9-1-2011

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Australasian Transport Research Forum 2011 Proceedings
28 - 30 September 2011, Adelaide, Australia
Publication website: http://www.patrec.org/atrf.aspx

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Abstract

Public transport is often deemed to be a solution to reduce traffic congestion problems. A positive perception of this service is vital to getting more and more people to use this efficient mode of transportation. Accurate and reliable positioning systems, also known as Automatic Vehicle Location systems, play a major role in enabling fleet management systems (FMS) to achieve better planning and scheduling outcomes and hence provide a positive perception of the service.

New positioning technologies are continuously being developed, due to ongoing demand of fleet management systems to provide better public transport services. However more research is required to determine what are the real positioning needs for different kinds of public transportation services.

The aim of this paper is to study positioning needs for fixed route bus services and demand responsive transport systems by analysing GPS accuracy inside and outside city canyons to achieve a better quality of service.

1. Introduction

The most common public transportation systems are represented by trains, trams, subways and buses. While trains, trams and subways are all rail based solutions common in most metropolitan areas, this research work is focused on road based public transport, such as buses, since the issues to be addressed around the requirements of accurate and reliable positioning are different.

For example, building a railway requires a large capital investment in time and money to setup the infrastructure required (Railway Technical 2011). Implementing a signpost/odometer positioning solution requires a relatively modest budget in comparison (Transportation Research Board 1997, p. 20). Also, the environment is closed ie the trains have right of way, and easily controllable. The number of lines to be established is planned; the number of stops are also planned in advance; commuting points can be setup and lines can be designed in such a way that there are no or only minimal interferences during running. No other type of vehicle has access to the infrastructure. All these conditions enable having an almost complete control on the parameters that might affect the service.

From a positioning perspective, railways run often completely or at least partially underground, with no clear lines of sight for GPS satellites, and dim environments. Hence signposts and odometers have proven to be the historical natural choice for this task.

Public buses (and trams, to a lesser extent), on the other hand, have a whole different set of issues, and operate in a less constrained environment. They run on roads that must be shared with other vehicles, pedestrians and sometimes even animals. As a result numerous variables can affect the quality of service.

Bus services rely on the idea of minimizing additional infrastructure costs while aiming for better services in a local area by providing more stops when compared to railways or

underground metro. For example the Metropolitan Transportation Authority in New York City rely on 12500 bus stops, compared to only 468 railway stations (MTA 2009).

The number of commuters on public transport services also affects vehicle priority. While it is commonly accepted that public buses have priority over private cars, they need in turn to give precedence to trains, near railway crossings. Therefore the set of challenges to be addressed is bigger and more complex. With this complexity comes the necessity to use most appropriate positioning technology. Most public buses run on fixed routes, with a fixed timetable (Daduna, Branco & Paixão 1995). So the interaction of public and private transport services is a key element of providing an overall efficient transport system.

Complicating this even further are the differing requirements for position accuracy and reliability of various public transport systems for example demand responsive transport (DRT) has a greater requirement to know where the vehicle is in real time so that it can be efficiently rescheduled to meet new passenger demands as they occur (Radbone et al , 1994). This paper will evaluate the issues associated with the provision of accurate and reliable positioning information for fixed route public transport, then go on to assess how these issues affect the positioning requirements of new types of DRT..

2. Fixed Route Public Transport

When using fixed route public transport, the timetable is generally planned in advance to provide the best level of service given the most typical conditions. Working days, weekends and holidays, are addressed separately, and tailored to the expected user demand.

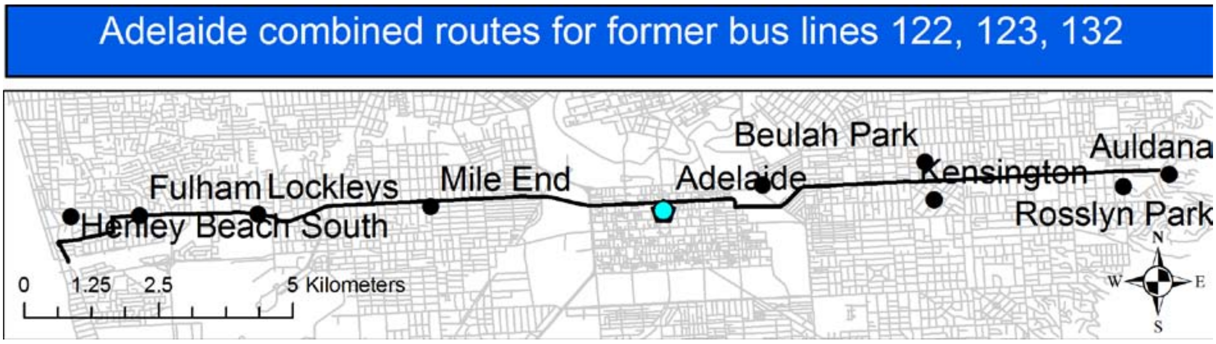
Expected trip speed is also influenced and planned in advance to consider the time of day when the bus service is running. For example, in the AM peak most of the commuters will try to reach destinations such as work places or schools. In the same way, during the PM peak is when commuters are expected to go back home. While during the inter-peak periods peoples travel choices are varied and are more likely to include social and recreational trips.

A commuter will be more tolerant to wait for a bus one or two minutes more, rather than miss a bus and wait for the next service because the expected bus was ahead in its schedule (van Oort 2008). This put additional requirements on bus driver to make decisions about when to depart a stop. For example if the bus arrives some minutes earlier to a bus stop but traffic jams are to be expected later, the bus driver cannot leave the bus stop earlier to balance the probable delay. Advanced driver and passenger information systems, public transport priority traffic systems have as their core positioning systems, that are able to reliably and accurately provide the position and timing information of a vehicle. This base data can then be further processed to provide drivers and passengers with expected arrival and departure times based on the current real time conditions. This paper will now go on to explore the positioning needs of public transport, using case studies and in-depth analysis of positioning data.

