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Technological Issues in the Design of Cost-Efficient Electronic Toll Collection Systems

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1. Introduction

Nowadays, communications become essential in the information society. Everyone can get information anywhere, even in mobility environments, using different kinds of devices and communication technologies. In this frame the vehicle is another place where users stay for long periods. Thus, in addition to safety applications, considered as the most important services, other networked applications could bring an additional value for the comfort of drivers and passengers, as well as for driving efficiency, in terms of mobility, traffic fluency and environment preservation.

The payment methods for road usage have received a great attention during the past two decades. More recently, new advances in ICT (information and communication technologies) have encouraged researchers all around the world to develop automatic charging systems aiming at avoiding manual payments at toll plazas while enabling administrations to deploy charging schemes capable to reduce congestion and pollution. The recent application of Global Navigation Satellite Systems (GNSS) on these charging platforms can present important advances, and the research community in ITS (Intelligent Transportation Systems) is aware of this.

Although charging systems for road use have been called in many different names, the two most extended have been toll collection and Road User Charging (RUC), which were established considering the prime two reasons for deploying these systems (Rad, 2001). Firstly, toll collection was initially employed for charging the users of certain road infrastructures, with the aim of recovering the costs in construction, operation and maintenance. Many studies defend the application of this economic model to finance future road networks (Yan et al., 2009), instead of using public taxes or charging vehicle owners with a periodic fee (this is the case of Spain, for instance). On the other hand, road user charging has been the term used when the final aim of the system is not only to obtain revenue for road deployment expenses, but also to modify certain traffic behaviors in order to reduce pollution or congestion (among others) (Fields et al., 2009). The application of ICT to automate the charging process has introduced new terms, such as electronic tolling or electronic toll collection. In practice, many authors in the literature use all these terms indistinctively.

During the past years, dedicated short-range communications (DSRC) have been a key technology to automate the charging process on roads. By means of an on-board transceiver, the vehicle is detected when passing toll points. In real deployments there are usually

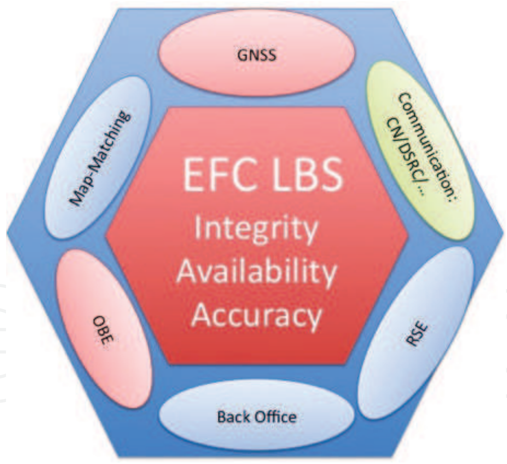

Fig. 1. Several elements comprise a GNSS-based electronic fee collection system.

speed limitations, since the communication channel between the on-board unit (OBU) and the roadside unit must be maintained for a while to allow the exchange of charging data. However, DSRC-based solutions present important problems, such as the cost of deploying roadside equipments when new roads want to be included in the system (a scalability problem) and a lack of flexibility for varying the set of road objects subject to charge. In this context, GNSS is lately considered as a good alternative. Essentially, GNSS-based RUC use geographic positions to locate vehicles in charging areas or roads, and this information is sent to the operator's back office to finally create the bill. The European Union is promoting the European Electronic Tolling Service (EETS) (Eur, 2009) as an interoperable system throughout Europe. This is based on a number of technologies, as it is shown in Fig. 1, although three of them are essential:

- Satellite positioning, GNSS;
- Mobile communications using cellular networks (CN);
- DSRC technology, using the microwave 5.8 GHz band.

Several standardization actions concerning electronic fee collection have been already considered by the European Commission, such as the security framework needed for an interoperable EETS, to enable trust between all stakeholders, and the definition of an examination framework for charging performing metrics.

Currently, some of the most important deployments of electronic RUC already use GNSS. In Switzerland, the LSVA system (also known as HVF for the English acronym of Heavy Vehicle Fee) complements a distance-based model that uses odometry and DSRC to check vehicle routes with GPS measurements. The role of GNSS in the German Toll Collect system is more remarkable, since GPS positions are used to identify road segments. Nevertheless, other extra mechanisms are used to assure vehicle charging in places where the GPS accuracy cannot guarantee the road identification. This problem has been analyzed for a potential deployment of a GNSS-based RUC in Denmark (Zabic, 2009), comparing the GPS performances obtained in 2003 and 2008. Although availability and accuracy problems had limited the usage of GNSS for RUC in the city of Copenhagen in 2003, more recent results showed that advances in receiver technology and updates in the GPS system made possible this application in 2008. This study supports this thesis primarily on the rise of the number of satellites in sight. In our opinion, these results must be taken with caution, since the experiments do not analyze how many satellites in view are affected by non-line-of-sight (NLOS) multi-path. In The Netherlands, the plans for creating a distance-based charging system for all vehicles on all roads also consider GNSS as the potential base technology (Eisses, 2008).

As it has been aforementioned, the accuracy of the position estimates is one of the main concerns towards the application of GNSS for RUC. It is necessary to provide a confidence level that assures that the estimate of the vehicle location is close enough to the real one with a certain high probability. This is the reason why the integrity concept is receiving a great attention in GNSS-based RUC these days (Pickford & Blythe, 2006). Per contra, the importance of the map-matching process is many times forgotten. When users are charged in accordance with the infrastructure used, the identification of charging objects (e.g. the road segment) is of key importance for the system. Even when the tariff scheme is not based on charging objects, the usage of additional digital cartography can be useful to improve the performance of the navigation system. Additionally, the communication subsystem, crucial for EFC, has not been properly attended in the literature so far. It is important to keep in mind that payment transactions cannot be completed if charging information does not arrive to credit and control centers. This chapter deals with these performance aspects regarding the navigation and communication subsystem and the map-matching algorithm used, all of these being key elements of EFC systems.

The rest of the chapter goes as follows. After presenting the concept of GNSS-based EFC in Section 2, more remarkable operation requirements and problems are analyzed in Section 3. The performance of the GNSS subsystem from the EFC perspective is then analyzed in more detail in Section 4. Next, some common methods for map-matching used in RUC are introduced in Section 5. Section 6 describes a proposal that further improves the performance of the navigation and map-matching subsystems, combining digital (and enhanced) maps with both GNSS and inertial sensors. Then, the performance of the communication subsystem when an on-board EFC unit is used is discussed in Section 7. Finally, Section 8 concludes the paper.

