) were chosen after a survey in the product market. According to the manufacturer, with WAAS enabled, the GlobalSat BT-338X should provide a geographical positioning within an error of 5 meters and a measurement error of speed less than 0.4 km/h while the Magellan SporTrak Pro should have positioning error within 3 meters and a measurement error of speed less than 0.2 km/h. There is no specific claim of GPS accuracy for the smart phone, we take 10 meters for positioning error and 0.5 km/h for speed tracking error (Djuknic and Richton, 2001; Herrera et al., 2010). The manufacturers make no claims about the acuracy in the measurement of elevation for all three types pf receivers.

We set intensive sampling intervals of every 1 second, 5 seconds and 30 seconds. Note that the 30 seconds implies that some of the vehicles will easily travel more than 500 meters between recordings. Such setting implies a coarse assessment of the vehicle’s mobility pattern. Hence, the levels of sampling frequency represent both dense and sparse data to track position, time, date, speed, and elevation. For BT338-X we also consider both enable and disable data logging when distance is less than the selected radius 20 meters, while the SporTrak Pro and the phone do not equip with this setting.

We are in possession of 15 BT338-X, 6 SporTrak Pro and 6 Samsung Galaxy S5 Mini; each of them is assigned with a unique identifying number. The experiment is combined with two phases. The first-phase mainly focuses on the influence of the change of transportation modes and travel environment on the data reliability. The second phase focuses on the influence of different types of receivers on the data reliability, which is described in Section 4 below. Table 1 summarizes the main factors and corresponding levels of first phase in the experimental design. In the data transferring phase, the recordings for bicycle, car and bus were transferred separately, and a filed was added to fill in the information of error. The BT338-Xs are randomly assigned to one of three groups of equal size and the sampling interval is set to 1, 5, and 30 seconds respectively to track bicycle, car and bus in the first phase. In each group two randomly selected receivers have the data logging disabled if distance is less than the radius of 20 meters. The data collection of the bicycle and the car is undertaken in Borlänge in Sweden. The data collection of the bus is undertaken along the bus line 151 between Borlänge and its neighbouring city Falun.

Table 1: Experimental design (*first phase*) of collecting GPS tracking data

Phase-I (BT338-X)							
Sampling Interval		1s		5s		30s	
Receiver No.		3 29 37	36 42	4 14 39	40 77	9 32 74	24 72
Distance Restriction		Distance radius 0m	Distance radius20m	Distance radius 0m	Distance radius20m	Distance radius 0m	Distance radius20m
Bicycle & Car	15km/h						
	20km/h						
	30km/h						
	40km/h						
	45km/h						
	50km/h						
Car	60km/h						
	70km/h						
Bus	80-100km/h						

It was difficult to fix the speed of the bus in advance as would be preferable. The speed varied along the scheduled route due to the traffic and the behaviour of the drivers. For this reason, only a segment of the route, where the speed varied smoothly between 80 km/h and 100 km/h was used for GPS tracking. Meanwhile the bus trip was filmed. The bicycle followed a strict setting of speeds ranging from 15-50 km/h in six levels. For the car, 15-70 km/h were considered. Travel diaries were used to note unexpected changes in route, speed, and emergent situation. The cyclist and the driver of the car was the same throughout the experiment.

Data for the bicycle was collected at noon in order to reduce the risk of deviation from the protocol caused by other people on the route. Likewise, data collection for the car was undertaken between 3 and 4 in the afternoon to avoid peaks in the traffic. The data collection for the bus was conducted after 6 in the afternoon thereby minimizing the variation in speed due to people waiting at bus stops.

An accurate speedometer of the vehicles is essential for the experiment. We calibrated the car speedometer by riding the bicycle and driving the car side by side and recording the speeds simultaneously. The relationship between the recordings from the bicycle speedometer and the car speedometer by means of linear regression: *Car = 1.0385*Bike* with a strong correlation of 0.998. The speedometer of the car was adjusted accordingly in the experiment.

The routes for the experiment were chosen having the need for maintaining a constant speed. As for the car, we also needed to consider the speed limits of the roads while a bicycle may be ridden at any speed on a bicycle path.

