Transport Research Laboratory

Techniques for Assessment of Road User Charging and Global Navigation Satellite Systems data: Final Report

by R Walker and D Naberezhnykh

RPN 428

CUSTOMER PROJECT REPORT

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by R Walker and D Naberezhnykh (TRL)

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Executive Summary

Traffic is forecast to grow, and congestion is forecast to grow at an even faster rate. Peak hours are spreading. Most congestion occurs in urban areas and on strategic long-distance routes in the vicinity of urban areas. Patterns of living, working and doing business are leading to more and longer road journeys, with reducing car occupancy rates. Motorised road transport has brought huge benefits, but at a cost to the environment, safety and congestion.

GNSS (Global Navigation Satellite Systems e.g. GPS or Galileo systems) are becoming commonplace and are being developed into a wide range of transport applications in fields such as safety and traffic management. The development of Galileo has lead to increased interest in satellite positioning based application within Europe.

One application for satellite positioning systems is Road Pricing. Forecasts using the National Transport Model suggest that a well-targeted national Road Pricing scheme has the potential to achieve £10 billion worth of time savings a year (at 2010 traffic levels) in Great Britain alone. Research projects funded by the Dutch Government and Transport for London indicate that Road Pricing systems are very likely to be based on GNSS in the near future. GNSS Road Pricing systems offer flexibility in terms of charging by time distance and place as they do not rely on roadside infrastructure to record vehicle passage.

This project consolidates and builds upon previous work in the field of GNSS and Road Pricing assessment to develop a more comprehensive assessment of GNSS Road Pricing data.

The analysis considers two types of GPS datasets: 'truth' (a dataset controlled by the tester and assumed to be of high accuracy) and 'vendor' (a dataset produced by a technology developer). The project builds on work from previous Road Pricing Projects and was undertaken in four phases:

Phase 1: Understanding of TRL analysis capability and established metrics

Phase 2: Development of innovative analysis techniques

Phase 3: Development of analysis procedure

Phase 4: Analysis of sample data

In reviewing historic analysis of GNSS Road Pricing data it was identified that the assessments made are generally of relatively narrow scope, answering the specific research questions of a road pricing authority, but not often investigating the wider reasons for differences in performance. Further, assessments are generally presented simply as raw numbers such as means and counts. This analysis has focused on understanding whether the variability and magnitude of measured differences in performance demonstrate genuine statistical differences in performance.

Development was undertaken using SQL server to process the large datafiles, with Excel and SPSS used to undertake the analysis and statistical testing. This has allowed the strengths of SQL server as a database tool for data processing and the flexibility and range of features of Excel and SPSS for ease of the data analysis.

Suitable performance metrics have been explored but have not been developed to the level of veracity that would be required for a full analysis of performance (as this was not the focus of the project). However, data has been validated where possible against outputs from previous GNSS Road Pricing studies. Where metrics are different, judgement has been applied to estimate validity.

This project provides a contribution to knowledge and it is anticipated that the work will have a positive effect on future GNSS Road Pricing analysis; for example suggesting some improved analysis techniques and undertaking a wider breadth of analysis.

Perhaps most importantly, the work underlines the benefits of undertaking rigorous statistical testing.

1 Introduction

National and local transport authorities across the world are looking at Road Pricing as a way of managing transport demand and as a potentially fairer way of collecting taxation.

Toll collection systems in use can be broadly split into two types:

1. Road-Side based systems where equipment is located on the street that detects the vehicle and communicates to a central processing facility
2. Vehicle based systems where journeys and positions are logged within the vehicle and are communicated directly to a processing facility

Vehicle based systems offer the most flexibility in terms of charging by time, distance and location as they do not require roadside infrastructure to record vehicle passages. However, vehicle based systems are generally less mature technologies compared with the Road-Side Equipment (RSE) based systems and development is still required.

TRL's experience in Road Pricing project highlighted an opportunity to provide more constructive results from trials data. The experience has shown the potential to develop innovative data analysis techniques for GNSS (Global Navigation Satellite System) data. This provided an opportunity for developing knowledge and skills not only on RUC (Road User Charging) data evaluation but on GPS (Global Positioning System) and Galileo (EU GNSS system in development) data as well.