2. GNSS-based electronic fee collection

In GNSS-based RUC, information from the GNSS sensor is used to locate vehicles at charging places. The use of GNSS as the main positioning technology to charge users for the road usage, has several benefits related to flexibility and deployment costs:

- A minimum set of roadside units would be needed for enforcement purposes.
- OBU capabilities can be as simple as reporting GPS positions to a processing center, or as complex as calculating the charge and reporting payment transactions.
- A software-based OBU allows for software updates, reducing maintenance and system upgrade costs.
- GNSS sensors are cheaper and cheaper, and its performance is increasing.
- Cellular networks, which are the main communication technology considered, have a wide coverage, more than enough data rates for RUC, and decreasing costs that are also subject to agreements with operators.

Due to the flexibility of GNSS-based RUC, multitude of approaches can be designed to charge users. As main distinction factor, GNSS-based RUC solutions can be classified according to the tariff scheme used in the system. According to the literature (Cosmen-Schortmann et al., 2009; Grush et al., 2009), three tariff schemes can be distinguished:

Discrete charging In this case toll events are associated to the identification of road objects subject to be charged. This group includes single object charging (bridges, tunnels, etc.), closed road charging on certain motorway segments, discrete road links charging, cordon charging, or zone presence charging.

Continuous charging The tariff is calculated based on a cumulative value of time or distance. Distance-based charging and time-in-use charging are included in this group.

Mixed charging A combination of aforementioned approaches is used. An example of this tariff scheme is charging for cumulative distance or time considering a different price for each road segment.

3. Measuring the performance of GNSS-based RUC

A clear definition of the performance requirements for a road user charging system is needed for two main reasons. First of all, the industrial consortiums that apply for a deployment must be equally evaluated and the final choice must be based on the goodness of each solution according to some previously established performance needs. Secondly, the interests of users and authorities must be guaranteed.

Performance requirements must be described in such a way that any possible implementation that fulfills the needs may be under consideration and verifiable by means of field tests. Thus, requirements must be independent of the technology and internal calculations for charging. As the authors of Cosmen-Schortmann et al. (2009) claim, the issue of the positioning errors must be addressed by the proposed system, but not directly evaluated by the third part examiner that will evaluate all the proposals. The description of the performance requirements depends on the final charging scheme. Since it is likely that any final charging scheme is based on a combination of continuous and discrete ones, let us analyze briefly both cases here.

For a discrete charging scheme, there are only four possible cases: a correct detection (CD), a correct rejection (CR), a missed detection (MD) and a false detection (FD). Last two cases cause undercharging and overcharging respectively. Because the consequences of a MD and a FD are not the same, it is necessary to analyze these effects separately, and not by a single index of overall correct detection rate. Therefore, there must be two different performance requirements to avoid overcharges (for users) and to ensure revenues by avoiding undercharges (for authorities). Furthermore, it must be decided whether the requirements must be satisfied any time, for any trip in any scenario and under any circumstance, or it is enough if the average and some statistical parameters show that the overall errors of overcharge and undercharge are within desirable thresholds. The latter may lead to persistent errors in the bills of some users who repeatedly drive trajectories not well covered by the RUC system, due for example to bad satellite visibility conditions in the area. These special cases should be handled as exceptions, because it cannot be accepted that a system does not treat fairly every user.

Analogously, for continuous schemes two parameters are also needed to protect the interests of both users and service providers. Inspired by the notation of the navigation community (Santa, 2009), some authors introduce the concepts of charging availability and charging integrity (Cosmen-Schortmann et al., 2006). Charging availability can be defined as the probability that the charging error is within a desirable error interval. This parameter protects the interest of both the user and the toll charger, since it covers positive and negative errors (overcharges and undercharges respectively). Its main mission is to provide the toll charger with a level of warranty that the user will pay for the road infrastructure usage. On the contrary, charging integrity can be defined as the probability that the error is not over an upper limit; this is, that the user is not overcharged, and its value must be more restrictive than the charging availability (this is why we claim that the main objective of charging availability is to protect the interests of the authorities).

Since the charging integrity cannot be compromised, the developers must find a way to be aware of the reliability of every charge. In case of reasonable doubt, it is preferable not to charge, rather than to charge wrongly. For this reason, some integrity indexes must be calculated to verify the certainty of the charges. If integrity indexes inform of a possibly unsafe charge and the user is finally not charged, the probability associated to charging availability becomes smaller, but not the one linked to charging integrity. On the contrary, if the user is charged wrongly, both values of probabilities become smaller and the charging availability and integrity are compromised. The tuning of the integrity indexes must be done in such a way that it satisfies the needs regarding availability and integrity. If this tuning cannot be found, the system is incapable of providing the aimed level of reliability and it must be disregarded. Although a good estimation of the integrity parameters is crucial for the developers, this aspect must neither appear in the definition of performance requirements, nor being tracked during the evaluations. It must be understood only as an internal parameter that eventually affects the charging availability and integrity.

Finally, one must bear in mind that the performance indexes coming from both discrete and continuous schemes must be transformed into a unique performance parameter, based for example on the impact of each error (discrete or continuous) on the eventual charge. This is necessary since despite the fact that the proposals coming from the industry could be based on different charging schemes, there must be a possible direct comparison for all of them and the final system must be seen as a sole charging system independent of the scheme particularities. Furthermore, the integration of continuous and discrete performance indexes turns into essential for mixed charging schemes.

4. GNSS performance issues

The main technological drawback of GNSS-based RUC is the performance of the GNSS sensor. The lack of availability of the GPS signals at places where there is no line of sight with satellites is a remarkable problem in urban canyons, tunnels or mountain roads, for instance. A research assignment demanded by the Dutch Ministry of Transport, Public Works and Water Management (Zijderhand et al., 2006) focuses on the accuracy and reliability of distance and position measurements by GNSS systems. The trials involved 19 vehicles during one month, and concluded that during the 13% of the traveling time there was no valid GPS position, although the overwhelming part of the unavailability was due to time to first fix (TTFF).