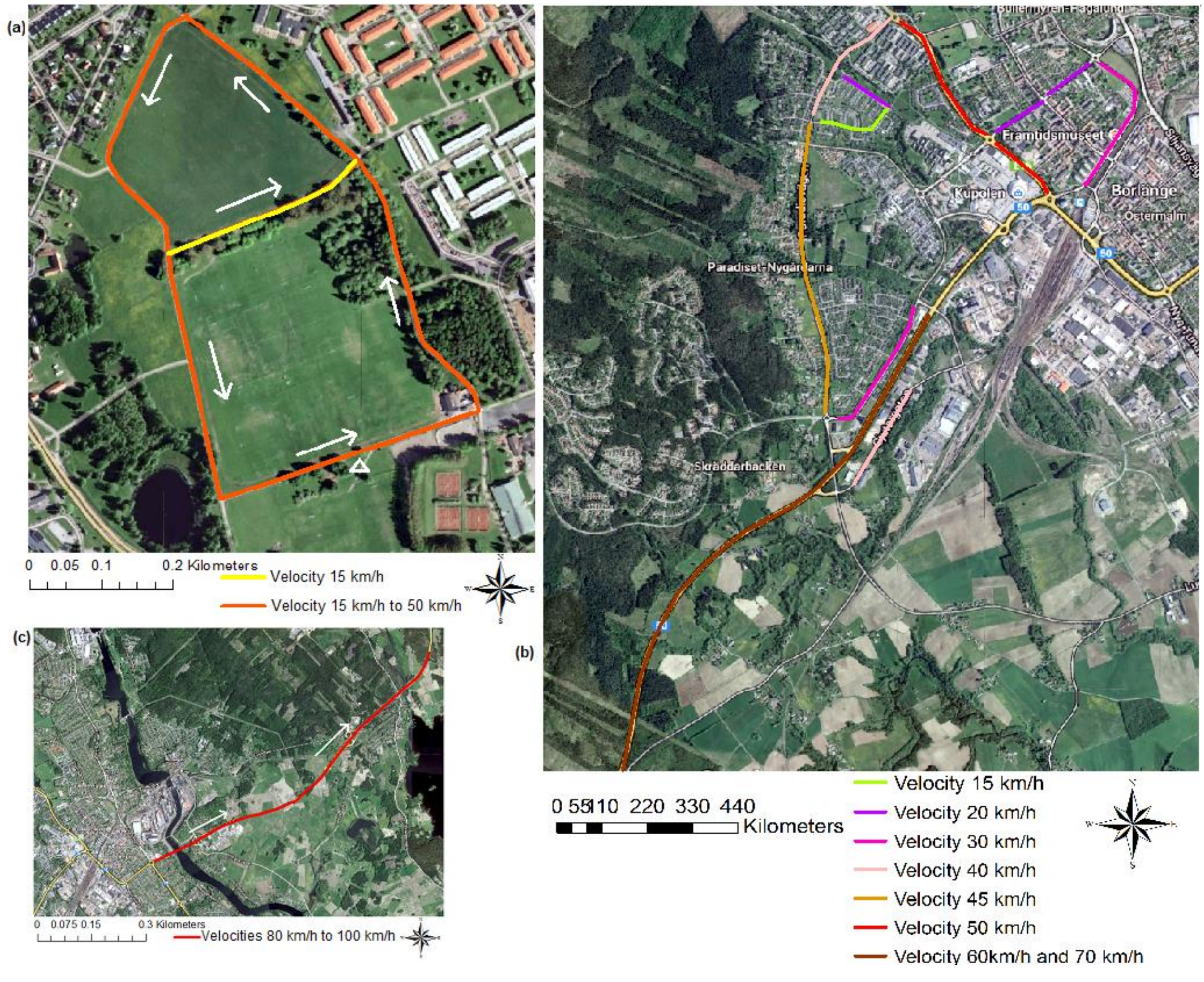

Figure 1: (a) The bicycle route; (b) The car route; (c) The bus route

Figure 1(a) depicts the route for the bicycle with arrows indicating the riding direction. The route is about 2 kilometres and it is a paved bicycle path. The route was used consecutively for each speed at a time. For instance, at the speed of 20 km/h there could be 360, 72, and 12 recordings per GPS receiver for the three levels of sampling frequency. The variation in elevation of the route is only a few meters.

Figure 1(b) depicts the route for the car. The route is segmented by colour representing the attained speed. The route was travelled 3 to 4 times on both directions to ensure sufficient recordings per cell. The range in elevation is 40 meters, maintaining a constant speed with a car in an ordinary traffic situation is of course difficult. The roundabouts and intersections in Figure 1(b) are identified in advance to highlight it is usually impossible to maintain the speed due to traffic rule and real conditions. The recordings pertaining to segments where the intended speed was not met according to the travel diary were removed. Figure 1(c) depicts the bus route. This route has a variation in elevation with a range of 37 meters.

The original GPS tracking data were kept into DataLogger files. The data were retrieved to a computer by using the software Global Sat Data Logger PC Utility directly after the experiment was completed. The receiver number 4 malfunctioned and did not record any data. The other 14 receivers worked well and we obtained in total 25,901 recordings of the car, 9,224 recordings of the bicycle, and 8,688 recordings of the bus.

4. EXPERIMENTAL RESULTS

4.1. *Geographical positioning*

The position and the trajectory of a car are restricted by the road network (Skog and Handel, 2009). The geographical positions of the mobile object are necessary to identify the objects' trajectory. In the experiment the trajectory of the vehicles is known by the road network and its digital representation. The concordance of the recordings and the road network is measured to be a statistic to assess the reliability of the geographical positioning obtained from the GPS receiver. Ideally the positional recornhdings should be on the underlying road network[3] given that the width of the driving road is 14-20 meters and 3.5 meters for the bicycle road.