This project has developed metrics and undertaken comparative analysis of two types of GPS datasets: 'truth' (a dataset controlled by the tester and assumed to be of high accuracy) and 'vendor' (a dataset produced by a technology developer). The project was undertaken in four phases:

Phase 1: Understanding of current TRL analysis capability and established metrics

Phase 2: Development of innovative analysis techniques

Phase 3: Development of analysis procedure

Phase 4: Analysis of sample data

The intention has been to develop new and innovative analysis techniques for GPS data and build the knowledge to undertake that analysis.

This report details the process that has lead to the metrics being developed and discusses the benefits and lessons from work.

2 Requirements Analysis

To define a series of metrics that assesses GNSS data in a useful and comprehensive way an understanding was needed on the use to which the data is likely to be put. To facilitate this, a review of GNSS requirements defined by the agencies looking to assess and implement RUC systems is investigated and is discussed in this section.

The assessment has focussed on a few key agencies, namely:

- Transport for London (TfL)
- The Department for Transport (DfT)
- Her Majesty's Revenue and Customs (HMRC)
- Ministerie van Verkeer en Waterstaat (VenW - Dutch Ministry of Transport, Public Works and Water Management)

What became clear during assessment of these studies is that the focus differed for each of the agencies.

TfL focussed on the ability to measure distance travelled with the ultimate aim being to establish the correct charge to be levied. This meant assigning the journey to specific roads and applying the correct charge on that road.

The DfT focus was across a range of objectives including identifying the correct charge location, the correct distance travelled and the correct charge. Further, the DfT defined specific performance criteria.

The VenW requirements are perhaps the most highly specified and wide ranging. The principal aim was to examine the distance accuracy measurement and charge location measurement accuracy. However, the analysis requirements extended beyond this to request the examination of specific behaviours and situations that could affect performance.

The HMRC work focused on correct charge allocation analysis and did not heavily focus on the quality of GPS solutions, rather the end product (however derived). As a result, this example carried less importance to this study compared with the other cases examined.

The requirements for the different agencies are diverse with different levels of emphasis being placed on position accuracy, distance accuracy and charge accuracy.

Ultimately it is likely that the most important factor will be the accuracy of the calculated charge, which will be dependent on the type of charging system prescribed by an authority.

The definition of a charge can be interpreted in a number of ways: for example, the accuracy on a single trip, or the accuracy over a number of trips making up a monthly or quarterly bill.

However the charge accuracy is defined, it is likely that it should be a natural consequence of position and distance measurement. As a result it was anticipated that both of these measures should be considered an important evaluation criteria in this work.

The requirements, identified through this work and covered in detail in Appendix A, were utilised to help specify metrics defined in phase 2 of the project and reported later in this document.

3 Previous Research

GNSS RUC studies have been undertaken by a number of organisations for a range of bodies. The analysis type has been quite variable, which is caused by the variability described in the requirements analysis section.

This study has specifically considered:

- ARMAS phase II (for ESA – the European Space Agency)
- Research on the accuracy and reliability for distance based measurement and determination of tariff for (Kilometre Price) KMP (for VenW)
- Distance Based Charging: Report on Transport for London's GPS OBU Trial (for TfL)
- Analysis of TfL GPS OBU Data (for TfL)
- HMCE Lorry Road User Charging: Report on GPS survey (for HMRC)

ARMAS phase II (for ESA – the European Space Agency)

The metrics presented in this study focus on the positional accuracy characteristics of the GNSS in use. This is a result of the focus of the work being to feed into map matching solutions where position accuracy is of high importance.

Cumulative position error plots seem to give a good indication of the performance characteristics of devices compared with other devices and the accuracy metrics here are generally well thought out. The report also breaks the data down by road type and other similar metrics which would appear to be a valid way of assessing and presenting the data.

The calculation of a latency metric (which measures the average delay between consecutive GPS position points that meet an accuracy criterion) is of interest for understanding the behaviour of the actual devices but does not inform position accuracy or distance accuracy directly and so is perhaps not directly relevant to the requirements.

No performance requirements were defined for this work and, as a result, assessments and statements of performance in relation to the requirements were not made.

Research on the accuracy and reliability for distance based measurement and determination of tariff for KMP (for VenW)

Clear and measurable performance criteria were defined for testing for this project; the principal one being the ability of systems to correctly measure distance travelled. The result is a series of figures and tables considering the distance performance in relation to these requirements. The assessments were well structured, of particular interest were:

1. Assessments of local features
2. The assessment of short journeys
3. The assessment of Time To First Fix (TTFF)

The assessments were part of the analysis which met the defined requirements for the work. It is thought that the analyses could be developed further through deeper disaggregation of the data. This will be drawn out in the metrics development.