Highly related to this, the continuity of the GPS services is also dependent on military decisions of the US government, since GPS is not a pure-civil navigation system. Moreover, the accuracy of the position estimates, although it has been improved thanks to enhancements in the space segment and in the receiver technology, is still not fully reliable to decide whether or not a user must be charged for supposedly using a road. Although some performance problems can be compensated (satellite clock bias, signal propagation delay, etc.), others such as multi-path effects in the user plane are not yet modeled and degrade the accuracy in urban canyons above all. All these problems can reduce the performance of a liability critical service such as RUC. The analysis made in Zijderhand et al. (2006) for GNSS positioning accuracy shows that its 95% level is 37 m. Nevertheless, this number must be taken with caution when considering RUC applications, because many other factors apart from the

GPS inaccuracies themselves can affect this result, such as inaccuracies in digital maps or errors in the map-matching process. The consequences of the positioning errors in the system performance would not be so severe if current GNSS devices provide a fully meaningful value of the reliability of the positioning: its integrity. In this case, although the performance of the system may diminish, its integrity remains and users would be protected against overcharge. It is then up to the authorities to decide whether or not the expected performance is good enough to deploy the system, in other words, to ensure the revenue of the investment. However, current integrity values provided for GNSS devices are inappropriate.

An approximation to provide integrity in GNSS-based positioning is given by the Receiver Autonomous Integrity Monitoring (RAIM) algorithm. This technique, initially created for aerial navigation, is based on an over-determined solution to evaluate its consistency, and therefore it requires a minimum of five satellites to detect a satellite anomaly, and six or more to be able to reject it (Kaplan, 1996). Unfortunately, this cannot be assumed in usual road traffic situations, especially in cities (Verhoef & Mohring, 2009). In addition, the RAIM method assumes that only one failure appears at once, something feasible in the aerial field, but not in road scenarios: it is usual that several satellite signals are affected by simultaneous multi-path propagations in an urban area. Satellite Based Augmentation Systems (SBAS), such as EGNOS (European Geostationary Navigation Overlay Service) or WAAS (Wide Area Augmentation System), also offer integrity calculation. By means of the information about the GNSS operational state, broadcasted by GEO satellites, it is possible to compute a parameter of system integrity (Bacci et al., 2005; Toledo-Moreo et al., 2008). However, this approach does not consider local errors such as multi-path, which are of key importance in terrestrial navigation. Due to these problems, in the last years some authors have suggested new paradigms to estimate the system integrity (Martinez-Olague & Cosmen-Schortmann, 2007; Yan et al., 2009). In concrete, the work described in Yan et al. (2009) shows an interesting approach for integrity provision based solely on GNSS that obtains interesting results. Fig. 2 illustrates the solutions provided by two different approaches (Santa, 2009; Toledo-Moreo et al., 2008; 2007) (among a number of the literature) for position integrity. The red line represents the HPL (Horizontal Protection Level) estimated by using the information provided by EGNOS. HPL does not include local errors at the user plane (such as multi-path) or the contribution of the aiding sensors. The green line shows the HIT (Horizontal Integrity Threshold) values along the trajectory. HIT represents the confidence on the horizontal position estimated by the filter that fuses the sensor data (this could be a particle filter or a Kalman filter, for instance). In Fig. 2, HIT does not show the peaks that appear in HPL caused by bad GNSS coverage, since HIT follows errors models that consider the vehicle and the aiding sensors. In this way, although HIT does not consider EGNOS integrity information for each satellite, it usually offers a better estimation of the real performance of the navigation system, since a multi-sensor approach (which supports periods of GNSS absence) is considered.

5. Map-matching for road user charging

In tariff schemes where the user is charged for driving along a road stretch or using a certain road infrastructure, the map-matching algorithm plays an essential role. However, as far as the authors know, there is not enough information in the literature about these algorithms applied to RUC, since current approximations are inside proprietary RUC solutions. This is identified as a problem towards standardization and calibration, apart from making more difficult the comparison between different algorithms.

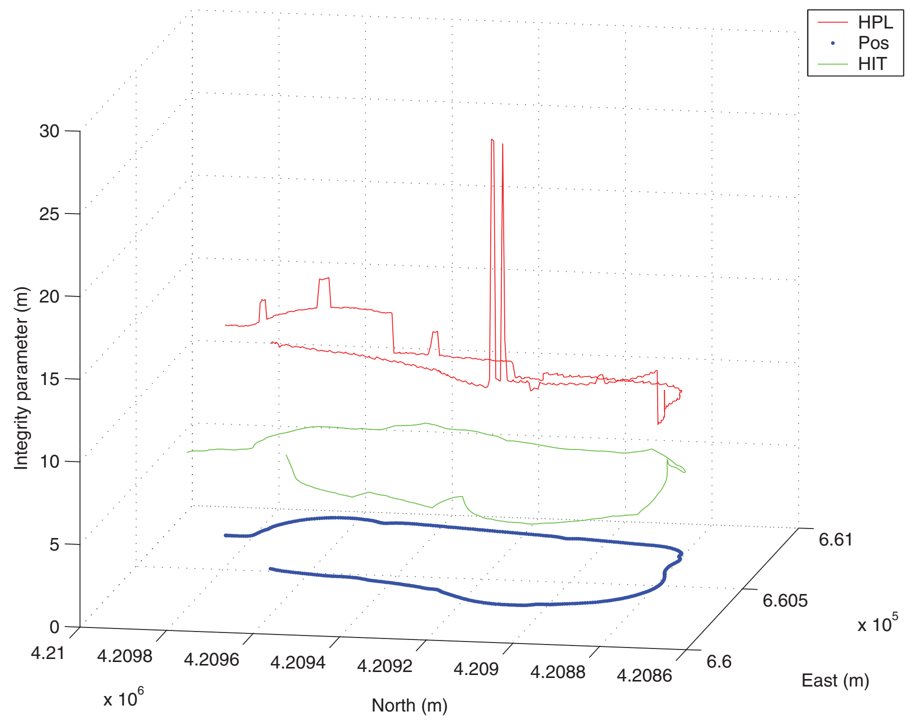

Fig. 2. Two different solutions for navigation integrity over the vehicle trajectory (in blue).

The most common algorithm used in map-matching is considering the distance between the vehicle location and the nearest road segment. In this way, apart from the GNSS sensor, digital information about the road network is necessary. Fig. 3 illustrates this algorithm, based on the point to segment distance. An ENU (East, North, Up) cartesian coordinate system is considered, and the computed fix for the vehicle at moment t_k is denoted as $P_{km} = (x_{km}, y_{km})$. The algorithm has three main steps:

1. Search for a road segment near the vehicle position, with coordinates $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$.
2. Calculate the distance d_m between P_{km} and the segment.
3. If current segment is closer than previous segments to the position estimate, take it as a candidate.