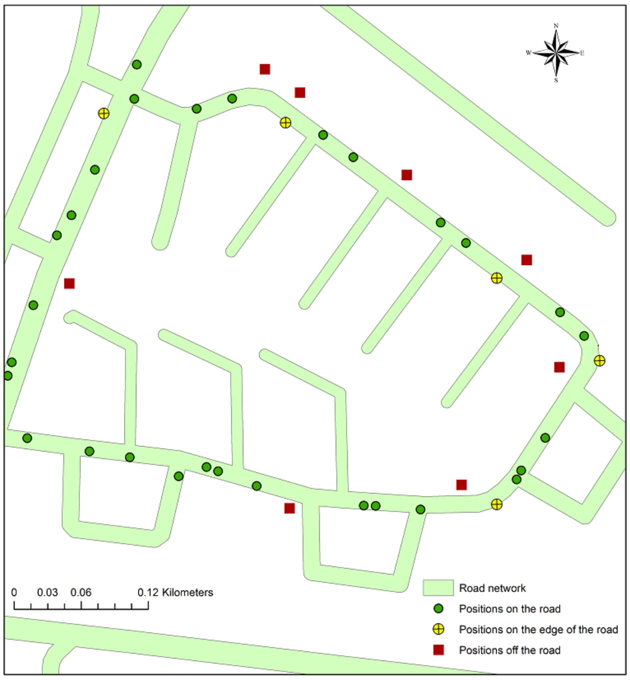

Figure 2: Example of positional recordings and the road network

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[3] The road network is provided by the National Road Data Base (NVDB) and is operated by the Swedish Transport Agency. The positional error of the road segments used in this study is within 0.2 meter.

Figure 2 shows an example of how the positions actually recorded on the car route. The green circles indicate the recordings that match the road network. The yellow circles indicate recordings on the edge of the road network are regarded as matching the road network well enough. The red squares indicate inaccurate recordings off the road network. In this example, 8 of the 42 recordings failed in giving an accurate position of the car, which we suspect how well the positional recordings match the road network. Figure 3 illustrates the empirical cumulative distribution of the positional error.

Given the width of the roads, almost all the recordings are expected to match the road network. However, people do not usually drive or ride right in the middle of the road, especially on two-lane roads. What's more, given the real travel circumstances with trees, buildings and other interference for GPS signals, the positional recording are not precisely on the roads. Figure 3 shows that more than 95% of positional recordings for the bus are accurate to be 0-meter error and the biggest error is 28.2 meters. The positioning of the car was accurate that around 80% to be 0-meter error while the biggest error is 158.4 meters. As for the bicycle, the biggest error is 54.8 meters; the recordings from 5-second and 5-second with 20-meter restriction frequently fail to identify its travel positions on the network while for the other settings, 90% are within 5-meter positional error whereas only 30% are with the 0-meter error.

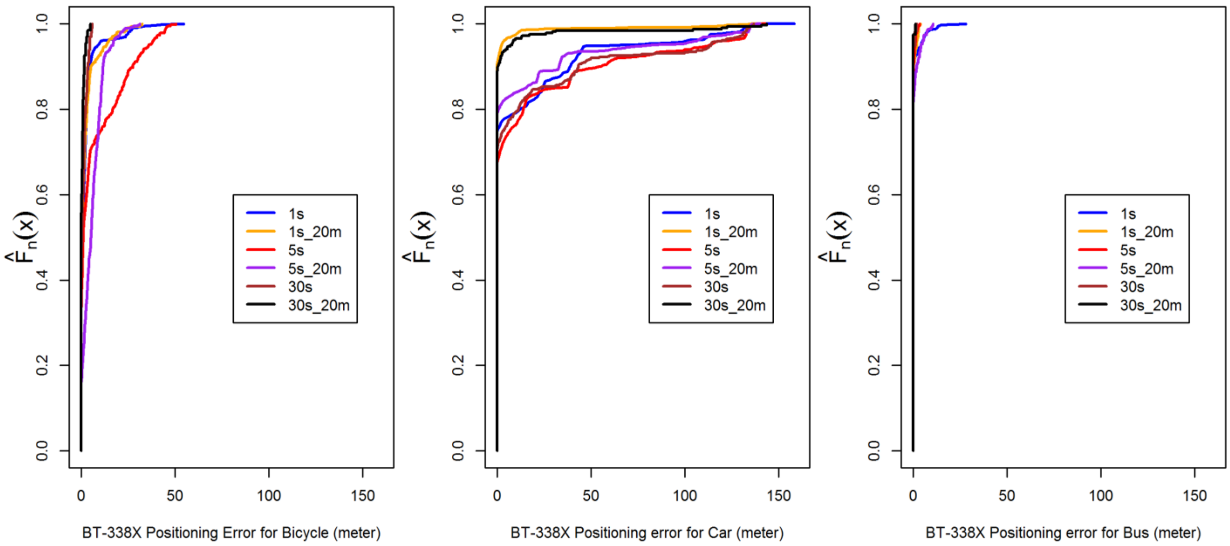

Figure 3: Empirical cumulative distribution of the positioning errors of BT-338X for bicycle, car and bus