2.1 Methodology

In 2003 Adelaide Metro (Turner 2003) conducted a smart bus stop trial using GPS on buses using routes extending from Henley Beach Road (in the Western suburbs of Adelaide) to The Parade (in the Eastern Suburbs of Adelaide), effectively traversing the whole Greater Adelaide from east to west, as shown in Figure 1. The system was in fact designed to provide real-time departure count-down information at the selected bus stops.

Figure 1. Henley Beach Road (left) to The Parade (right) route, crossing Greater Adelaide



As part of the Adelaide Metro trial, GPS data together with in-vehicle odometer readings were collected. Logs spans were over several days for several bus routes, including routes 122, 123 and 132. Only a portion of this data, related to a random day, was considered for the experiments related to this paper.

Part of the information was stored in human readable log text files (see Figure 2), with buses sending their position every 15 seconds to a centralised system.

Figure 2. Fragment of the human readable log text file reporting the bus information

```
2003-07-16 17:40:23,611 (Fleet:1775)-(Shift:3755)-(Route:132)-(Dist: 8439)-(Lat: 3492471)-
(Lng: 13858578)

2003-07-16 17:40:23,611 (PathId:20)-(RouteDBId:10)-(TripDBId: 899)-(State:2)-(Alarms:0x0) -
(Cut Out: false) - (Sch:1)-(Time:17:40:21) - ( Odo:225532)

2003-07-16 17:40:23,611
,1775,3755,132,8439,20,3492471,13858578,10,899,2,false,1,36,1000,0x0,17:40:21,225532
```

For this experiment, these files were parsed to extract positioning data, both coming from the GPS and the in-vehicle odometer. Extracted data have been then imported in ArcGIS, using the appropriate Geographic Coordinate System (in this case WGS-84 converted to GDA 1994, used for the street map). Bus routes overlaid on the road network has enabled the identification of corresponding street segments on RoadNet data licensed by MapData Services Pty Ltd (MapData Services 2011).

A python script based on ArcGIS geoprocessing scripting layer was coded to correlate bus positioning data with the road network. GPS accuracy has been estimated by computing the distance of the GPS signalled location from the route. In this case, point to segment distances measures have been evaluated to associate every logged position with the nearest street segment on the route.

The logged data have enabled, the analysis of each bus individually, using fleet, shift and trip identification numbers. Statistics on positioning accuracy in the Adelaide CBD and other suburbs crossed by participating buses have then been extracted using Microsoft Excel's Analysis Toolpak. However, in the absence of a proper ground truth, accuracy measures extrapolated in this study should be considered only a reasonable estimate for three reasons.

Because odometers were affected by noise, this rendered the recording useless as an additional strategy to validate GPS accuracy and have not been further considered..The road network description, while reporting if a road or street is two-ways or one-way, does not provide information about the number of lanes on each street segment. Moreover, each coded RoadNet street segment shows only the centreline of the street. In Adelaide, where streets with multiple lanes are frequent, the uncertainty introduced by the lack of the information regarding which lane the bus was in during a run must be considered even in the presence of accurate positioning.

Positioning errors, given the method (point to segment distance) employed, can account only for the inaccuracy made on the axis perpendicular to the direction of the street. However,

since GPS errors are greater on the vertical axis but similar on the whole horizontal plane (Misra, Burke & Pratt 1999), the accuracy measured on the axis perpendicular to the direction of travel can be considered a valid approximation on the error made in the direction of travel. The frequency and distribution of these error will be a key consideration in quantifying the accuracy and reliability of the GPS position system used.

2.2 Results analysis

Bus routes 122, 123 and 132, running through bus stops involved in the pilot program for real-time count-down information system, were considered in this analysis.