Distance Based Charging: Report on Transport for London's GPS OBU Trial (for TfL)

The analysis in this trial focused very heavily on the use of map matching techniques. The reason was due to the assessment criteria defined by TfL which assessed the OBU supplier data against pre-defined map data with associated distances.

This type of analysis for TfL cannot be utilised with the data that is available for this project, as no map data for the test data is available and, as a result, similar analysis for this project will not be pursued.

The integrity analysis gives a good example of how this type of data could be progressed and provides ideas for undertaking similar analysis where available data permits.

Analysis of TfL GPS OBU Data (for TfL)

The assessment of TTFF is an important aspect for short journeys as reduced accuracy or lack of GPS position for a short period of time during a short journey could have a large effect on the accuracy of the assessment over this type of journey.

The work of accuracy of position and distance seem to be sensible and workable approaches to the assessment of these measures.

HMCE Lorry Road User Charging: Report on GPS survey (for HMRC)

The GNSS analysis undertaken for this project was of a different focus to the other reports assessed in this review. The result being that the report is on aspects not specifically considering the GPS performance, rather the different technologies involved. As a consequence the HMCE report does not inform the metrics to be used in this project.

4 GNSS analysis in other domains

Assessment techniques used in other industries or for other applications can provide insights into different analysis techniques. Some examples are reviewed in this section. The review focuses on:

- Imperial College GPS Receiver Performance Review
- TRL HARRIS Vehicle analysis
- TRL Norwich Union analysis
- Maritime GNSS analysis
- Aviation GNSS analysis
- Rail GNSS analysis

Imperial College GPS Receiver Performance Review

This university review is relatively simplistic covering major aspects of GPS positioning techniques including Satellite Availability, Coverage and Accuracy of position, utilising relatively simplistic metrics. The metrics form a good basis for developing further in-depth analysis.

TRL HARRIS Vehicle analysis

TRL have developed and operate the Highways Agency Road Research Information System (HARRIS) vehicle which uses an Applanix DGPS and inertial system. The paper written by TRL assessing this system contains assessments potentially useful to this study.

The TRL HARRIS analysis is applicable to this research covering aspects such as availability and positional accuracy. Skills developed in the assessment will be useful for later phases of the project.

TRL Norwich Union analysis

This project extracted data from GPS units fitted into privately owned vehicles. A paper discusses the level of acceptance of the sample population for use of GNSS equipment to log their journeys. However, the paper does not go into detail on the benchmarking of equipment and as a result is not relevant for this project.

Maritime GNSS analysis

The Marine industry uses GPS for navigation and requires knowledge of local conditions such as rocks, shallow water, and wrecks which are common obstacles.

GPS tends to be used in conjunction with other methods, including compasses and charts, to help mitigate equipment failure.

Some applicable research has been undertaken in the maritime area. However, the metrics do not add to the assessments currently used in Road Pricing applications.

Aviation GNSS analysis

The aviation industry utilises GPS for a number of applications over the course of a flight, from journey planning, through the flight itself and into the approach and landing.

The safety critical nature of aviation means that there are more backups than in typical road vehicle systems and that a greater amount of research and development has been put into integrity aspects of the systems.

The aviation industry does not appear to undertake comparative analysis for the assessment of GPS equipment and is, instead, more interested in the ability of the system to report errors accurately through integrity monitoring.

The use of integrity monitoring along with potential applications for simulation are the two principal outputs of benefit from this area.

Rail GNSS analysis

Currently, GNSS systems on trains tend to be used for applications such as tracking and gaining real time journey information.

Systems are available and are fitted to trains but assessment such as that required for road use has not been found.

As a result, GNSS performance analysis is not well progressed at this stage in the rail industry and no results are presented in this section.

5 Metrics developed

The following section discusses the metrics developed and implemented through analysis of user requirements. Using this understanding the core analysis requirements were identified and data summaries defined.

Through this process it became apparent that the specifications developed by Road Pricing Scheme owners (i.e. TfL, DfT, VenW) can be broken into Metric categories. These categories are discussed below: the statistical measures and definitions are recorded in detail in Appendix B.

