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GNSS technologies for electronic toll collection

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ABSTRACT
Problems with infrastructure financing, pollution and congestion are leading different countries to the implementation of Road Pricing schemes. GNSS appears as one of the most flexible and cost efficient technologies for the implementation of large ETC systems. However, due to the nature of GNSS with random and occasionally large position errors, GNSS based ETC still has some constraints that need to be overcome. The use of a signal with guaranteed integrity, as the one available in WAAS or EGNOS combined with advanced OBU algorithms provides an efficient solution that guarantees the correctness of the charging. This paper presents the results of the trials in which this technology has been used and demonstrates how the probability of overcharging can be controlled and dramatically reduced in a GNSS-only system. These trials have been executed in London, Madrid and The Netherlands.

KEYWORDS: Electronic Toll Collection, Road Pricing, GPS, telematics

1. Introduction

GNSS has been identified as the most flexible and cost efficient technology for the implementation of large ETC and Congestion Charging systems both for urban and roads networks. In particular, different studies have economically compared GNSS and DSRC technologies and have concluded that whenever the road network in which ETC is to be applied overpasses some few thousands of kilometers, GNSS technology is clearly more cost efficient than the DSRC. In addition, if other considerations such as either flexibility and expandability, or provision of additional telematic services are taken into account the GNSS technology is clearly superior.

In this context, The Netherlands has already approved the development of a Road Pricing scheme, named ABvM, that will charge all vehicles in the entire road network including private roads. Cities like London are also evaluating the capabilities of GNSS to support a congestion charging scheme.

Despite the GNSS technology advantages some weaknesses have to be overcome. In particular, the random position errors and temporal occultation of signal are of special concern for the application of GNSS for ETC. While today GPS receivers on average show very accurate positioning in an open environment, extensive trials performed in different cities show probable large errors and a clearly not Guassian behavior that makes the bounding of the errors a very difficult tasks. It is obvious that these large errors affect the capabilities of the ETC and can lead to unacceptable incorrect charging. In order to cope with these limitations different technologies are being proposed including the use of additional sensors and road side infrastructure, map matching algorithms etc. This paper investigates the results of a set of trials that exploits position integrity as the most robust and cost-efficient solution for an ETC system of guaranteed performance.

It is important to emphasize that map-matching mechanisms applied to GPS positions implicitly rely on the assumption that large biased errors are extremely unlikely. Since they do not make use of any Integrity mechanism, the actual probability of introducing large errors is not well determined and thus the likelihood of making the wrong decision is a complete unknown.

This paper will analyse first the different Road Pricing schemes focusing on the Distance Based Charging (DBC) and will later identify the applicable performance requirements that will be taken as reference for the trials evaluation. Later on the way Integrity is used in the ETC system is described. Last, and as a main focus of the paper, the results of some exhaustive trials campaigns performed in London, Madrid and The Netherlands will be shown. The paper will concentrate on the last one having as reference the ABvM requirements.

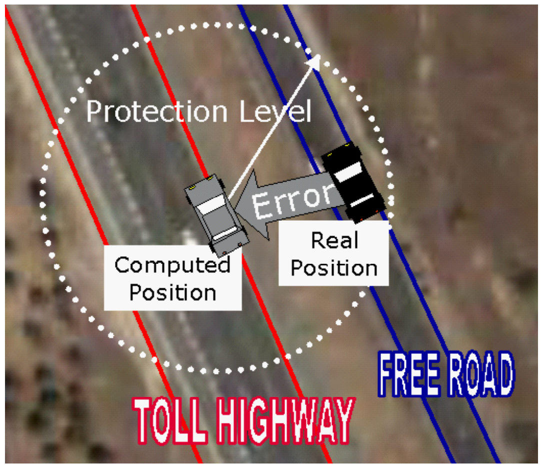

Fig. 1. Protection level concept

2. Different road pricing schemes

Different payment schemes have been defined based on time, travelled distance, use of a particular zone or combinations of them. Even in a pure DBC scheme (i.e. the driver pays as a function of the kilometres driven and not simply to enter a zone), the system has to usually detect the zone (or road segment) in which a vehicle is, since the price per kilometre depends on it. This mechanism facilitates the reduction of congestion as congested areas are charged in excess. This is in particular intended in the Dutch ABvM approach and it is expected to become the reference approach for most of the future systems.

Thus, concerning the information needed to charge a vehicle, a typical road pricing scheme involves two main basic steps:

- Detection of zones/segments (called geo-objects in European standards) and
- Travelled Distance measurement.

When zones have a single entrance and exit, the travelled distance could, under some assumptions, be directly derived from the zones detection. This is as a matter of fact the approach used in most of the private highways.