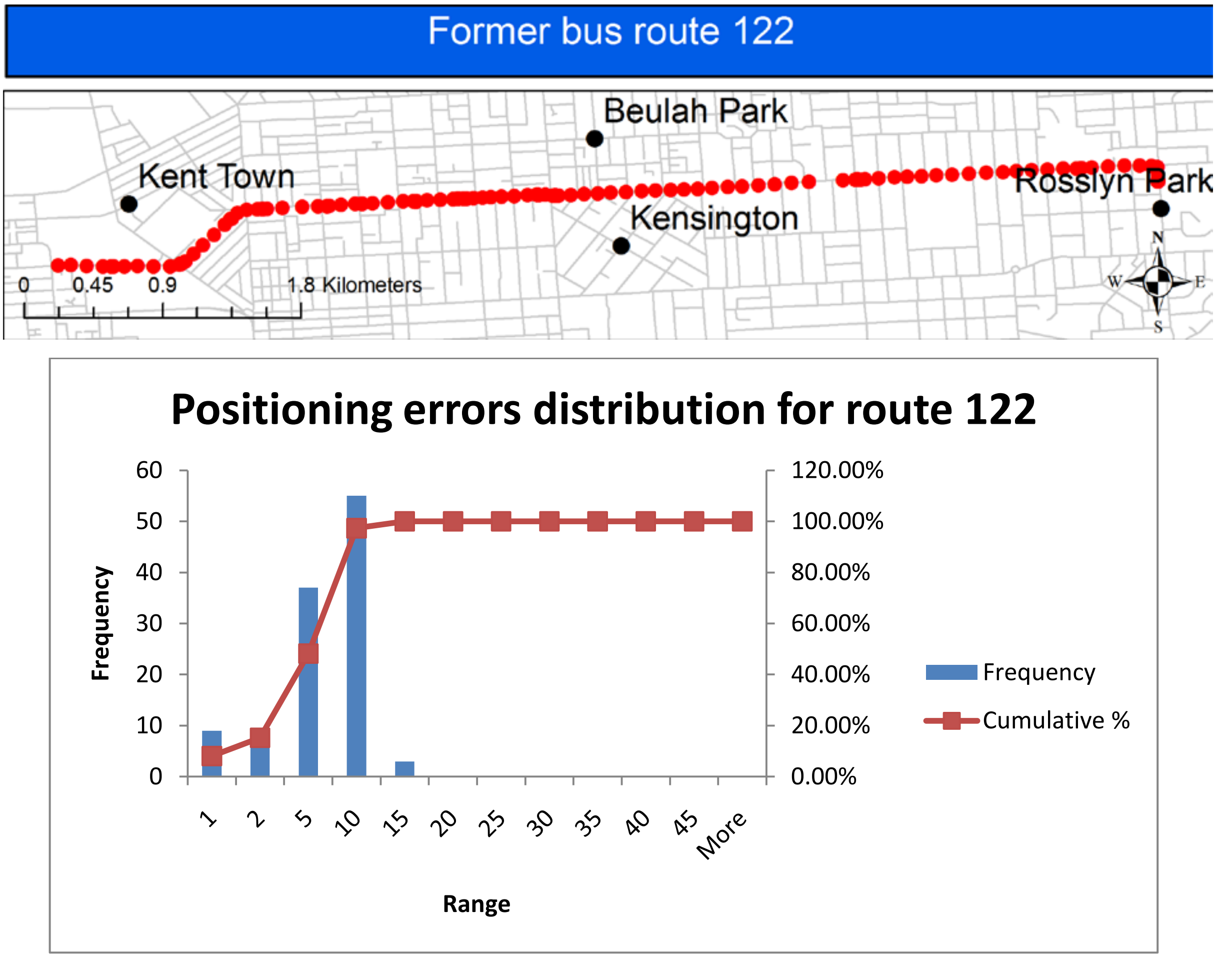
While data logs showed bus route 132 spanning the whole path from Henley Beach Road to The Parade, bus route 122 was found to run only on The Parade segment (see Figure 3), and bus route 123, starting from The Parade, crossed the Adelaide CBD, all the way to Mile End.

For the bus routes entering the Adelaide city business district, two separate statistics were calculated, inside CBD and outside. Overall data predictably showed the largest GPS accuracy errors in the CBD, where most of the tall buildings in Adelaide are concentrated.

Bus route 122, shown in Figure 3, ran through The Parade road. This extends for about 5 km east of Adelaide, entering the city through Bartels Road, connecting Adelaide to Kent Town. Overall, it proved to be the route showing the smallest error.

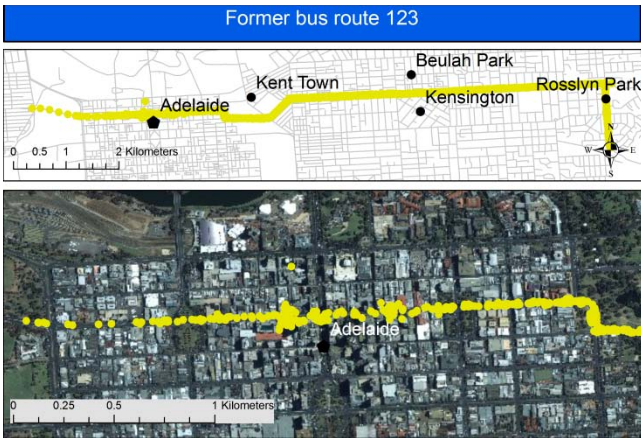
GPS accuracy on this road was consistently under ten metres for 97% of the time. Considering that the accuracy was measured against the centreline of a two-ways road, with two lanes in the average for each direction. GPS proves to be an affordable and reliable positioning solution on road segments where there is a clear line of sight to the GPS satellites, although not capable of guaranteeing sub-metre accuracy.

Figure 3. Accuracy results for bus route 122



GPS positioning accuracy and reliability is degraded in the inner city canyons as shown by buses servicing the route 123, crossing Adelaide CBD through Grenfell Street and Currie Street. Figure 4, 5 and 6 show the accuracy on this extended path.

Figure 4. Route 123 weak spots



Bus Route 123 and CBD detail

Weak spots for GPS positioning, near Westpac building (top) and near Dacosta Arcade (bottom)