As an overall finding drawing on Figure 3, there is no clear pattern emerging from the factors considered in the experiment. Possibly the longest sampling interval tends to lead to better positioning; the setting of the distance of restriction does not have obvious influence in positioning; the receivers generally give higher accuracy in positioning for the bus and the car but tends to have large variation on bicycle. However, we have noted a serial correlation of the recordings implying that an inaccurate recording is likely to be followed by another if the time interval is short. Especially, numerous inaccurate recordings from the first phase experiment are found in the three areas marked with the white circle and the two triangles depicted in Figure 4.

The circled area is nearby power lines located to the north and 200 meters to the east. The areas indicated by triangles have trees with a height of 8-10 meters. We speculated that the positional recordings of the bicycle were interfered by the surrounding environment. We also suspected that the single choice of one specific receiver is partial for the experiment; therefore in the secondary phase of the experiment, we randomly chose 6 BT338-X and added the 6 SporTrak Pro and 6 Samsung Galaxy S5 mini. The speeds 15km/h and 30 km/h and frequency 5s and 30s are chosen for the experiment on the bicycle route and the car route. Table 2 illustrates the factors and corresponding levels the second phase in the experimental design. Figure 4 depicts the two routes travelled by the bicycle; the red route coincides with the route used in the original experiment while the yellow route is a part of the car's route.

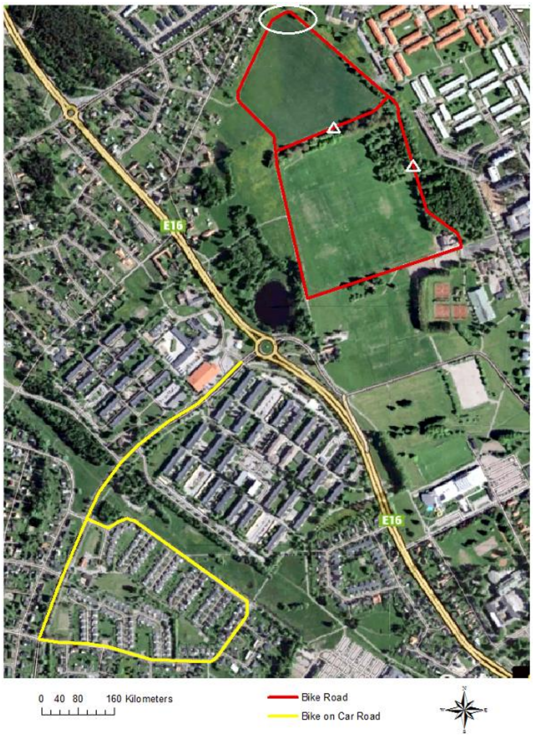

Figure 4: Bicycle and car routes in the secondary experiment

Table 2: Experimental design (*second phase*) of collecting GPS tracking data

Phase-II			
Sampling Interval		5s	30s
Receiver No.	BT338-X	1-6	1-6
	SporTrak Pro	7-12	7-12
	Samsung Galaxy S5 mini	13-18	13-18
Bicycle & Car Speed	15km/h		
	30km/h		

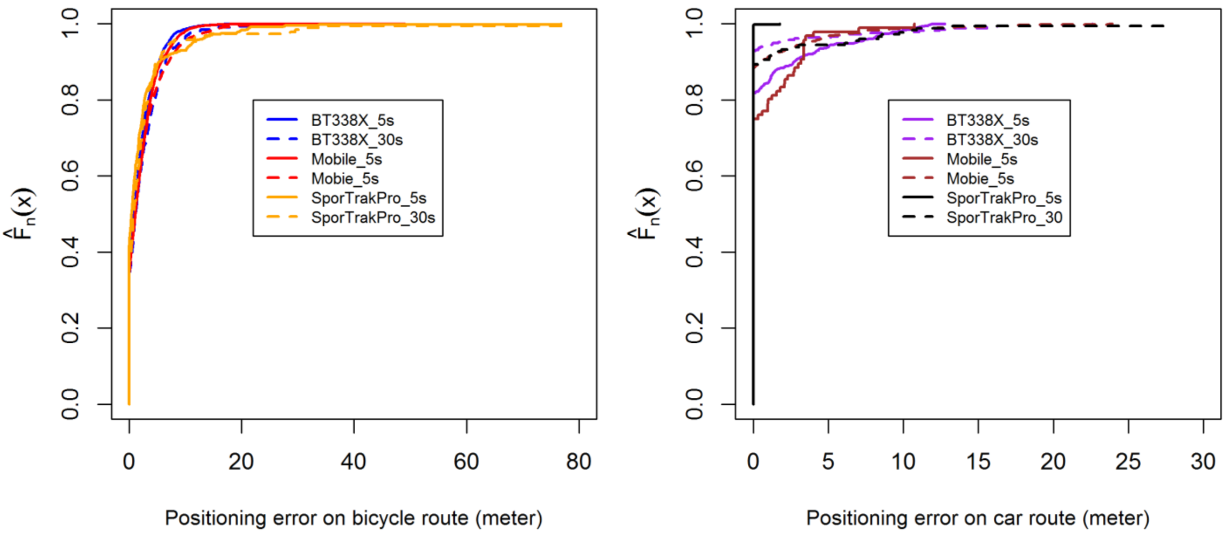

Figure 5: Empirical cumulative distribution of the positioning errors for the three types of receivers on bicycle and car route