The process to be followed will be to produce data tables of summarised data which can then be summarised to produce the metrics.

5.1 Position Measurement

Assessment of position accuracy was not identified by any of the Road Pricing Scheme Owners specifications as being a key deliverable. However understanding of the positional accuracy is considered to be important due to the role this plays in understanding the performance of Distance Accuracy, Object Recognition and Charge Accuracy.

5.1.1 Calculation of position error

The position error is calculated using the Haversine method for each point as:

For two points on the surface of the earth with latitudes $\theta 1$ and $\theta 2$, and longitudes $\lambda 1$ and $\lambda 2$:

Latitude difference $\Delta\theta = \theta 1 - \theta 2$

Longitude difference $\Delta\lambda = \lambda 1 - \lambda 2$

R = Earth's radius (mean radius = 6371km)

$a = \mathrm{Sin}^2(\Delta\theta/2) + \mathrm{Cos}(\theta 1).\mathrm{Cos}(\theta 2).\mathrm{Sin}^2(\Delta\lambda/2)$

$c = 2.\mathrm{Arctan}(\sqrt{a} / \sqrt{(1-a)})$

Distance between the points = R.c

5.1.2 Position error data tables

5.1.2.1 Total journey accuracy

From second by second data identify the overall journey accuracy.

Output: Mean position error (by OBU, by Route, by Journey)

Output: Position variance (by OBU, by Route, by Journey)

5.1.2.2 Binned journey accuracy

From second by second data identify the accuracy from second to second and bin the output.

Output: Position error in 1m bins (by OBU, by Route, by Journey)

5.1.3 Position Error Analysis

These tables allow the production of outputs including:

- Overall Location Error
- Location Error Cumulative Distribution
- Location Error Summary Statistics

5.2 Distance Measurement

Distance Measurement Accuracy is one of the key drivers of a Road Pricing system. This section will describe the ability to measure distance for long and short journeys where performance may expect to vary. Consideration is given to the sign and the magnitude of the errors.

5.2.1 Measures

5.2.1.1 Distance Deviation (Signed)

$$DDS = D_{ref\,(start)} - D_{ref\,(end)} + D_{obu\,(end)} - D_{obu(start)}$$

5.2.1.2 Distance Deviation (Absolute)

$$DDA = |DDS|$$

5.2.2 Accuracy on long journeys

For the entire journey examine the distance accuracy

Output: DDS (by OBU, by Journey)

Output: DDA (by OBU, by Journey)

5.2.3 Accuracy on short journeys

For short journeys defined as the time the reference device achieves the $D_{ref(end)}$

$D_{ref(end)}$: 1km, 2km, 3km, 4km, 5km, 6km, 7km, 8km, 9km, 10km

Output: DDS (by OBU, by Journey) for each Distance

Output: DDA (by OBU, by Journey) for each Distance

5.2.4 Distance Error Analysis

These tables allow the production of outputs including:

- Overall Distance Error
- Short Journey Distance Error
- Distance Error Summary Statistics

5.3 Object Recognition

Object recognition is the ability of an OBU to identify that it has entered a specific area in a charging scheme. This could be a charged road segment, a charged zone, a different country and so on. Generally in these areas an alternative tariff would be levied. The ability to make a correct object recognition in terms of time identified and distance travelled is important for undertaking charging.

5.3.1 Measures

From the second by second data the following measures are derived.

5.3.1.1 Entry identification

Time difference between reference OBU entry identification and tested OBU identification

Output: Entry (by OBU, by Object, by Journey)

5.3.1.2 Exit identification

Time difference between reference OBU exit identification and tested OBU identification

Output: Exit (by OBU, by Object, by Journey)

5.3.1.3 Distance measurement

Distance measurement of the charge object from the tested OBU

Output: Distance (by OBU, by Object, by Journey)

5.3.1.4 Proportion of Flags

Number of flags between reference OBU Entry and Exit identification and tested OBU Entry and Exit identification

Output: Entry (by OBU, by Object, by Journey)

5.3.1.5 Proportion of Correct Object Recognition

For each object a tally of the ability to recognise the object

Output: Entry (by OBU, by Object, by Journey)

5.3.2 Object Recognition Analysis

These tables allow the production of outputs including:

- Object recognition performance
- Object measurement performance
- Object Summary Statistics

Further, the Weekly data will be used to derive comparative statistics.