Figure 5. Positioning errors in Adelaide CBD for route 132

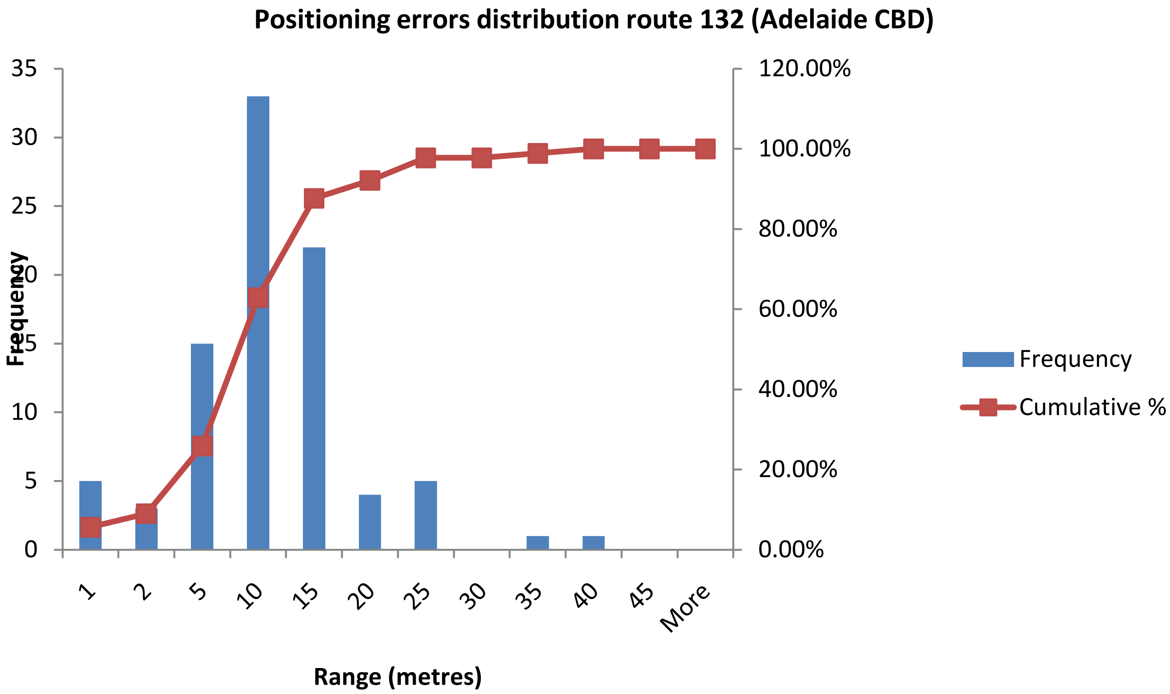
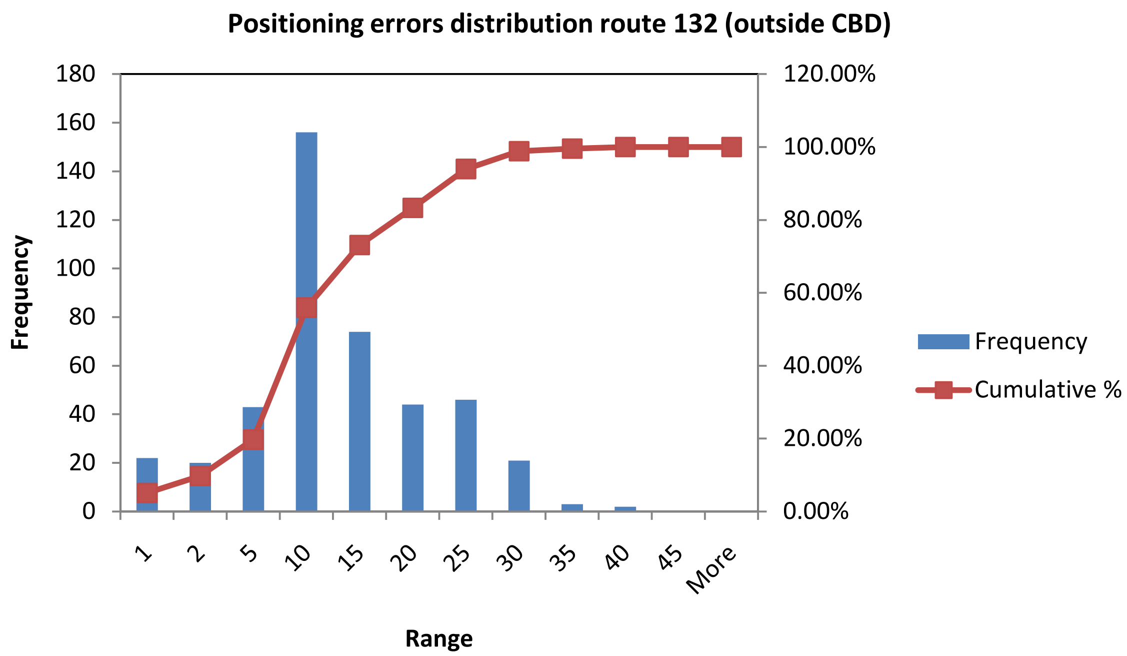
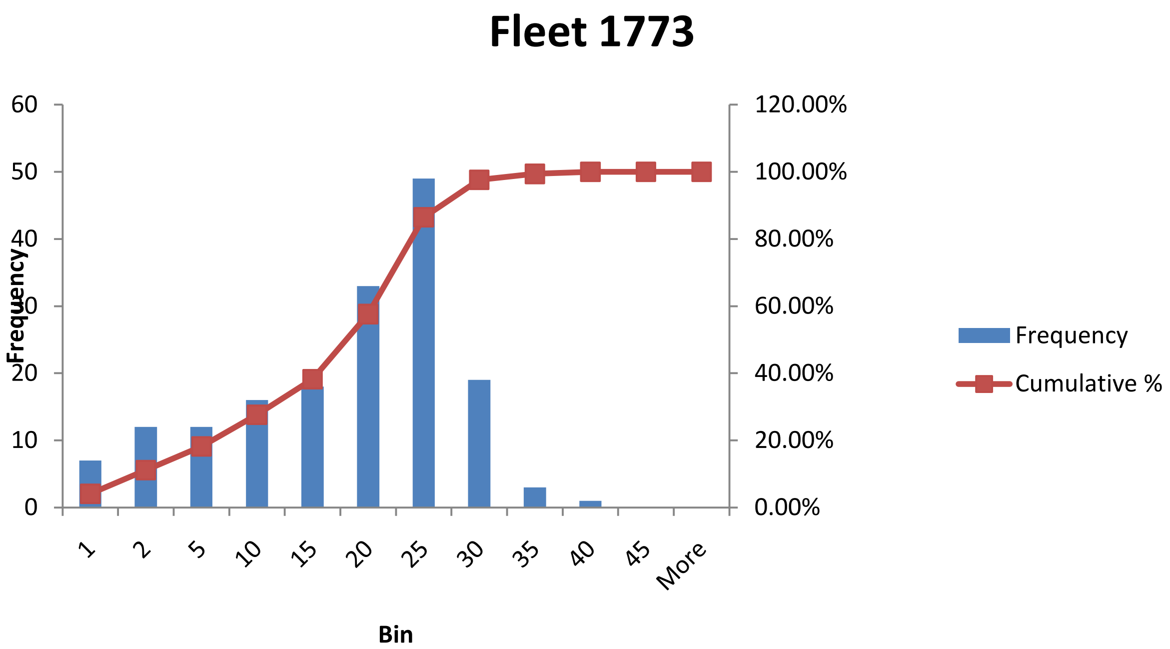