Distance measurement is usually derived from three sources of information, namely: the available data about the distance of the road segment in which the vehicle is detected, satellite navigation information and/or information derived from the vehicle itself (e.g. distance measured by the odometer). The first one is not considered as an option in the ABvM system because of two main reasons: First, a very accurate map needs to be made available and, even more difficult, efficiently maintained. Second, because it cannot measure the real travel distance, for instance if the car deviates from the main route to refuel in a fuel station.

The paper will show a comparison of the performances achieved when using only satellite navigation, odometer information or a combination of both. The paper will also compare different ways to access to the odometer information and the resulting performance.

The second process (identification of zones/segments) is more critical as a wrong identification may have a major impact in the charging computation. Note that in a system as the one proposed in The Netherlands where vehicles are to be charged as a function of the kilometres travelled within the country, the concept of geo-object appears both for the definition of The Netherlands borders but also for the definition of special areas and roads that during peak hours are subject to an extra charging.

3. Major ETC performance requirements

For the evaluation of the trials' results it is important to clearly establish the performance requirements that will serve as reference for the assessment.

For a "fixed tariff" (as it is the case of London Congestion Charging or a particular highway segment) the two main requirements can be formulated as:

- The system has to charge a very large percentage of the users, e.g. >99.9%." and
- The system has to ensure with a probability of mistake very small (e.g. <10-6) that vehicles not using the infrastructure are in fact not charged."

For a distance based charging (DBC) scheme the requirements need to be reformulated in a different manner and are established in terms of the travelled distance accuracy (or the equivalent in charging) and the probability of overcharging. In particular for the ABvM system two requirements (which associated figures could potentially evolve) are identified:

- The mechanism to determine the driven distance must be accurate to within 1% and
- Such that the incidence of over-charging is limited to <0.1% of all invoices issued

While this formulation seems to be very clear, it is subject to potential different interpretations and is also very much depending how often the user drives in congested areas subject to a higher tariff. The paper will propose an alternative formulation that is believed to be more appropriate.

It is very important to understand that the capability of the system to satisfy those requirements is strongly and simultaneously affected by the capabilities of the two previously identified processes, namely: the detection of zones/segments and the travelled distance measurement. The paper will analyze in detail the capabilities of different technologies for both processes and the relationship between these capabilities and the related requirements.

4. The use of GNSS integrity

GNSS Integrity is used in the two main processes involved in a DBC scheme. On the one hand the position Integrity helps in the distance measurement process guaranteeing that the distance will not be measured in excess. Two approaches are possible including the use of GNSS only information and, as an alternative, the calibration, using the GNSS information, of the measurement provided by the odometer.

Second and more important, the position Integrity is used in the process of zones detection. The way integrity is used to guarantee that vehicle is in the zone and thus avoiding the overcharging of a vehicle that did not enter that zone was already presented in a previous paper but is briefly recalled here. The main steps are as follows:

- A GNSS Rx with built-in Integrity provides not only the position but also the associated Protection Level, i.e. a circle around the estimated positions in which the real position is guaranteed to be with an extremely high probability
- In the simplest implementation, the charging algorithm decides the vehicle is within the road only when the Protection Level centred in the computed position is completely within road limits and thus probability to have a wrong decision is extremely small.

The following diagram shows (Fig.1.) how the use of protection levels avoids that a probable large position error is translated in a wrong segment identification and, hence, a wrong charging.

In the real implementation, different combinations of:

- probability of the protection levels (and hence their size) and
- the number of epochs required to charge are possible to guarantee that the vehicle is using infrastructure.

In order to show the weaknesses of GPS when integrity is not used, the following shows the output of a real GPS receiver installed in a car travelling in Amsterdam. The actual trajectory is highlighted in green and runs out of the channel while the GPS computed position is shown as a blue line and is on the other side of the channel. If the zone at the north of the channel was a charging zone, the vehicle would have been charged incorrectly. The use of position integrity would have shown the problem as PLs would indicate that the vehicle could be out of the charging zone.

However, the use of position integrity may have a negative impact in the charging availability as in the case that none PLs is fully contained in the zone/segment the system would not detect that the vehicle has used the infrastructure. However, this problem becomes negligible if the zones are properly defined. Note also that because of the overcharging probability requirement is much more demanding than the charging availability (100 to 1000 factor in terms of probability) the potential small impact in charging availability is clearly compensated by the fulfilment of the overcharging requirement,

This effect becomes clear in the following figure, which shows a particularly demanding example of a toll highway segment delimited by two ramps (one is an exit and the other one is an entry to the highway). The segment is very short (less than 1 Km) due to the presence of the ramps (which lead to or come from other roads that in principle could be free of charge) and also very narrow (due to the presence of side roads not belonging to the highway, and therefore also, in principle, free of charge). In such cases