Figure 5 gives the empirical cumulative distribution of the positional error for the three types of receivers on the bicycle and the car routes. Although the proportion of accurate recordings on the original bicycle route is higher and with smaller variation, it is still rather low comparing to the car route which is substantially accurate. The biggest error on car route is 27 meters while it is 78 meters on the bicycle route. The errors (≤5 meters) of three types of receivers differ but not big than 5% under the same route with same speed and settings. Most inaccurate recordings are identified that happened again at the three areas that are previously identified as problematic. This illustrates that the GPS receiver may generate (infrequent) errors due to the interferences with the surroundings such as trees and built-ups in a non-obvious way (Modsching et al., 2006).

4.2. *Estimating the speed*

It goes without saying that it is more difficult to estimate a changing speed than a constant speed. Drivers (and cyclists) need to adjust their speed in line with the traffic but also at intersections, roundabouts, tortuous locations (Jia et al., 2012) and traffic lights. This is also true in conducting an experiment of this kind. We used the travel diary of the car and the bicycle to delete recordings where the intended constant speeds were not possible to maintain. As for the bus, the films were used for deleting recordings where the speeds were not constant.

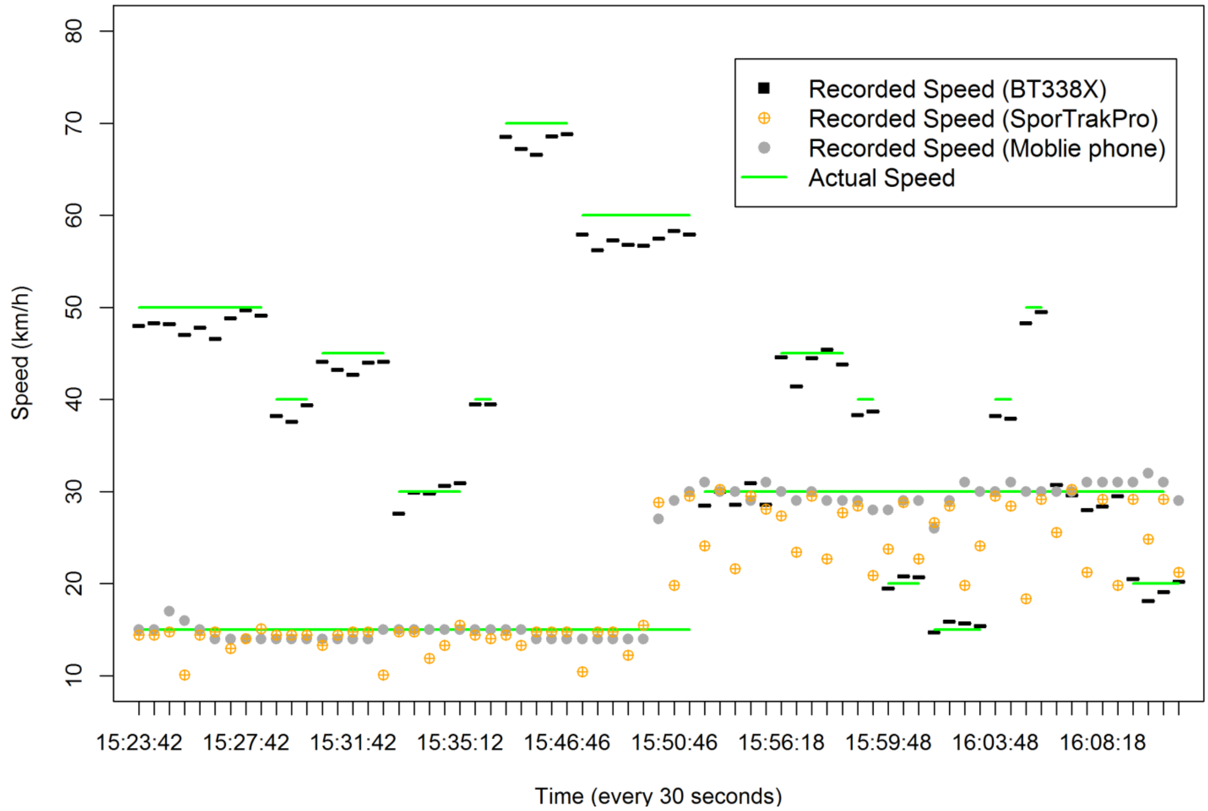

Figure 6: Recorded speed versus actual speed as measured by three types of GPS receivers