Figure 6. Positioning errors outside Adelaide CBD for route 132



Multipath problems were frequent near WestPac building and Dacosta Arcade. When comparing CBD performance with performance on eastern suburbs serviced by bus route 123, almost 25% of the time GPS errors were higher than ten metres (Figure 5), when compared to a smaller 10% on the suburbs serviced also by route 122 (Figure 3). On the other hand, it should be considered that both Grenfell Street and Currie Street have a higher number of lanes (three) in both directions most of the time.

Figure 7. Positioning accuracy for bus fleet 1773



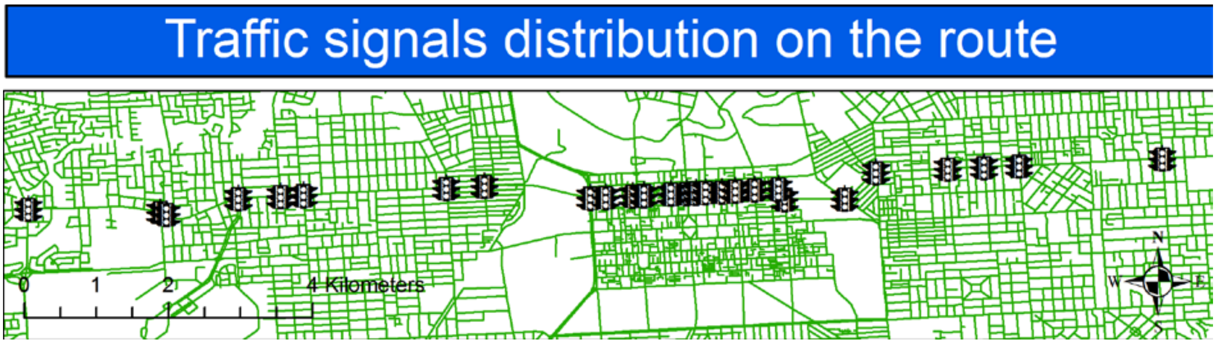
Geographic analysis using ArcGIS, Google Maps and Google Earth revealed inaccuracy spikes in unexpected spots. After further investigation, the most important anomaly source was found in only one particular bus, its identification number is: fleet 1773, whose performance is shown in figure 7, while other buses although reporting variable degrees of accuracy, showed a behaviour more in line with the theoretical GPS response. It can be concluded that that GPS performance in Adelaide CBD and on outer suburbs is different. In residential suburbs performance is in the same range expected from a theoretical point of view ie ±15m 95% of the time, however as soon as the receiver is within a "urban canyon", that is near high rise buildings, the accuracy and reliability degrades. In this case, more than 20% of the time, accuracy errors larger than 15 m occur, and this error can reach up to 40 metres in the Adelaide analysed.

While these errors have been estimated on the direction perpendicular to the road followed, they are for symmetry also valid for the direction of travel (Misra, Burke & Pratt 1999). How then can this kind of positioning error affect the reliability of bus services?

To answer to this question, it is necessary to relate the accuracy to the road traffic conditions that a bus can find on its route. An approach which can be evaluated is to consider the traffic control signals that a bus meets on the route it is travelling on.

Figure 8 shows all the intersections where traffic signals are located among the path from Henley Beach Rd to The Parade, with Adelaide central business district (CBD) in the middle of the picture. In the CBD the number of signalled intersection is almost half of the total count from Henley Beach Rd (west of the city) to The Parade (east of the CBD). That is, while the average distance between two consecutive traffic lights in the suburbs is about 816 m, inside the city the bus will usually encounter a new signalled intersection every 200 m.

Figure 8. Traffic signals on the route from Henley Beach (left) to The Parade (right)



If in the analysis we consider, based on traffic signalling data provided by the Department of Transport, Engineering and Transport[1] (DTEI), that the cycle time of signalised intersections in Adelaide ranges between two to three minutes and presuming, given that the speed limit within the Adelaide CBD is 50 km/h, that there is an average speed of approximately 30 to 40 km/h in the CBD[2], the connection between precise positioning and time adherence starts to emerge. One of the solutions which are being used in some cities to control time adherence is to use bus priority on strategic bus corridors, like the Public transport information and priority system (PTIPS) system being tested in Sydney by the Roads and Traffic Authority of New South Wales (Jarjees & Mehaffey 2008). However the system is dependent on getting reliable positioning and timing information from the buses, the two key pieces of information are, 1. When the bus is expected to cross the intersection, 2. If that particular bus is in need of bus priority due to the degree of late running it is experiencing in real time.