5.4 Environmental Effects

It is highly desirable to be able to associate measures of precision with specific features or route characteristics. If this were tenable then it may be possible to determine the overall route precision by combining, in a weighted way, the component parts. To this end, effects of features including EM Radiation, Tall buildings and Dense Foliage are analysed in terms of the distance and position accuracy and aspects such as the number of satellites in view.

5.4.1 Time to first fix data tables

Time To First Fix will be affected by where the vehicle may have been kept overnight, the ability of the systems to hold the last position.

5.4.1.1 TTFF

From second by second data identify the time of the first reported position compared to when the vehicle began moving based on INS data.

Output: TTFF (by OBU, by Journey)

5.4.1.2 TTFF Distance Accuracy

Output: Average, variance and sample size of distance accuracy for first 0-X seconds [X=1 sec to 120 secs, step 1 sec] (by OBU, by Journey)

Output: Average, variance and sample size of distance accuracy for first 0-X seconds [X=15 secs to 300 secs, step 15 secs] (by OBU, by Journey)

Output: Average, variance and sample size of distance accuracy for first 0-X seconds [X=30 secs to 900 secs, step 30 secs] (by OBU, by Journey)

5.4.1.3 TTFF Position Accuracy

Output: Average, variance and sample size of positional error for first 0-X seconds [X=1 sec to 120 secs, step 1 sec] (by OBU, by Journey)

Output: Average, variance and sample size of positional error for first 0-X seconds [X=15 secs to 300 secs, step 15 secs] (by OBU, by Journey)

Output: Average, variance and sample size of positional error for first 0-X seconds [X=30 secs to 900 secs, step 30 secs] (by OBU, by Journey)

5.4.1.4 TTFF Satellites in View

Output: Number of satellites in view for second X [X=1 sec to 120 secs, step 1 sec] (by OBU, by Journey)

Output: Number of satellites in view for second X [X=15 secs to 300 secs, step 15 secs] (by OBU, by Journey)

Output: Number of satellites in view for second X [X=30 secs to 900 secs, step 30 secs] (by OBU, by Journey)

5.4.2 TTFF Analysis

These metrics allow the development of metrics to define the TTFF over the first 15 minutes of the journey and allow the plotting of effect on position accuracy over this period as well as providing summary statistics.

5.4.3 Tall building effects

An area (rectangle) is defined by 2 points with a latitude and longitude to identify an area of tall buildings that will cause multipath effects. The entry and exit from the area is defined by the entry and exit from the area as recorded by the reference OBU and the analysis taken between these two points.

5.4.3.1 Distance accuracy

Output: Average, variance and sample size of distance accuracy (by OBU, by Journey)

5.4.3.2 Position accuracy

Output: Average, variance and sample size of positional error (by OBU, by Journey)

5.4.3.3 Satellites

Output: Number of satellites in view (by OBU, by Journey)

5.4.4 Tree obscuration effects

An area is defined by 4 positions producing 2 crossings of a road. The analysis identifies journey segments that cross the first line and subsequently cross the second line. The analysis is then performed in the area between these crossings.

5.4.4.1 Distance accuracy

Output: Average, variance and sample size of distance accuracy (by OBU, by Journey)

5.4.4.2 Position accuracy

Output: Average, variance and sample size of positional error (by OBU, by Journey)

5.4.4.3 Satellites

Output: Number of satellites in view (by OBU, by Journey)

5.5 Charge Accuracy

It is not felt to be of benefit to generate tariffs to consider the effect of charge in the scope of this project; however this could be derived from the Distance and Charge Object measurement accuracy.

5.6 Technology Solutions

In order to assess technology solution differences it is necessary to have a single vendor providing solutions based on a variety of technology mixes in order to remove vendor specific effects.

For analysis purposes data from a number of vendors treated as if it were from one vendor using a variety of technology mixes can be considered.

5.7 System Considerations

It is not within the scope of this project to assess the wider behaviour of a Road Pricing system, involving factors such as the average charge and susceptibility of a system to fraud.

6 Data Handling

Generally the type of equipment that will be assessed will be prototype, which may be prone to failure due to its nature. This behaviour is assumed to be the prevalent factor in gross errors and in order to identify and exclude this type of data, a filtering technique was devised.