An scenario which illustrates a correct operation of the previous algorithm is shown in Fig. 4. The vehicle is correctly detected at the entrance and exit points in the charing link, and the K road segments pertaining to the stretch are also identified. However, in real complex scenarios, GNSS performance problems can imply misdetection of road segments and overcharging or undercharging.

An extra problem appears when vehicles drive near a charge link but the real driving road is not present in the digital cartography. An umbral factor to detect roads can help to solve this problem. Fig. 5 illustrates this solution over a distance-based charging scheme. It considers a 57 km travel of a vehicle along a mix of charge and free roads. The last ones were selected from the available secondary roads which are parallel to the main highway. For this case, a threshold of 10 m was found useful to solve the misdetection problem. According to our large

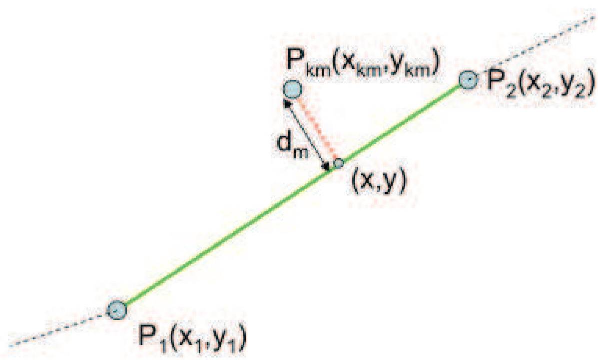

Fig. 3. Point-segment distance in map-matching.

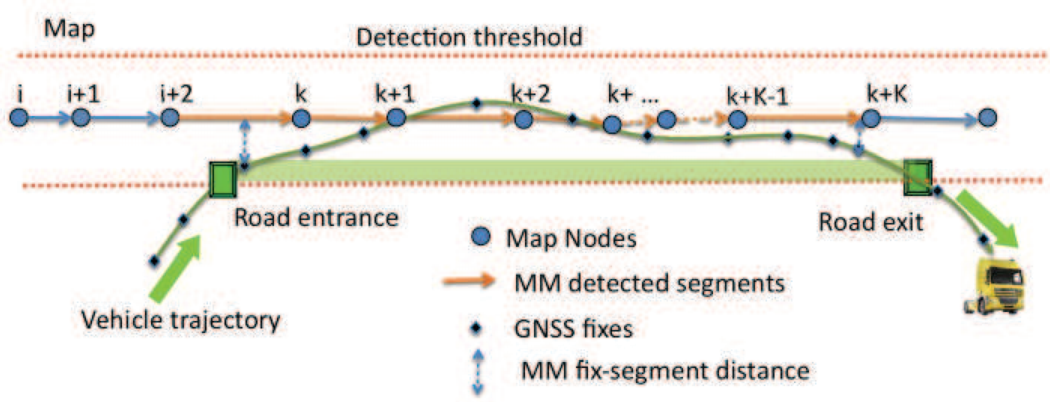

Fig. 4. Correct operation of map-matching using point-segment distance.

number of tests on Spanish roads, this technique and a suitable threshold can be useful to solve the problem of non-digitalized parallel secondary roads. However, further mechanisms are necessary to assure the correct identification of roads under potential GNSS performance errors and when more than one applicable road require a disambiguation decision.

6. Complementing GNSS in RUC

According to the current literature and our own tests, at its present form, the simplest approach for GNSS-based location for RUC based on single GPS positioning or GPS positioning map-matched to a standard digital cartography is not capable to ensure the demanded levels of performance availability and integrity. To enhance these results, standard positioning can be aided by different sensors in both the onboard equipment (OBE) and the road side equipment (RSE). We analyze in this section the main benefits of GNSS aided location with on-board sensors and maps for the purpose of RUC and its effect on the provision of performance integrity, with a especial emphasis on map aided road user charging.

6.1 Aiding positioning sensors

Many advanced positioning systems employ a minimum set of a GNSS receiver, an odometer for speed values and a gyroscope for heading estimates. This configuration presents a good balance between performance and budget. During GNSS outages, the dead-reckoning system

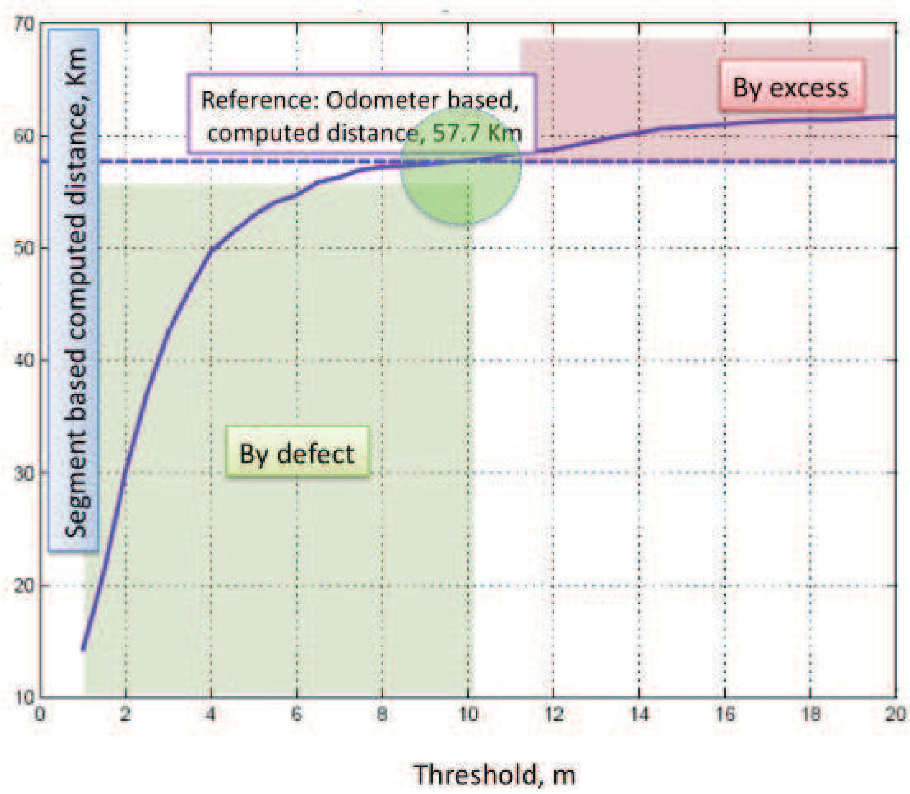

Fig. 5. Undercharging and overcharging and the selection of a threshold value in map-matching.

keeps estimating positions. The magnitude of position drifts depends primarily on the quality of the aiding sensors, but also on the skills of the algorithm used for sensor integration. Some interesting examples of GNSS-aided positioning in either loose or tight coupling modes can be found in Farrell & Barth (1998); Toledo-Moreo et al. (2007); Yang & Farrell (2003).

