GNSS-based Road Charging Systems - Assessment of Vehicle Location Determination -

An increasing demand for satellite-based road charging systems is developing in Europe. Satellite-based road charging involves charging road users for their road usage by allowing the vehicles to locate themselves within a certain charge area using Global Navigation Satellite Systems (GNSS). The research presented in this thesis deals with the performance and technological challenges of vehicle location determination within GNSS-based road charging systems.

GNSS-based road charging systems may take on a number of different forms. Depending on the charging objective, these road charging systems can be designed in various forms and varied by both policy and technology but they all share the overall function of charging vehicle users for their road usage. The first part of the thesis presents a comprehensive overview and classification of the various forms of road charging systems and enabling technologies; supplemented with a review of different worldwide examples. Next the system fundamentals are defined and presented in a conceptual framework which forms the basis for the research presented in this thesis. In order to understand the structure and behaviour of GNSS-based road charging systems, it is important to highlight the overall system architecture and define the essential system functions and describe the relationship among them. The framework is used as a means to structure the discussion about the technological challenges of GNSS-based road charging systems.

The thesis discusses the overall performance requirements for the road charging process within GNSS-based road charging systems. GNSS allows for time-distance-place charging, where charges are calculated for each individual vehicle based on the distance driven, the time of the trip and the vehicle’s geographic position. Timedistance-place charging is therefore considered a more fair and efficient way of charging as these systems levy charges proportionally to the distance travelled, and thereby reflects a usage-based approach more accurately than other charging policies. However, road charging on the basis of the distance travelled is technically challenging and is seen as one of the most complex schemes. Determining the distance driven is the key part of the charging process and the main dependability concerns therefore revolve around the road charging process and the performance of the vehicle location determination function. The thesis provides a thorough review of the different GNSS-based trials and experiments conducted within recent years to assess the performance and possibilities of GNSS-based charging systems. In 2007–2009, a GNSS-based road charging experiment was conducted in Copenhagen as part of this research in cooperation with Siemens to assess the performance and technical challenges of GNSS-based road charging systems based on state of the art road charging technology. This thesis presents the experiment conducted and provides an assessment of the vehicle location determination function within GNSS-based road charging systems. Previous trials and performance assessments of GNSS-based road charging systems have generally focused on the possibilities of the charging systems rather than on the impossibilities. Often it has not been clearly described which errors and shortages existed in the collected data, but instead they have just been excluded as invalid data prior to the assessments which then concluded that more focus should be placed on the errors occurred. Hence, it has been deliberate in this PhD research not to exclude faulty and incorrect data in the assessment. The results presented in this thesis are based on all the collected data from the experiment, in its original for, as it would be used as input for the automated charge calculation process in a road charging system. Furthermore, new methodologies are developed for assessing the performance of the vehicle location determination function in terms of data reliability and navigation function performance. The results from the assessments conducted in this thesis demonstrate that although significant performance improvements have happened during the last five years, there are significant challenges to overcome in relation to implementation and operation of GNSS-based road charging systems. The technical experiment conducted in this PhD study proved to suffer from different technical challenges which had different impacts on the overall system dependability. Due to these challenges, data includes both inaccurate and incomplete data information, and it is hence concluded that with these high levels of data invalidity and deficiency, data could not be used in its current form as basis for a road charging process. The results underline the importance of a data processing functionality prior to the road charge calculation and usage determination in the road charging process. The assessment of the vehicle location determination function show significant difference in the required navigation performance. While the accuracy requirement in Copenhagen was partly met, the continuity and hence availability required for vehicle location determination suffered from severe gaps in the positioning data. These gaps were due to both satellite unavailability, caused by poor urban signal reception and long receiver acquisition times, and furthermore due to the various technical problems and configuration faults which occurred during the experiment. As both the satellite visibility and the positioning accuracy had improved significantly, the results indicate that the main challenges related to vehicle location determination are not as often stated due to positioning inaccuracies but rather due to a high level of positioning interruptions mainly caused by GPS. From the performance assessment it is furthermore concluded that the main concerns regarding the unavailability of the vehicle location determination should be how to eliminate the large downtime and configuration gaps and reduce the occurrence of the many GPS gaps. As data outages and failures may affect the determination of the distance driven in continuous charging schemes, the thesis provides means to assess and understand the positioning gap occurrence, contribution and effects in relation to GNSS-based road charging systems. Hence, an assessment of the driven distance determination tolerance towards these different positioning related outages is provided. The assessment is conducted on the basis of a simulation methodology developed in this thesis. It analyzes the influence of positioning gaps on the determination of the driven distance in both distance-based and distance-related GNSS-based road charging schemes. The gap tolerance of the distance determination in both types of charging schemes is important for the road charging system’s ability to meet the performance requirements and charge the road users correctly for their road usage. The simulation analyses of the gap influence on the driven distance determination show that the distance determination function is relatively
robust against small gaps of less than 10 seconds in the positioning. However, with several medium and large gaps in the trips, both distance determination methods have trouble in reproducing the driven distances with distance deviations more than 1 % from the truth. The importance of these results is that for the majority of trips the distance driven can be determined with less than 1 % distance deviation as the occurrence of small gaps is most frequent in trips.

GNSS-based road charging systems are considered liability-critical systems, where denial of service and undetected fault and failures generate significant legal or economic negative consequences. Any fault or failures that lead to incorrect charging may cause economic loss or provoke wrong legal decisions as the economic liability is associated to the legal aspects due to the repercussion of potential claims. Hence, the thesis introduces the use of system dependability of GNSS-based road charging systems. The concepts of system dependability, adapted from computer engineering, provide an effective means of managing various concerns for road charging systems within a single conceptual framework. Dependability is an important requirement for a GNSS-based road charging system as the system must provide fair charging and gain user trust by ensuring system reliability and liability. This thesis discusses the impact of the assessment results in relation to system dependability and provides a qualitative dependability risk matrix for the vehicle location determination function.

To ensure high dependability of the road charging process, fault tolerant design should hence be considered in relation to many different components and functionalities within the process. Based on fault tolerant methodologies, this thesis provides guidelines of how to maintain correct service in the presence of different faults caused by technical problems related to vehicle location determination. The main objective of fault tolerant design within the road charging process is to ensure fair charging of the road users. This means that redundant systems, procedures and components should be implemented to ensure that when fault and failures occur within the road charging process, the road charge foundation will still be dependable and provide fair results towards both the road users and the road charging system. This thesis therefore concludes that though the vehicle location determination performance is fair, the focus of the system performance concerns should be placed on how future GNSS-based road charging system can be designed to work reliably with the occurrence of both data invalidity and data deficiency. It is therefore important to widen the focus from technical challenges and component inaccuracies alone to a focus on the system dependability as a whole. There is however still some technological challenges to overcome, which to a greater extent are remediated by better collaboration across the many different subject areas. As with many other ITS systems, a successful design, implementation and operation of a system is only achieved when the many different stakeholders understand each other’s requirements to the system. The system architecture as a conceptual design together with the system engineering methodology can help to involve all the different parties in the system development and hence minimize the misunderstandings which at the end can become very costly for the system.

Based on the several findings of this PhD research, some general guidelines are finally formulated for future GNSS-based road charging systems. The proposed guidelines described in the thesis address both GNSS-based road charging trials in general and a future GNSS-based road charging system in Denmark.

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