The filtering technique is described in detail in Appendix C. In summary the technique uses a statistical test to look for gross differences in distance or position error on a single run compared with runs by the same OBU on the same route. Due to the low (approximately 10) number of runs expected within individual routes a manual check followed this to identify if an obvious outlier had been missed or alternatively an appropriate run had been inappropriately excluded.

7 Conclusions

This project has considered metrics for the assessment of Road Pricing data. What has become clear is the variety of requirements from Road Pricing scheme operators and the myriad of ways that these have been looked at by organisations assessing Road Pricing data. Across the different studies assessed in this project the types of analysis and the representation of results has been varied. This work has produced a consolidated set of metrics which bring the differing types of analysis together to provide the knowledge required to make a more comprehensive assessment of GNSS Road Pricing data.

The principals behind the metrics developed has been to maintain a flexible approach that allow the data to be assessed in a variety of ways. This facilitates a variety of outputs to be produced that meet the requirements of a number of the Road Pricing scheme owners.

This work has provided new capabilities in the statistical analysis of data. None of the previous studies reviewed have looked at the level of confidence in assessing differences between OBUs, or performance in different types of environment, choosing instead to present data, figures and tables in isolation.

This development of metrics suitable for statistical analysis has lead to the ability to differentiate between OBUs with a level of confidence previously not reported, consequently it is the recommendations of this report that similar types of analysis be undertaken when studies of this type are run.

Sample data was processed as part of the metric testing, but is not presented in this report being outside of the main focus.

Mechanisms for filtering data have been highlighted as a concern in this project and additional effort would be needed to ensure procedures are implemented robustly in the future. A rigorous approach for the filtering of the data with justification for the decisions has been presented.

In undertaking this work the development of flexible database techniques and structures have been made which would facilitate further analysis on different GPS data. Future analysis could take the metrics developed in this short study further with more advanced filtering and analysis of integrity data.

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Glossary of terms and abbreviations

ARMAS	Active Road Management Assisted by Satellite
CAA	Civil Aviation Authority
DBC	Distance Based Charging
DGPS	Differential GPS
DfT	Department for Transport
DIRECTS	Demonstration of Interoperable Road-user End to end Charging and Telematics Systems
DR	Dead Reckoning
ECDF	Empirical Cumulative Distribution Function
ESA	European Space Agency
EGNOS	European geostationary Navigation Overlay Service
GALEWAT	Galileo and EGNOS Waterway Transport
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPV	Galileo Performance Validation
HARRIS	Highways Agency Road Research Information System
HMRC	Her Majesty's Revenue and Customs
HPL	Horizontal Protection Level
IALA	International Association of Lighthouse Authorities
INS	Inertial Navigation System
ITN	Integrated Transport Network
KMP	Kilometre Price
LRUC	Lorry Road User Charging
MARGAL	Maritime Galileo
NEMO	Navigation, Environment and Mobility
OBU	On Board Unit
OS	Ordnance Survey
RAIM	Receiver Autonomous Integrity Monitoring
RUC	Road User Charging
SIS	Signal In Space
TfL	Transport for London
TSP	Total System Performance
TTFF	Time To First Fix

Appendix A Requirements Assessment

This Appendix describes the client requirements in the GNSS projects which have been undertaken for the following organisations looking at introducing Road Pricing systems. These include:

- TfL (Transport for London)
- DfT (Department for Transport)
- VenW (Ministerie van Verkeer en Waterstaat - Dutch Ministry of Transport, Public Works and Water Management)
- HMRC (Her Majesty's Revenue and Customs)

Each section will discuss the requirements described by the contracting organisation.

A.1 TfL

TfL have undertaken a series of technology trials in London. In TfL, 2006 the following overarching objectives were identified:

1. Learn about the state of maturity of products available from the vendor community;
2. Gain first hand, practical experience of implementing these products;
3. Investigate the practicality of a DBC (Distance Based Charging) scheme in London;
4. Understand the performance of these products, when applied to the London environment;
5. Formulate a clearer idea of how a larger trial could be structured;
6. Define the optimal topics, measures (metrics) and methodology for larger future trials;
7. Predict how the performance of the current generation of Road Pricing systems might be affected by future developments in satellite positioning technology, in particular the launch of the Galileo system.