Aiding positioning supports RUC because as long as the quality of the position is kept and guaranteed, the road user charging system can stay available. Another advantage comes from the fact that hybridization algorithms smooth the noisy trajectories generated by the GNSS positions and represent more realistically the movements of vehicles, what can be useful to eliminate to some extent the overcharge accumulated in distance-based charging schemes that employ the GNSS positions to estimate the distance. It is also possible to compare the odometer distance and the GNSS-based one for enforcement purposes.

6.2 Exploiting enhanced maps for road user charging

Most Geographical Information Systems (GIS) represent roads with one or two polylines depending whether or not lanes with opposite driving directions are physically separated, being these polylines series of nodes and shape points, connected by segments. Apart from the global inaccuracy (from 5 m in urban areas up to 20 m in intercity roads) and the inaccuracy consequences of the local approximation of the road by series of linear segments, standard maps lack in contents. All these factors limit significantly the benefits of map-aided location for RUC.

The concept of enhanced maps (Emaps) was introduced with the objectives of reaching decimeter accuracy both globally and locally, respecting the shape of the road, and

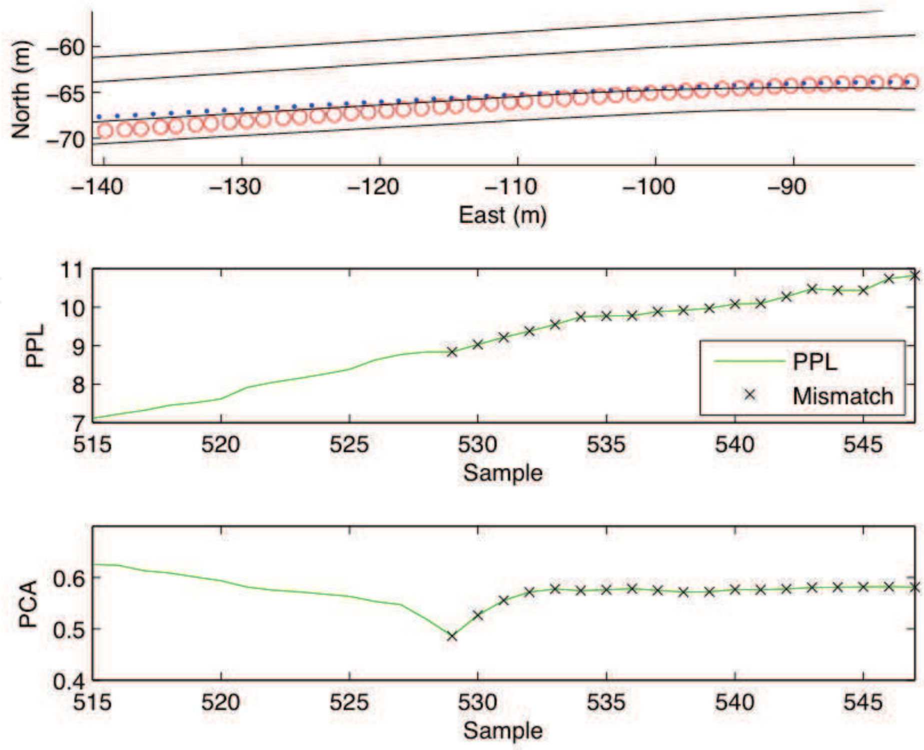

Fig. 6. (Top) Stretch of the trajectory during a period when the position estimates drifted as a consequence of a simulated GPS outage: solid black lines are the map; blue dots are the assumed true positions given by DGPS; red circles are the position estimates given by the PF. (Middle) PPL values during the period when the GNSS coverage is gone. The period of lane mismatch has been marked manually with black crosses. (Bottom) PCA during the same period.

representing all the lanes of the carriageway and their topological links. Our group collaborated with the Geolocalization research team of the Laboratoire Central des Ponts et Chaussées of Nantes, France, in the creation of a novel Emap introduced in the frame of the European Cooperative Vehicle Infrastructure Systems (CVIS) project (*Cooperative Vehicle-Infrastructure Systems (CVIS) project*, n.d.). This work proved to be useful for enhanced positioning and map-matching at the lane level (Bétaille et al., 2008). It is the authors' opinion that the benefits of Emaps can be exploited for RUC in the scenarios where standard maps fail.

Fig. 6 shows a stretch of one test carried out for a demonstration of the CVIS project. In the upper image the lanes are plotted from the data stored in the Emap. The high accuracy of the lanes allows one to distinguish at the first sight the drift in the position estimate that was caused by the simulation of GPS outage. The map building process, based on kinematic GPS integrated with inertial sensors and off-line processing, assured an error lower than five centimeters with respect to the driven middle-lane. Therefore, it can be claimed that the vehicle is actually on a lane if the confidence on the positioning is high enough. Blue dots represent the assumed true trajectory given by DGPS during a test. Middle and bottom images are to present the benefits of the confidence indicators, to be explained in next section.

6.3 Integrity provision

Independently of the charging scheme applicable for a road stretch or area, toll chargers need to know the level of reliability on the charge. For continuous schemes based on cumulative distance, this level can be represented by error-free positioning estimates, such as the one presented in Martinez-Olague & Cosmen-Schortmann (2007). However, as it has been previously stated, continuous charging schemes are likely to be completed with discrete ones, bringing the need of map-matching. It is the authors' opinion that when map-matching is needed for making the decision of whether or not a user should be charged, a single integrity indicator of the positioning error is not enough to represent the situation.