Figure 6 illustrates how the recorded speed of the car varies around the pre-set constant speed of a sample from tracking interval 30 seconds of all data of phase-I and phase-II. There is a tendency that the recorded speed is lower in general than the actual speed for all three types of receivers. For BT-338X, the errors are within 5km/h while the manufacturer claimed that the error is within 0.4 km/h. As for the smart phone, the errors are smaller to be within 3km/h; SporTrak Pro had the worst performance with the error to be -10km/h under the test speed 30km/h while the manufacturer claimed that the error is within 0.2 km/h. The speed recordings from SporTrak Pro also exhibited the biggest variation comparing to the other two types of receiver. The analysis of variance (ANOVA) was conducted to formally test for the factors that affect the performances of speed recordings. The response variable is the error between the recorded and the set speed in the experiment. The error increased with the speed. Table 3 shows the specific results. There was no significant difference for whether the distance restriction was on or off. The sampling frequency interval was related to the error but less significant. It's found that longer sampling interval was associated with a (marginal) increase in the error. The type of the travel route corresponding to the vehicle type significantly influences the accuracy of the speed recordings. There is significant different performance among the types of receivers. It was strongly significant suggesting that if the positional recording was inaccurate, there will be a greater underestimation of the speed.

Table 3: Analysis of variance table (a) Results from recordings of experiment phase-I; (b) Results from recordings of experiment phase-II

Analysis of Variance Table **(a)**
Response: Error

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Set_Speed	1	719.1	719.1	465.5412	< 2e-16 ***
Distance_Radius	1	2.4	2.4	1.5403	0.21459
Time_Frequency	2	7.1	3.6	2.3098	0.09932 .
On_Off_Road	1	119.7	119.7	77.5258	< 2e-16 ***
Vehicle_Type	2	6533.1	3266.5	2114.8093	< 2e-16 ***
Residuals	14346	22158.8	1.5		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Analysis of Variance Table **(b)**
Response: Error

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Set_Speed	1	714.3	714.35	225.8096	< 2.2e-16 ***
Receiver_Type	2	321.0	160.49	50.7323	< 2.2e-16 ***
Time_Frequency	1	16.3	16.26	5.1403	0.02341 *
On_Off_Road	1	157.9	157.88	49.9061	1.783e-12 ***
Route_Type	1	61.3	61.32	19.3838	1.086e-05 ***
Residuals	6421	20312.7	3.16		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

4.3. *Elevation*

Elevation is useful in providing information when two dimensional positioning is not sufficient to identify overlap points on roads with different heights. Moreover, elevation is also influential in travelling cost considering the time and energy use, it is necessary in route scheduling, and environment control. The accuracy of elevation are commonly expected to be poorer than the geographical position due to the requirement of satellites availability for signal strength in estimating elevation.

In order to check the accuracy in the recorded elevation, the geo-information of elevation in Borlänge from the national elevation database (NNH)[4] is referred for validation. Each position of the vehicle where a recorded elevation occurred is related to the nearest point in the actual elevation layer. The maximum distance between the recorded position and the actual elevation layer is 21 meters. This is an inconsequential approximation as the road network covered in the experiment does not contain any steep up- and down-hills.

The error in recorded elevation with respect to the actual elevation is large for all three types of receiver. No receiver showed substantially good measurement comparing to others. Most of the errors were within the range of -100 meters and 100 meters, but frequently the error exceeded 150 meters. Considering for instance that the bicycle path travelled in the experiment was essentially flat, and even for the car road the elevation change is within 40 meters, such a magnitude in error is enormous and peculiar given error in GPS elevation readings is generally twice as high as horizontal error (Noronha & Goodchild, 2000) and even better (Zandbergen, P. 2009).

5. CONCLUDING DISCUSSION

Current studies have rarely focused on the problem of examining the reliability of dynamic GPS data in the validation phase after data transfer but before further analysis, especially have neglected influences from the variation of road network. This paper focuses on evaluating the reliability of GPS-based transportation data from three different types of portable GPS receivers (including the commonly-used smart phone). The evaluation focuses

[4]The elevation data is provided by Sweden's Mapping, Cadastral and Land Registration Authority (www.lantmateriet.se). The elevation model is made by laser scanning and has an average elevation error of 0.1 meter and 0.4 meter in the plane.

on data of geographical position, speed, and elevation by tracking vehicles in a complex road network with varying transportation modes, environmental conditions and collection settings in real settings. The experimental method can be reproduced, reorganized and reformed into different combinations according to the applications.

The GPS tracking data identified the actual positions of the vehicles fairly successfully. The three types of receivers performed with not big than 5% differences of accuracy on the same route with same speed and settings. The surroundings of the experiment had no obviously interfering attributes like high built-ups, forests, magnetic fields, and so on; the partially poor identification of the bicycle's positions by trees and in the vicinity of magnetic fields shows however that the positional error of the GPS is highly vulnerable to the surroundings. Overall, the positioning accuracy meets the requirement of applications like routing, mobility pattern recognition, destination imputation and other location based services.