A.2 DfT

The information in this section is from the DfT Road Pricing Framework Division document "Demonstrations Project Statement of Requirements" and covers the requirements for the GNSS aspect. This data is from the report DfT Road Pricing Framework Division, 2007.

Correct Charge Object Recognition:

The probability that a charge record is generated when an eligible vehicle incurs a charge liability according to the charging rules by encountering a charge object.

Initial 85%, Target: 98%

False Charge Object Recognition:

The number of occasions that a charge record is incorrectly generated when an equipped vehicle is not eligible for a charge according to the charging rules.

Initial: 1 per 10 road-users per Month; Target: 1 per 100 road-users per Month

Distance Measurement:

The mean error and standard deviation of the distance reported in a charge record, compared with the actual driven distance.

Initial: Mean Error = 0 ± 9% St Dev = 8%; Target: Mean Error = 0 ± 2% St Dev = 3%

Charge Calculation:

The probability that the charge reported in a charge record is calculated using the correct charge parameters.

Initial: 95%; Target: 99%

Total Charge Accuracy:

The mean error and standard deviation of total charges as reported in charge records compared to the true charges.

Initial: Error = 0 ± 8% St Dev = 8%; Target: Error = 0 ± 1% St Dev = 2%

Charge Allocation

Proportion of charges reported in charge records that appear in the correct road-user statements.

Initial: 95%; Target: 99%

Revenue Allocation:

Proportion of charges reported in charge records in returns to the correct Scheme Owner.

Initial: 95%; Target: 99%

Cost of charge collection:

Cost per mile travelled, assuming: - charges normalised to 1000 miles per month and - calculation still needed when not being charged

Initial: Service Provider to propose; Target: To be confirmed

A.3 Dutch Ministry of Transport, Public Works and Water Management

The most relevant GNSS analysis requirements from the project "Research on the accuracy and reliability for distance based measurement and determination of tariff for "Kilometre Pricing in The Netherlands" VenW, 2007 are given here.

Requirement 3:

Combined charge based on distance travelled and location shall have an accuracy of at least 99%

Requirement 12:

The Road Pricing system shall be sufficiently reliable to ensure correct and adequate road user charging.

The reliability requirements are as follows:

- correct charging (within 1% accurate): >99% of all invoices
- over charging: < 0.1% of all invoices (where over charging is defined as a charge > 101% of true)
- Mean time between failures of the On Board Unit: 25 years

Further analysis requirements included:

- What level of accuracy of the distance travelled?
- To what extent does differentiation by location affect the accuracy and reliability of the system?
- What specific conditions affect performance, i.e. make solutions perform much worse than average
- What (combinations of) technologies are likely to fulfil the draft requirements of the KMP from an accuracy and reliability perspective?

A.4 HMRC (Her Majesty's Revenue and Customs) – Lorry Road User Charging

Information is not available at time of writing.

A.5 Discussion

The requirements for the different authorities are clearly quite diverse with different levels of emphasis being placed on position accuracy, distance accuracy or charge accuracy.

Ultimately it seems likely that the most important factor will be the accuracy of the calculated charge, which will be dependent on the type of charging system prescribed by authority.

The definition of a charge can be interpreted in a number of ways, as for example the accuracy on a single trip, or alternatively the accuracy over a number of trips making up a monthly or quarterly bill.

However the charge accuracy is defined it is likely that this should be a natural offshoot of position and distance measurement. As a result it is anticipated that both of these measures should be considered an important evaluation criteria in this work.

Appendix B Statistical Measures and Definitions

B.1 Statistical Measures

Under assumption that the precision data are approximately Normally distributed, then useful summary statistics such as the mean (average) and variance may be computed. However, if there are large numbers of outliers or if the data distribution is very skewed then such statistics may be confusing and others such as the mode or median may be more appropriate.

B.1.1 Average

The arithmetic mean of a set of values is the quantity commonly called "the" mean or the average. Given a set of samples $\{x_i\}$, the arithmetic mean is:

$$x = \frac{1}{n}\sum_{n} x_i$$

B.1.2 Variance

The sample variance m_2 (commonly written s^2 or sometimes s_N^2) is the second sample central moment and is defined by

$$m_2 = \frac{1}{N}\sum_{i=1}^{N}(x_i - m)^2$$

where $m = \bar{x}$ the sample mean and N is the sample size.