In the frame of the CVIS project, a double integrity indicator that represents the reliability of an algorithm for positioning and map-matching at the lane level was proposed in Toledo-Moreo et al. (2010). We believe that this paradigm can be exploited for road user charging purposes. To do it so, the proposed integrity parameters should represent the confidence on the positioning itself, as well as the confidence on the assignation of a position (or trajectory) to a road segment. The combination of both indexes may offer a representative idea of the positioning and map-matching process because they complement one another. The interest of the confidence on the position for continuous charging schemes is clear and it was discussed before. Nevertheless, there may be cases where the confidence on the position estimates is low due to bad GNSS coverage, but the map-matching problem is trivial, and the final confidence on the assignment can be high. On the contrary, even with a high confidence on the position estimates, if map-matching is difficult in a concrete scenario, the overall confidence should probably be low. In Toledo-Moreo et al. (2010) our paradigm of a double integrity index was proven to detect a significant number of wrong assignments at the lane level, improving the overall perception of the vehicle location. This can be exploited for road user charging purposes. The readers are welcome to follow this reference for further details.

The advantages of using these integrity indicators for the distinction of two adjacent lanes of the same carriageway is shown in Fig. 6. This situation could represent the RUC scenario of having contiguous lanes of a highway subject to different charges or the common case of two roads with different tariffs that go parallel and close along a certain distance. As it can be seen in the upper image of the figure, at one point of the trajectory the position estimates drift as a consequence of a simulated GPS gap (in this test the vehicle moves from the left to the right side of the image). The aiding sensor-set keeps the position estimates in good track for a while, but due to its low cost, eventually drifts and locates the vehicle in the contiguous lane. The increasing lack of confidence on the position is represented by the Positioning Protection Level (PPL) value and visible in the middle image of Fig. 6. PPL represents here a protection level based on the covariance of the positioning variables of the filter. However, even with lack of GPS coverage, the positioning and map-matching algorithm would not have allocated the vehicle in the wrong lane if both lanes would not be topologically connected: i.e., if due to physical or legal constraints the vehicle could not make a lane change to the left at that point. This is because the topological information stored in the Emap binds the vehicle location to the areas of feasible maneuvers. In that case, PPL values would still be high and the confidence on the position low, even though the vehicle is correctly assigned to the lane. The use of the Probability of Correct Allocation (PCA) indicator provides the information needed to distinguish between these two scenarios and deciding whether or not the vehicle can be charged. At the bottom of Fig. 6 it can be seen how PCA values become lower and lower, reaching the lowest value when the lane mismatch begins (the PCA value confirms the mismatch). Therefore, PCA enables the decision making of whether or not a rise of the PPL value corresponds to an incorrect lane allocation.

7. Performance of the communication link

There is another part of the OBU of key importance to perform payment transactions in GNSS-based EFC: the communication subsystem. Independently of the OBU capabilities to save the vehicle route or calculate the toll fee, a communication channel is necessary to send this information on time to a processing center. The performance of this link is also relevant, since payment transactions must be committed on the back office.

Among the different communication technologies used in vehicle telematics, the most considered for GNSS-based EFC are cellular networks. These are highly useful for EFC, since they offer vehicle to infrastructure communications by means of a wide deployment along road networks. Other communication technologies, such as DSRC or WiFi, are less suitable, since they are against the flexibility principle of GNSS road-pricing schemes, but they can be considered as complementary technologies. A set of communication performance parameters must be assessed in a GNSS-based EFC system, in order to include the necessary OBU capabilities to cache/calculate charging information or choose a telecom operator. Main performance issues of cellular networks include network coverage, network capacity, mobility conditions or vehicle speed (Santa et al., 2006).

Network availability is one of the main drawbacks of CN systems. Telecom operators do not offer the same service over the terrestrial surface. In urban environments, the CN coverage is excellent, due to the number of base stations where the mobile terminal can connect. In rural areas, however, the CN deployment is poor, or even null in some places. It is also important to differentiate between two important concepts regarding network availability in CN: coverage and capacity. Coverage can be understood as the possibility of the mobile terminal to use the network, because in this exact location, an operator has deployed (or not) the necessary infrastructure. However, even under good coverage conditions, the user can be rejected to establish a call or a data connection if the capacity of the network has been exceeded. Depending on several technological issues, such as modulation, frequency allocation and time slot scheduling, this effect has a different behavior. This way, the number of users who are concurrently using the network also restricts the CN availability. Since capacity or coverage problems can appear suddenly, the OBU must be ready to cache all charging information, which will be sent as soon as a data link is available again.

Apart from potential access to the network, some problems arise due to mobility effects. Handoffs between base stations are also important, due to potential decrease of performance in the process. If the mobile terminal is moving at locations far away from the base station without performing a handoff, poor latency and throughput results can be obtained (Alexiou et al., 2004). However, this effect is not remarkable in EFC environments these days, since most of the charged road networks are highways, where handoffs are less frequent. Nevertheless, the distance between two physical edges in the communication is not the only noticeable effect of mobility. Interference with other radio equipments and especially bad orography conditions could also cause communication problems in CN systems.

Finally, the speed is also a noticeable issue in cellular networks (Litjens, 2002). At the physical level, effects such as Doppler shift, Rayleigh fading and multipath propagation limit the bit rate allowable in CN at high speed. At link level, handoff issues must also be considered. Because the handoff process takes time (depending on the type), vehicles at high speed could have problems in places where the base station density is too high. For this reason, a high rate