The tracked instantaneous speeds are quite accurate with a tendency of underestimation. The error is monotonically increasing with the speed and the inaccurate position recording. It should however be noted that we did not study the accuracy regarding acceleration and deceleration which are common phenomena in ordinary traffic. More overlapping speeds for different transportation modes should be tested as well. Concerning the recorded elevations in the tracking data, we found it to be highly inaccurate and we suggest disregarding this parameter in practical use until further investigations.

The reliability seems to be unrelated to the sampling frequency. Of course, intensive positional recordings provide more details regarding the mobility pattern. However, it comes at the expense of more aggressive data rendering communication, storage, data processing, data mining, and data analysis. Balancing between these aspects is necessarily specific to the domain of application.

There is drawback of GPS receivers due to a short effective lifespan of the battery (Ryan et al., 2004; Stopher and Speisser, 2011). The data collection part of the experiment in this paper lasted at the most for three hours; the duration of the receivers was not a concern here as the operational time for the receiver is about 11 hours after being fully charged and in continuous mode. However, the lifespan may be a costly drawback in full-scale applications especially for the smart phone (Bierlaire et al., 2013).

Finally, this study examined three specific standard GPS receivers. It would be interesting in the future to conduct further analyses including other types of GPS receiver on larger sample sizes, longer recording periods and more possible environment settings by using the experimental method outlined in this study. What's more, the ground-truth data used for evaluation are inaccurate in a limited tolerance, the choice of the "true value" and the confidence assigned to them has become a general issue to be considered in evaluating the reliability of GPS-tracking data.

References

[1] Bierlaire, M., Chen, J., & Newman, J. (2013). A probabilistic map matching method for smartphone GPS data. Transportation Research Part C: Emerging Technologies, 26, 78-98.

[2] Chen, C., Gong, H., Lawson, C., & Bialostozky, E. (2010). Evaluating the feasibility of a passive travel survey collection in a complex urban environment: Lessons learned from the New York City case study. Transportation Research Part A: Policy and Practice, 44(10), 830-840.

[3] Chang, Y. J., Paruthi, G., & Newman, M. W. (2015, September). Challenges in using wearable cameras and phone logs to generate ground truth of transportation activities. In Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers (pp. 1361-1366). ACM.

[4] Djuknic, G. M., & Richton, R. E. (2001). Geolocation and assisted GPS.Computer, 34(2), 123-125.

[5] Herrera, J. C., Work, D. B., Herring, R., Ban, X. J., Jacobson, Q., & Bayen, A. M. (2010). Evaluation of traffic data obtained via GPS-enabled mobile phones: The Mobile Century field experiment. Transportation Research Part C: Emerging Technologies, 18(4), 568-583.

[6] Huang, D. (2013). Evidential problems with GPS accuracy: device testing (Doctoral dissertation, Auckland University of Technology).

[7] Jia, T., Carling, K. & Håkansson, J. (2013). Trips and their CO2 emissions to and from a shopping centre. Journal of Transport Geography, 33, 135-145.

[8] Kamboj, S., & Dahiya, R. (2011). Application of GPS for Sag Measurement of Overhead Power Transmission Line. Intern. J. on Electrical Engineering and Informatics, 3(3), 268-277.

[9] Leduc, G. (2008). Road traffic data: Collection methods and applications. Working Papers on Energy, Transport and Climate Change, 1, 55.

[10] Li, X., Ge, M., Dai, X., Ren, X., Fritsche, M., Wickert, J., & Schuh, H. (2015). Accuracy and reliability of multi-GNSS real-time precise positioning: GPS, GLONASS, BeiDou, and Galileo. Journal of Geodesy, 89(6), 607-635.

[11] Lindsey, G. et al. (2013). Feasibility of Using GPS to Track Bicycle Lane Positioning. Technical report CTS 13-16. Intelligent Transportation Systems Institute, Center for Transportation Studies, University of Minnesota.

[12] Marchal, F., Hackney, J., & Axhausen, K. W. (2005). Efficient map matching of large global positioning system data sets: Tests on speed-monitoring experiment in Zürich. Transportation Research Record: Journal of the Transportation Research Board, 1935(1), 93-100.

[13] Meng, Y., Li, Z., Chen, W., & Chen, Y. (2004, December). Reliability and Integrity Issues for Vehicle positioning Systems. In the 2004 International Symposium on GNSS/GPS, Sydney, Australia.

[14] Modsching M., Kramer R., & ten Hagen K. (2006, March). Field trial on GPS Accuracy in a medium size city: The influence of built-up. In 3rd Workshop on Positioning, Navigation and Communication , 209-218.