B.1.3 Median

The statistical median is an order statistic that gives the "middle" value $\bar{x}$ of a sample. More specifically, it is the value $\tilde{x}$ such that an equal number of samples are less than and greater than the value (for an odd sample size), or the average of the two central values (for an even sample size).

B.1.4 Mode

The most common value obtained in a set of observations. For example, for a data set (3, 7, 3, 9, 9, 3, 5, 1, 8, 5), the unique mode is 3. Similarly, for a data set (2, 4, 9, 6, 4, 6, 6, 2, 8, 2), there are two modes: 2 and 6.

B.1.5 Sample Size

Sample size is the number of valid observations in a sample.

B.2 Definitions

B.2.1 Journey

The journey is defined by the point in time of the first movement of the Reference INS system to the time of the last movement of the INS system.

Appendix C Data Considerations

C.1 Data filtering

Data filtering by a rule is generally not appropriate for the types of data used in Road Pricing analysis due to variations in OBU characteristics or experimental effects. As a result position and journey accuracy will be examined in the first instance in order to identify erroneous data and excluded appropriately.

A dual approach to identify outliers will be used. The statistical approach is to calculate the average and the standard deviation from the 10 or so replicates for each of the routes driven by each vendor. The 95% confidence interval is then computed (taking into account the sample size) and individual runs identified which lay outside of the confidence interval.

This statistical approach works well in most cases where there were are either no rogue values or just a single obvious rogue value. For example in the following table, the average value of the following % distance errors is 3.51% with an associated standard deviation of 5.84% giving a 95% confidence interval from -9.34% to 16.35%. It is clear from the data that the 21.41% value is an outlier or rogue value, and it lays outside of the confidence interval.

Example 1. Where the statistical approach works as required

replicate	% distance error	Indicator, 0=exclude
1	0.39%	1
2	1.58%	1
3	1.37%	1
4	21.41%	0
5	1.37%	1
6	4.03%	1
7	3.89%	1
8	2.70%	1
9	1.87%	1
10	0.05%	1
11	3.88%	1
12	-0.44%	1

The statistical approach works less well when there are a few outliers which had the effect of generating a large standard deviation and hence a wide confidence interval. In this instance not all of the fairly obvious outliers were identified for exclusion. In the example below the calculated the average % distance error is -14.38% with a standard deviation of 23.14% giving a 95% confidence interval from -65.32% to 36.55%. Hence the % error of -66.00% was outside the confidence interval but the value of -61.15% was within, albeit that it is clearly an outlier.

Example 2. With two outliers resulting in a wide confidence interval

replicate	% distance error	Indicator, 0=exclude
1	-66.00%	0
2	-2.18%	1
3	-5.68%	1
4	-5.30%	1
5	-61.15%	1
6	-2.99%	1
7	-6.65%	1
8	-5.70%	1
9	-1.94%	1
10	0.59%	1
11	-8.94%	1
12	-6.68%	1

The statistical approach also does not work that well when the % distance errors are small and fairly consistent, but there is one value just a little bigger (or perhaps negative when the rest were positive). The approach then may suggest excluding a value which looked perfectly acceptable. The following example illustrates this point, where the average was 0.10% with a standard deviation of 0.07% giving a 95% confidence interval from -0.06% to 0.26%. It does not seem reasonable to exclude the only (slightly) negative value, and hence the statistical 'exclusion' criterion is too strict.

Example 3. Where the statistical approach is too strict

replicate	% distance error	Indicator, 0=exclude
1	0.09%	1
2	0.13%	1
3	-0.07%	0
4	0.11%	1
5	0.14%	1
6	0.01%	1
7	0.11%	1
8	0.19%	1
9	0.09%	1
10	0.15%	1
11	0.10%	1
12	0.20%	1

As such the approach adopted is to identify outliers uses a combination of the strictly statistical approach combined with a 'reality' check. The statistical approach was first employed and identified those runs which lay outside of the computed 95% confidence interval. The results from the statistical run are then examined and changed if it is clear that an obvious outlier had been missed (example 2) or had been inappropriately excluded (example 3).

C.2 Data merging

As the data sets used in this project are already time matched there is no requirement on merging the reference and vendor datasets.

C.3 Data table flexibility

The data should be stored in a way that will not prohibit the use of the database structures for use with similar GNSS Road Pricing datasets that are ordered differently or have different field sets.