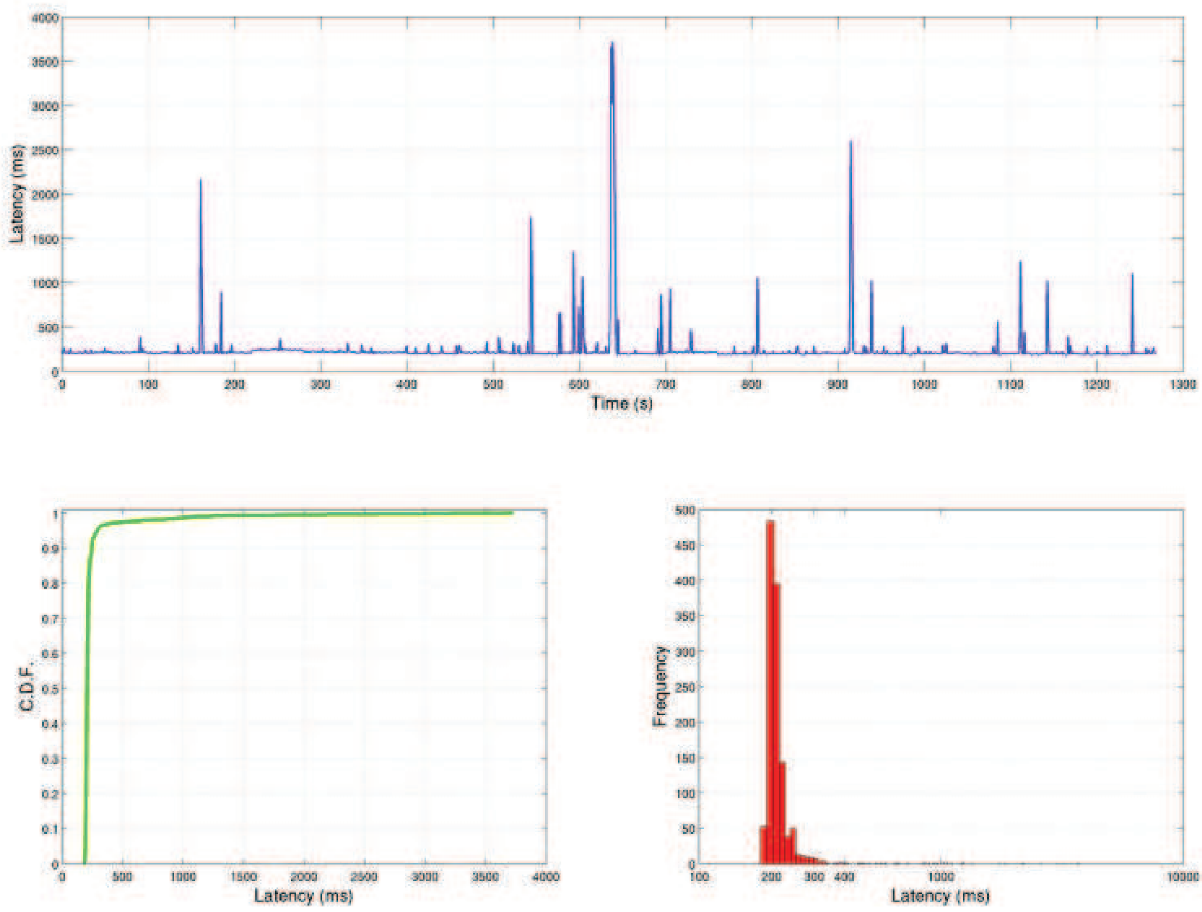

Fig. 7. An evaluation of a vehicle-to-infrastructure communication test using the UMTS cellular network.

of base stations at highways is favorable, apart from the obvious reduction in deployment costs. The tests shown in Fig. 7 illustrates some of the previous communication issues using a UMTS (Universal Mobile Telecommunications System) link. The on-board system considered in the field trials (Santa et al., 2010) uses the cellular network to send periodical messages to a server connected to Internet at the infrastructure side. The first graph shows the delay values for each message sent from the OBU. At a first glance, it is noticeable how mobility conditions cause continuous delay peaks.

There are three main problematic areas in the results shown in Fig. 7, which are noticeable in the groups of delay peaks observed in the first graph. The first one, between times 150 s and 200 s, comprises a road stretch where the car drives near a parking area covered with a metallic roof. Since radio signals are partially reflected, the network performance decreases. The second problematic area is more evident, between times 540 s and 700 s. The vehicle reaches the farthest position from the CN base station used for the connection and several buildings also block the line of sight with it, provoking a severe coverage problem. After leaving this area, the vehicle comes back towards the base station, where the network performance is good again. However, just before reaching the base station, the vehicle turns and goes across a third problematic zone between times 900 s and 950 s. At this location, a small hill between the vehicle and the base station decreases the channel quality. The graph that illustrates the cumulative distribution function (CDF) of the delay results shows that values between 180 and

240 ms comprise more than 90% of the messages. The rest of latency values are distributed in a quasi-logarithmic trend, since high latencies are less and less common. The last graph in Fig. 7 clearly illustrates this distribution of values, showing a histogram plot of the latency results with containers that are situated in a logarithmic scale on the axis of abscissas.

As it has been checked, mobile conditions in real scenarios cause performance variations when a cellular link is used to communicate with a node located in the wired Internet. Due to this, a good EFC system must be capable of caching enough charging information to commit payment transactions when the network is not available. Nonetheless, it is important to realize the good performance of new UMTS networks (a mean delay of 240 ms in the previous test) in places where telecom operators have deployed the necessary infrastructure. This should encourage researchers and engineers to consider this communication technology for telematic services such as road user charging in the next years.

8. Conclusion

The deployment of GNSS-based road pricing schemes needs to consider the impact of the different technologies involved in such a great system. The performances of the navigation and communication subsystems are found essential for a correct operation of a GNSS-based EFC but, as it has been described, the design of the map-matching algorithm is also a challenge. The analysis carried out in this chapter is considered as a first step prior to the assessment of high-level performance measurements in GNSS-based EFC, as charging reliability.

For today, it seems really difficult that any solution exclusively based on GNSS for positioning can ensure the high standards for charging reliability for road user charging. For this reason, it is the authors opinion that GNSS technology must be supported by aiding information coming from onboard sensors and even digital maps, following the line given in this chapter. Moreover, the calculation of integrity factors that indicate the position goodness at any time is considered a key need to measure and track the performance of the navigation system in liability critical services such as road charging, independently of the navigation system used. A proposal introduced in this chapter shows how the integration of multi-sensor navigation systems and next generation digital maps presents interesting advances to provide integrity and further map-matching capabilities.

Cellular networks have been identified as a good communication technology for GNSS-based EFC, due to their wide deployment and recent advances. However, several performance issues in real environments indicate that on-board units must be prepared to overcome eventual communication problems with backend systems. Among all these issues, the coverage and the capacity of the network in road segments are identified as the most important ones. In fact, these are being considered by telecom operators nowadays, installing more base stations or making the most of the available frequency spectrum. Only a reliable communication link can assure that payment transactions are committed at the back office of an electronic RUC system.

A deep study about all performance requirements in GNSS EFC is needed, or at least considering these three important elements: navigation subsystem, communication technology and map-matching technique. According to authors understanding, this preliminary analysis is needed for any GNSS-based road tolling system subject to be widely deployed in real environments, in order to guarantee both the user service and a fair charging scheme.