Relying only on standard GPS performance might not be sufficient in a CBD situation. As the analysis above has shown drifts of 40m can locate the bus: on the wrong side of the intersection, and or on the wrong road link, thereby not allowing PTIPS to properly allocate the bus priority. To properly address the challenge, better positioning can be provided both by using different sensors and by other means. In the first case, a GPS/INS solution is recommended. While inexpensive GPS/INS units use noisy MEMS gyroscopes and accelerometers, their performance is still acceptable to provide a level of accuracy that matches what is required to help buses to keep time adherence. Another possibility is to address the issue by other means. For example the bus driver can explicitly ask for priority when it departs from the last bus stop before the signalled intersection.

3 Demand Responsive Transit

Demand Responsive Transport (DRT) is a form of public transport that tries to address user needs by arranging run schedules dynamically in real time on flexible routes (Schweiger, Kihl & Labell 1994, pp. xvi). The idea is to provide a service that is a blend between a taxi service and a fixed route bus service. DRT services are usually run in rural areas, where demand is still too low to justify fixed route services but where there is interest in providing public transport services to the local community.

Small to medium fleet sizes are usually involved. Positioning proves very important in DRT services. Since DRT services allocate resources (buses) dynamically, allocation algorithms rely on the position and the current path planning of each vehicle in the fleet. In order to

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[1] For more information relating to Traffic Signals in Adelaide, contact DTEI via their web page http://www.transport.sa.gov.au.

[2] This is based on the assumption relating to the movement of vehicles between intersections with light-medium traffic conditions. Start-stop and queue dispersals have an effect on the time it takes to travel through the chosen investigation path. The next step is to investigate the actual average speed through this section of road.

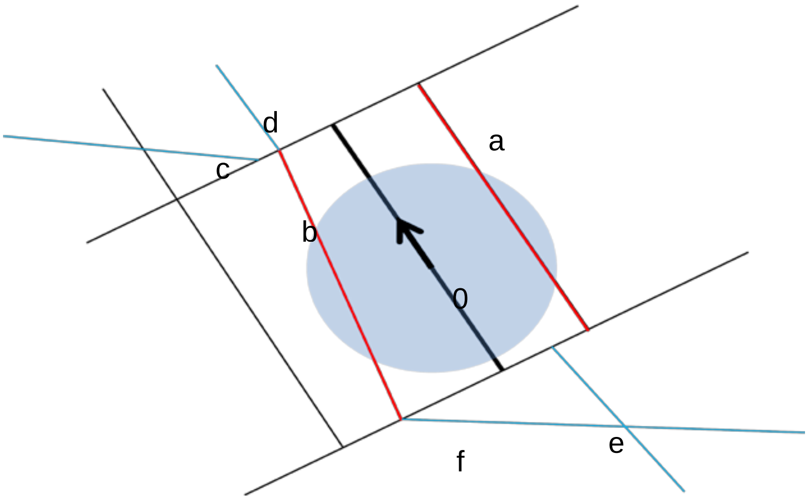
study the positioning needs on DRT services the methodology outlined in the next section builds on the analysis done on GPS accuracy obtained inside CBD and in suburbs, as reported in the previous study for fixed route bus services.

3.1 Methodology

To evaluate the impact of positioning in demand responsive transport services two affected parameters are considered: (1) effects of accurate or inaccurate positioning for the bus driver and (2) effects of inaccurate positioning on fleet management systems (FMS) for the correct handling of real-time bookings. The first effect is concerned with the consequences that inaccurate positioning can have at the driver level. At the same time, inaccurate positioning can have consequences for the FMS in the optimal allocation of resources.

In particular the study is concerned with the affect of positioning in the identification of the road link the vehicle is on, and how inaccuracies can influence it, as summarised in figure 9.

Figure 9. Effect of positioning inaccuracy on road link identification



In figure 9, the arrow indicates the position and direction of travel of a vehicle. The circular area shows a fictional zone where GPS readings could report the vehicle. In this study, consequences for wrongly positioning the vehicle on road links *a* or *b* will be considered, while situations where the vehicle is reported on links *c*, *d*, *e*, or *f* are not considered. The reasoning for this is that during the trip the vehicle positioning is likely to be wrongly associated on links *c*, *d*, *e*, or *f* only for a limited fraction of road link 0, while the vehicle might be wrongly associated on street segments *a* and *b* instead of the reference link *0* uniformly over the whole street length. In this study, near street segments parallel to other street segments will be considered the primary source of misjudgements. On the contrary, segments which are not parallel (*c* and *f* among other links) or are far (links in black which are not labelled) will not be considered probable cases for misjudgement. Links *e* and *d* will not be considered potential sources of misjudgements as well. In this case, although they are parallel to the street is travelling on, the vehicle might be wrongly associated with these street segments only near the endpoints of street link *0*.

This study is therefore concerned with the effect of street orientation and street density in relation with GPS accuracy errors. To analyse the number of street links where this problem can be observed, SQL spatial queries have been executed on PostGIS. The authors have in fact evaluated that the spatial operations provided by GIS analysis tools such as ArcGIS did not give enough expressive power to identify street segments that can be sources for misjudgement. In order to find street segments that are parallel or almost parallel and that can be sources of link identification errors, the spatial query makes use of the Hausdorff distance. This measure is defined as the maximum distance of a set A to the nearest point of another set B (Rote 1991).

$$d(A,B) = \max\left\{\max_{a \in A} \min_{b \in B} |b - a|, \max_{b \in B} \min_{a \in A} |a - b|\right\}$$