[15] Montini, L., Prost, S., Schrammel, J., Rieser-Schüssler, N., & Axhausen, K. W. (2015). Comparison of travel diaries generated from smartphone data and dedicated GPS devices. Transportation Research Procedia, 11, 227-241.

[16] Murakami, E., & Wagner, D. P. (1999). Can using global positioning system (GPS) improve trip reporting? Transportation research part c: emerging technologies, 7(2), 149-165.

[17] Noronha, V., & Goodchild, M. F. (2000). Map accuracy and location expression in transportation–reality and prospects. Transportation Research Part C: Emerging Technologies, 8(1), 53-69

[18] Quiroga, C. A., & Bullock, D. (1999). Travel time information using global positioning system and dynamic segmentation techniques. Transportation Research Record: Journal of the Transportation Research Board, 1660(1), 48-57.

[19] Quddus, M. A., Ochieng, W. Y., & Noland, R. B. (2007). Current map-matching algorithms for transport applications: State-of-the art and future research directions. Transportation Research Part C: Emerging Technologies, 15(5), 312-328.

[20] Ryan, P. G., Petersen, S. L., Peters, G., & Grémillet, D. (2004). GPS tracking a marine predator: the effects of precision, resolution and sampling rate on foraging tracks of African Penguins. Marine Biology, 145(2), 215-223.

[21] Shen, L., & Stopher, P. R. (2014). Review of GPS travel survey and GPS data-processing methods. Transport Reviews, 34(3), 316-334.

[22] Schipperijn, J., Kerr, J., Duncan, S., Madsen, T., Klinker, C. D., & Troelsen, J. (2014). Dynamic accuracy of GPS receivers for use in health research: a novel method to assess GPS accuracy in real-world settings. Frontiers in public health, 2.

[23] Schönfelder, S. & Antille, N. (2002). Exploring the Potentials of Automatically Collected GPS Data for Travel Behaviour Analysis: A Swedish Data Source. ETH, Eidgenössische Technische Hochschule Zürich, Institut für Verkehrsplanung, Transporttechnik, Strassen-und Eisenbahnbau IVT.

[24] Schüssler, N. and Axhausen, K.W. (2009a). Map-matching of GPS traces on high-resolution navigation networks using the Multiple Hypothesis Technique (MHT). Working Paper, 568, IVT, ETH Zurich.

[25] Schüssler, N. and Axhausen, K.W. (2009b). Processing GPS raw data without additional information. Transportation Research Record, 2105, pp. 28-36.

[26] Skog, I., & Handel, P. (2009). In-car positioning and navigation technologies—A survey. Intelligent Transportation Systems, IEEE Transactions, 10(1), 4-21.

[27] Shoval, N. (2008). Tracking technologies and urban analysis. Cities, 25(1), 21-28.

[28] Sun, Z., & Ban, X. J. (2013). Vehicle classification using GPS data. Transportation Research Part C: Emerging Technologies, 37, 102-117.

[29] Stopher, P., FitzGerald, C., & Xu, M. (2007). Assessing the accuracy of the Sydney Household Travel Survey with GPS. Transportation, 34(6), 723-741.

[30] Stopher, P. R., & Speisser, N. (2011). Evaluation of gps device properties for a possible use in future household travel surveys. In Transportation Research Board 90th Annual Meeting (No. 11-4271).

[31] Stopher, P., Greaves, S., & Shen, L. (2013, September). Comparing two processing routines for GPS traces—lessons learnt. In Proceedings of the 36th Australasian Transport Research Forum ATRF.

[32] Theiss, A., Yen, D. C., & Ku, C. Y. (2005). Global Positioning Systems: an analysis of applications, current development and future implementations. Computer Standards & Interfaces, 27(2), 89-100.

[33] Van der Spek S., Van Schaick J., De Bois P. & De Haan R. (2009). Sensing human activity: GPS tracking. Sensors, 9(4), 3033-3055.

[34] Zandbergen, P. A. (2009). Accuracy of iPhone locations: A comparison of assisted GPS, WiFi and cellular positioning. Transactions in GIS, 13(s1), 5-25

[35] Zheng, Y., Li, Q., Chen, Y., Xie, X., & Ma, W. Y. (2008, September). Understanding mobility based on GPS data. In Proceedings of the 10th international conference on Ubiquitous computing (pp. 312-321). ACM.

[36] Zito, R., d'Este, G., & Taylor, M. A. (1995). Global positioning systems in the time domain: How useful a tool for intelligent vehicle-highway systems? Transportation Research Part C: Emerging Technologies, 3(4), 193-209.

[37] Zumberge J. F., Heflin M. B., Jefferson D. C., Watkins M. M. & Webb F. H. (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks. Journal of Geophysical Research: Solid Earth (1978–2012), 102(B3), 5005-5017.

[38] Zhao, X., Carling, K., & Håkansson, J. (2014). Reliability of GPS based traffic data: an experimental evaluation. Working papers in transport, tourism, information technology and microdata analysis (2014:17), ISSN: 1650-5581, Dalarna University, Sweden.