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10. References

Alexiou, A., Bouras, C. & Igglesis, V. (2004). Performance evaluation of TCP over UMTS transport channels, *Proceedings of International Symposium on Communications Interworking*, Ottawa.

Bacci, G., Principe, F., Luise, M., Terzi, C. & Casucci, M. (2005). Soft-rec: A gps real-time software receiver with egnos augmentation, *Proceedings of Workshop on EGNOS performance and applications*, Gdynia.

Bétaille, D., Toledo-Moreo, R. & Laneurit, J. (2008). Making an enhanced map for lane location based services, *Proceedings of 11th International IEEE Conference on Intelligent Transportation Systems*, Beijing.

Cooperative Vehicle-Infrastructure Systems (CVIS) project (n.d.). http://www.cvisproject.org.

Cosmen-Schortmann, J., Azaola-Saenz, M., Martinez-Olague, M. & Toledo-Lopez, J. (2006). Integrity in urban and road environments and its use in liability critical applications, *Proceedings of 2008 IEEE/ION Position, Location and Navigation Symposium*, Monterey.

Cosmen-Schortmann, J., Grush, B., Hamilton, C., Azaola-Saenz, M. & Martinez-Olague, M. (2009). The need for standard performance definitions for GNSS road use metering, *Proceedings of 16th World Congress on Intelligent Transport Systems*, Stockholm.

Eisses, S. (2008). The distance-based charging project in the netherlands, *Proceedings of 7th European Congress and Exhibition on Intelligent Transport Systems and Services*, Geneva.

Eur (2009). *Decision 2009/750/EC of the European Commission on the definition of the European Electronic Toll Service and its technical elements*, document c(2009) 7547 edn.

Farrell, J. & Barth, M. (1998). *The Global Positioning System and Inertial Navigation : Theory and Practice*, McGraw-Hill, USA.

Fields, G., Hartgen, D., Moore, A. & Poole, R. (2009). Relieving congestion by adding road capacity and tolling, *International Journal of Sustainable Transportation* 3(5): 360–372.

Grush, B., Cosmen-Schrtmann, J., Hamilton, C. & Martinez-Olague, M. (2009). GMAR standard performance definitions for GNSS road use metering, *Proceedings of 16th World Congress on Intelligent Transport Systems*, Stockholm.

Kaplan, E. (1996). *Understanding GPS: Principles and Applications*, Artech House, USA.

Litjens, R. (2002). The impact of mobility on UMTS network planning, *Computer Networks* 38(4): 497–515.

Martinez-Olague, M. & Cosmen-Schortmann, J. (2007). Gnss based electronic toll collection system of guaranteed performances, *Proceedings of 14th World Congress on Intelligent Transport Systems*, Beijing.

Pickford, A. & Blythe, T. (2006). *Road User Charging and Electronic Toll Collection*, Artech House, USA.

Rad (2001). *Minimum Operational Performance Standards For Global Positioning System/Wide Area Augmentation System Airborne Equipment*, RTCA/DO-229C edn.

Santa, J. (2009). *Service Deployment Platform for Intelligent Transportation Systems*, Lambert, Germany.

Santa, J., Toledo-Moreo, R., Zamora-Izquierdo, M., Ubeda, B. & Gomez-Skarmeta, A. (2010). An analysis of communication and navigation issues in collision avoidance support systems, *Transportation Research Part C: Emerging Technologies* 18(3): 351–366.

Santa, J., Ubeda, B., R., T.-M. & Skarmeta, A. (2006). Monitoring the position integrity in road transport localization based services, *Proceedings of IEEE Vehicular Technology Conference Fall*, Montreal.

Toledo-Moreo, R., Bétaille, D. & François, P. (2010). Lane-level integrity provision for navigation and map matching with GNSS, dead reckoning, and enhanced maps, *IEEE Transactions on Intelligent Transportation Systems* 11(1): 100–112.

Toledo-Moreo, R., Santa, J., Zamora, M., Úbeda, B. & Skarmeta, A. (2008). A study of integrity indicators in outdoor navigation systems for modern road vehicle applications, *Proceedings of IEEE/RAS 2nd Workshop on Planning, Perception and Navigation for Intelligent Vehicles*, Nice.

Toledo-Moreo, R., Zamora-Izquierdo, M., Ubeda-Miñarro, B. & Gomez-Skarmeta, A. (2007). High-integrity IMM-EKF-based road vehicle navigation with low-cost GPS/SBAS/INS, *IEEE Transactions on Intelligent Transportation Systems* 8(3): 491–511.

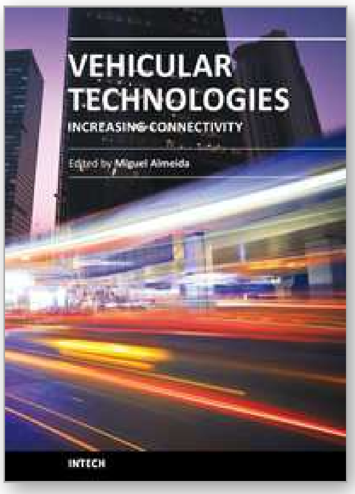
Verhoef, E. & Mohring, H. (2009). Self-financing roads, *International Journal of Sustainable Transportation* 3(5): 293–311.

Yan, G., Chen, X. & Olariu, S. (2009). Providing VANET position integrity through filtering, *Proceedings of 12th IEEE Intelligent Transportation Systems Conference*, St Louis.

Yang, Y. & Farrell, J. (2003). Magnetometer and differential carrier phase GPS-aided INS for advanced vehicle control, *IEEE Transactions on Robotics and Automation* 2(2): 269–282.

Zabic, M. (2009). Road charging in copenhagen: A comparative study of the GPS performance, *Proceedings of 16th World Congress on Intelligent Transport Systems*, Stockholm.

Zijderhand, F., Van Nifterick, W. & Zwiers, A. (2006). Accuracy and reliability of distance and position measurements by GNSS systems, *Technical report*, ARS Consulting, The Hague.



Vehicular Technologies: Increasing Connectivity
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This book provides an insight on both the challenges and the technological solutions of several approaches, which allow connecting vehicles between each other and with the network. It underlines the trends on networking capabilities and their issues, further focusing on the MAC and Physical layer challenges. Ranging from the advances on radio access technologies to intelligent mechanisms deployed to enhance cooperative communications, cognitive radio and multiple antenna systems have been given particular highlight.