Fig. 2. GPS errors and potential overcharging

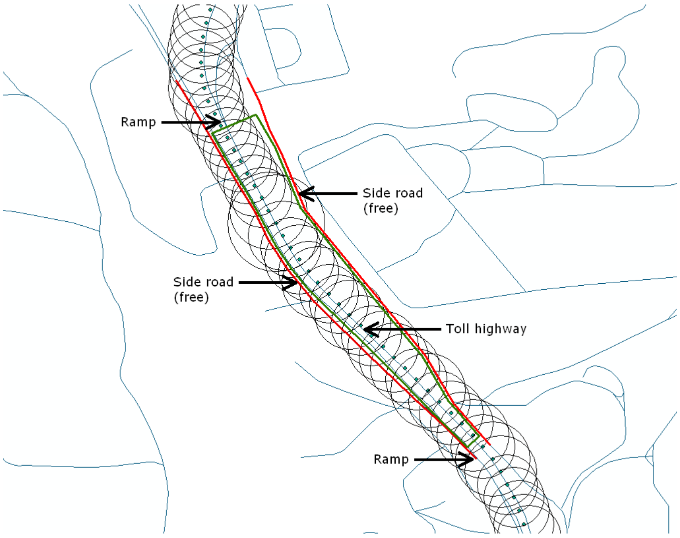

Fig. 3. Potential impact of the use of PLs in charging availability

it may happen (as it is the case in the figure) that none of the few protection levels computed along the segment (depicted as black circles around their associated computed positions) is small enough to ensure that the vehicle has used that highway segment at all. As a consequence, the integrity-enabled geofencing technique would fail to detect the usage of the segment, and therefore the user could not be charged for a single meter traversed inside the segment.

5. Considerations on the use of maps

With the proposed approach the use of road maps is not required as the only information that needs to be geo-referenced is on the Geo-objects but not the complete roads/streets network. This allows a very substantial simplification of the system in particular in what concerns the update process, problems associated with the accuracy of maps and, in the case of fat or smart OBUs architecture, the problems of maps upload to the OBU.

Some manufacturers propose the use of map-matching technologies as the way to perform Geo-object identification and, potentially, as a mechanism for distance measurement. However it is important to highlight that, in addition to the operational problems previously stated, classical map-matching techniques are having the following additional problems:

- They cannot solve all the GPS weaknesses since combination of GPS biases and parallel roads can lead to wrong road identification. The example described in the previous section can perfectly illustrate this limitation.
- Resulting performances are very difficult to be formalized so they cannot be applied if some performance requirements are established since validation would not be possible.
- They cannot measure real travelled distances as the estimated distance is based on the theoretical road segment.

These limitations have led this technology to be explicitly excluded in some ETC systems as the one being defined in The Netherlands.

For the resolution of the first two problems, the authors have defined an improved map-matching technique that uses the position integrity information. However, because of the mentioned operational problems this is not used for the proposed system.

6. Trials results

Different exhaustive trials have been executed in the city of London, the Netherlands and Madrid Region with the objective to analyse and compare different technologies in the application to an ETC system and demonstrate the added value of the use of integrity. In particular, the following technologies have been compared having as reference the identified requirements:

- Use of position Integrity vs. classical position-only solutions
- Use or not of odometer information also comparing different ways to access to odometer information.

Results have shown that high accuracies in distance measurements (less than 1%) are achievable with the technology and that probability of overcharging is extremely small if position Integrity is used. As a matter of fact, when using Integrity, overcharging has never happened during the different trials. Those results are fully compliant with the ABvM requirements and leave a large margin to introduce a more demanding overcharging requirement.

It is important to emphasize that, in line with ABvM requirements, map information has not been used for these trials what implies that solution is highly robust and not depending at all on maps accuracy and availability what is a major problem in classical map-matching algorithms.

7. Conclusions

This paper has presented an ETC system based on GNSS that allows satisfying the requirements of the infrastructure provider, measured mainly in terms of distance measurement accuracy and, especially, probability of overcharging. Unlike other GNSS based ETC systems, the proposed system does not require the use of additional technologies and/or infrastructure what provides maximum cost efficiency. The major step forward with respect to existing systems is the use of the GNSS integrity. These capabilities have been demonstrated to be essential in order to guarantee the correct charging performance.

The paper has also identified the key ETC requirements as currently stated by institutions and governments and has also proposed an alternative formulation that is considered to be better suited for a better system definition and for the assessment of its capabilities.

The different functions involved in the charging process have been described showing how integrity plays a critical role for ensuring the charging reliability.

Finally, the results of the trials that have been performed in The Netherlands and Madrid based on this technology have been shown. As a previous step a methodology for assessing the performance capabilities of the system has been proposed. Results show that with the use of integrity an overcharging has never been produced and distance accuracy is according to ABvM requirements. It is however important to highlight that due to the limited amount of data, results cannot be considered as definitive and that more exhaustive trials are needed. GMV is currently planning to perform a set of larger, in terms of time and number of vehicles involved, trials in the Netherlands in order to conclude on the system capabilities..

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