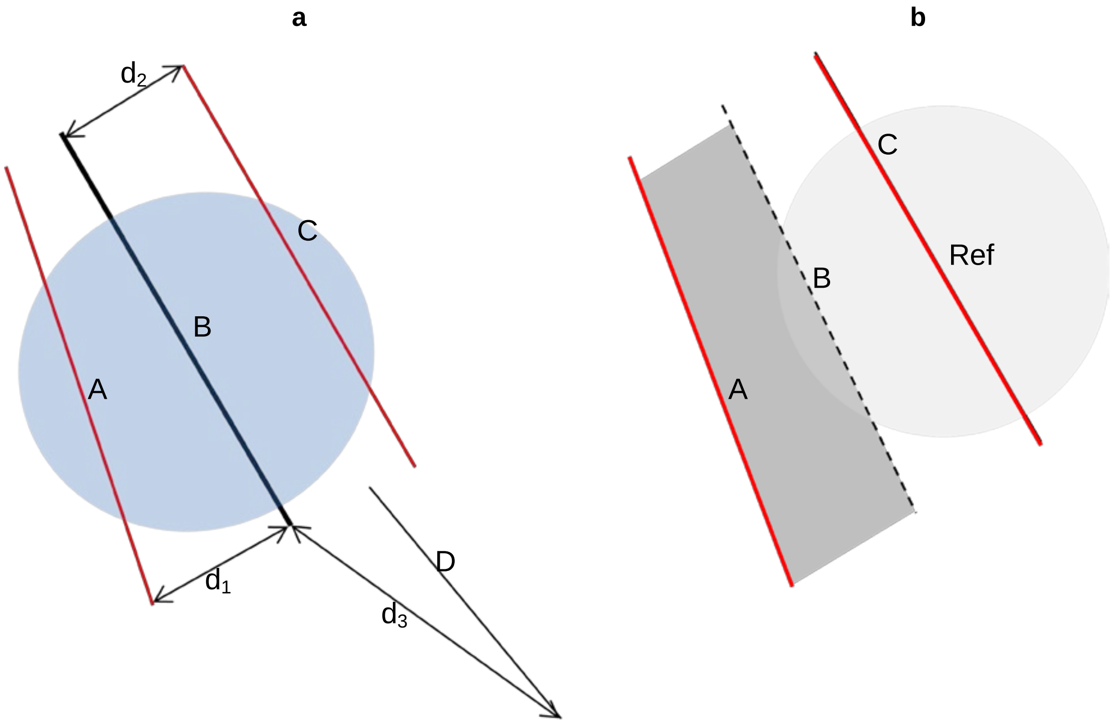
Considering figure 9 and limiting the observations to a few feature segments, the hausdorff distance is concerned with providing the measures reported in figure 10.

Figure 10a shows three different Hausdorff distances, namely:

1. d_1, is the Hausdorff distance between link A and B, ie the maximum distance between link A and B
2. d_2, is the Hausdorff distance between link B and C, ie the maximum distance between link B and C
3. d_3, is the Hausdorff distance between link B and D, ie the maximum distance between link B and D

Figure 10b does not show a Hausdorff distance, but shows diagrammatically that if a vehicle is driving along link C, with an positional error circle as shaded, the vehicle could mistakenly be assigned to link A, if the error circle radius is greater than half the distance between links A and C ie is greater than the perpendicular distance between link C and bisector B.

Figure 10. Measures computed by the Hausdorff distance



The approximation for the Hausdorff distance provided in PostGIS by ST_HausdorffDistance (Refractions 2011) has been used. This approximation is valid only for the discrete version of the hausdorff distance (the one reported in the equation), but it is sufficient to solve the problem at hand.

3.2 Analysis

The analysis builds on some results in the previous chapter and in particular on the GPS accuracy that has been found inside the Adelaide CBD.

Given the fact that the measured accuracy is usually a function of the presence or not of high-rise buildings, for each test area, two threshold distances are used, 40 metres and 20 metres. For the Adelaide test case Figures 4, 5 and 6 show that there are cases where the maximum errors are up to 40m, however they tend to be extreme cases(outliers) that do not occur often. Hence a lower threshold distance of 20m has also be chosen to approximate the more common situation of distance errors.

Positioning needs of demand responsive transport are analysed in this paper through the use of GIS analysis and SQL spatial queries on the road network of three Australian cities: Adelaide, Melbourne and Sydney.

Three areas in the cities have been chosen, however the method is applicable to other cities and suburbs as well. The city centre of Adelaide has well known boundaries, defined in the very early days of its inception. The results are shown in figure 11. Streets are usually spaced more than 20 metres apart, with only a few of the darker line segments showing street less than 20 metres apart. The situation changes if the second threshold is used. In this case, more than 30 % of the area considered is susceptible to uncertainty in estimating which street the vehicle is on.

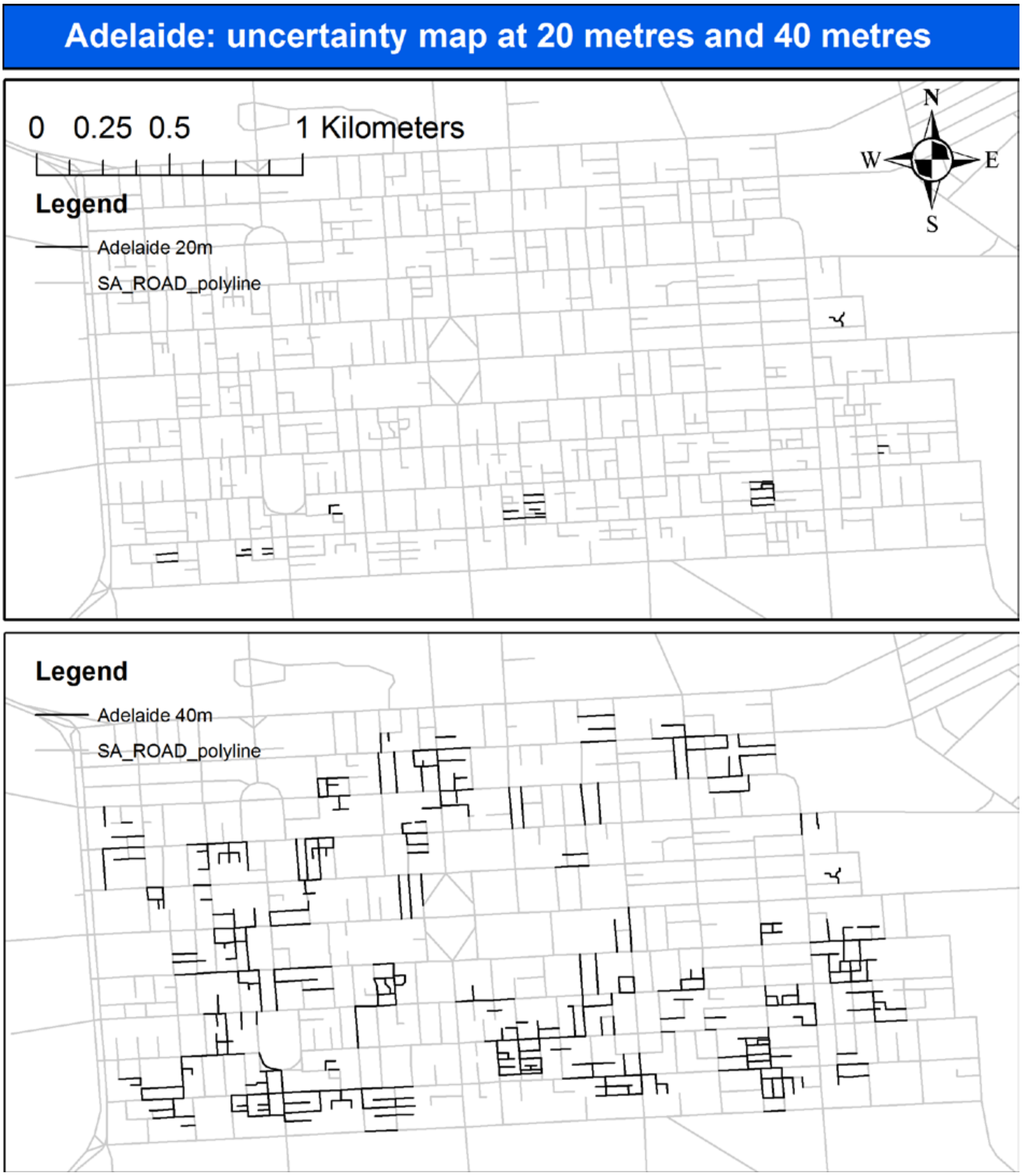


Figure 11. Adelaide uncertainty map

In figure 12, the Sydney test is shown. The area of Sydney considered has a different topography with a low street density. In this case, even considering by hypothesis the whole area of Sydney affected by multi-path problem, the association of GPS position estimation to the right street link is only mildly affected.

Figure 12. Sydney uncertainty map

Figure 13 shows the analysis on the Melbourne area. In this case the street density is higher than in other cities, and as a consequence of this even considering the best case scenario, there is still some space for street mismatch while driving in some streets, with highly probable problematic situations affecting almost the whole area, as it can be inferred by looking to figure 13.

Figure 13. Melbourne uncertainty map

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Given these analyses, some questions arise? Is GPS accurate enough to provide reliable information to the DRT service driver in a CBD area? How much GPS accuracy and reliabilty can affect resources allocation for fleet management systems providing real-time bookings?

The three areas shown in this study do not give a final answer. It depends on the topology of the area investigated, although some answers can still be extracted. Misjudgements in street link associated with a moving vehicle might show a vehicle "jumping" from one street to another in Adelaide and Melbourne, while Sydney study area is less affected. If the driver needs to rely on GPS and car navigator because they are not familiar with the area, they will be affected and will need to double-check the information given by the navigator, speeding down the service. A driver with local streets knowledge will not be affected.

How much GPS accuracy and reliabilty can affect resources allocation for fleet management systems providing real-time bookings? This will likely be a function of the number of users of the DRT service and the number of fleet vehicles used to provide the service. In cities with high streets density, provided that there is high user demand and a large number of fleet vehicles are used, then GPS (in)accuracy can severely impact the quality of the service. In this case using more reliable positioning systems, like a GPS/INS unit can provide tangible advantages. In all other cases, even in the presence of multi-path problems, the gain obtained by using better sensors will likely be minimal or not noticeable.

4.1 Conclusions and future works

This paper has shown that transport services are differently impacted by the accuracy and reliability of GPS receivers in hostile environments. For traditional bus services, provided that a bus priority traffic system is used, switching from GPS to GPS/INS will actually provide more schedule adherence in places like CBDs where there is a high number of bus stops and traffic signalled intersections. In this case by having a more reliable knowledge of the bus position, the traffic controller can operate more efficiently. For DRT services, while GPS inaccuracy will likely slow-down drivers with no knowledge of local streets, a better positioning system is required only when high streets density, high user demand and a large number of fleet vehicles happen at the same time. The CBD is a place where this could occur, however this needs to be balance with where most DRT system operate ie in outer low density suburbs that cannot justify a fixed route public transport system.

Future work might be required to improve the model used in this analysis. In this study two thresholds were used based on findings in areas with or without high-rise buildings and then used for the whole area. In future work, the use of a 3d city model, like the one provided by Adelaide City Council (Adelaide City Council 2009) and a tool to mathematically simulate GPS accuracy by setting related parameters, like the Trimble Planner (Trimble 2010), will likely enable to compute better uncertainty maps.

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