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A HIGH-LEVEL FUNCTIONAL ARCHITECTURE FOR GNSS-BASED ROAD CHARGING SYSTEMS

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ABSTRACT

Within recent years, GNSS-based road charging systems have been highly profiled on the policy makers' agenda. These types of systems are however technically challenging and are considered one of the most complex types of charging systems. To understand the structure and behavior of such road charging systems, it is important to highlight the overall system architecture which is the framework that defines the basic functions and important concepts of the system. This paper presents a functional architecture for GNSS-based road charging systems based on the concepts of system engineering. First, a short introduction is provided followed by a presentation of the system engineering methodology to illustrate how and why system architectures can be beneficial for GNSS-based road charging systems. Hereafter, a basic set of system functions is determined based on functional system requirements, which defines the necessary tasks that these systems must accomplish. Finally, this paper defines the system functionalities; and provides a generic high-level functional architecture for GNSS-based road charging systems.

Keywords: Architecture, GNSS, Road Charging System, System Engineering, Framework

BACKGROUND

As many other ITS applications, GNSS-based road charging systems use various technologies (computers, communications, sensors etc.) and include a continuous exchange of information within the system. These systems may be designed in various ways, depending on the charging objective [9]. In these complex systems, it is therefore essential to define and specify the system concepts in an overall system architecture which is the conceptual framework that defines the important concepts and the basic system functions. The system architecture hence becomes a central part in helping stakeholders to understand the structure and behavior of

GNSS-based road charging systems. However, little research has been done on defining the overall system architecture for GNSS-road charging systems. In general, the focus has been on the technological design options rather than specifying basic system functions and architectures. To the author's knowledge, no comprehensive definition of system functions and architecture of GNSS-based road charging exist. In the literature, Vonk Noordegraaf et al. [1] define a functional architecture for road charging schemes with focus on the functions that can be enabled by state-of-the-art technologies. The article highlights the technology options for the three road charging functions: Road Use Measurement, Data Communication, and Enforcement and Inspection and gives an overview of the technologies available and the criteria for technology choices. Burnham [2] has identified four main road charging system components which any road charging system needs from a system perspective. The article describes the characteristics of the technologies commonly considered for road charging systems and discusses different types of scheme design. In Brown [3], the basic functions for charging systems for infrastructure usage are derived. The article demonstrates how operational issues give rise to design and architectural considerations and presents a system architecture for road tolling systems including the main components and key interfaces. None of the above mentioned articles derive their functional architectures based on system requirements, which is a prerequisite in the system engineering methodology of bringing systems into being.

With the increasing demand for GNSS-based road charging systems in Europe, more attention is now being paid on defining standards and developing ITS architectures as reference for the large number of different types and combinations of GNSS-based road charging systems that are being developed throughout Europe (refer to the European ITS Framework Architecture [4]). As interoperable road charging has become one of European Commission's objectives, research projects are conducted on specifying and validating interoperability possibilities for the German, Swiss, French, Spanish, Italian and Austrian tolling schemes (see the CESARE Project [5]). Furthermore, the Road Charging Interoperability (RCI) project is contributing to the development of an open integrated framework that enables interoperability based on existing and planned European road charging systems [6].

Based on the concepts of system engineering, this paper therefore presents a generic high-level system architecture for GNSS-based road charging systems.

SYSTEM ENGINEERING METHODOLOGY

A high-level system architecture describes a system by defining the fundamental or logical structure of the individual components within the system's boundaries and interactions among them. System architectures come in many forms and may be created from a specific

perspective and be more or less detailed, focusing on specific aspects or parts of the complete system. In general, the functional architecture presents a top-level description of the system structure including its several functional blocks, sub-functionalities and components [7]. Each of these functional blocks, may additionally be decomposed into a series of sub-functions which can be further dissected to the component level. A functional architecture is derived by transforming the functional and non-functional requirements into a logical description of the system functions. The description is typically done by arranging the functions in logical sequences, where functions are decomposed into lower-level functional units and constraints are allocated from higher- to lower-level functions to support the integrated system design.

System architectures are an important part of the system engineering process of bringing a system into being; as it transforms needs and requirements into a set of system product and process descriptions and provide input for the detailed design which enables the system to be implemented [7]. Generally, architectures are used as a means of structuring the planning and discussion about the development of a desired system. It serves as an important communication, reasoning and analysis tool and becomes the point of reference to all parties involved. Especially within integrated systems, system architectures are important in order to have a clear and unambiguous understanding of the overall concepts, so that system designers can work in parallel on the development of individual basic components within the system framework [8].

FUNCTIONAL SYSTEM REQUIREMENTS

Every road charging systems has its own set of system requirements. The system requirements depend on the road charging objective as they define both what the system is required to do and under which constraints it is required to operate. In this paper, the focus is on identifying the functional architecture in order to highlight the necessary tasks that the system must accomplish, and describe the basic functions that any GNSS-based road charging system has to perform. Therefore, any commitment to specific design or operational constraints is at this point to be avoided so that the system architecture is described only in a functional manner with no technical specifications.

The overall concept of GNSS-based system is to charge the road users for their individual instance of road usage. In order to do so, the system must identify both the vehicle and user and measure their individual road usage. This collected data must be distributed within the system in order to calculate and allocate a charge to the identified road user. In addition, the system should be able to process the payment from the user and manage the revenue income from several road users. Regardless of which system or technology solutions are adopted, road charging systems must include some basic functional requirements in order to meet the

overall objective of charging road users for their road usage. The functional architecture presented in this paper, is based on the functional requirements determined by Zabic [9]. The functional requirements needed to deploy a GNSS-based road charging system is listed in Table 1 [9].

Table 1: Functional Requirements.

Functional Requirements for GNSS-based Road Charging Systems	
Identify vehicle and user	Handle verification of usage detection and transactions
Manage user registration	Minimize revenue leakage and fraud
Handle classification of vehicle characteristics	Produce evidence of charge evasion
Provide information and notification to users	Correlate user data
Provide facility to access in-vehicle equipment	Allocate charges to the road users
Provide continuous/discrete location determination	Handle collection and settlement of charges and penalties
Measure individual instance of road usage	Process payment from the road users
Report from vehicle equipment to enable charge	Handle compliance from road users
Distribute data and information within the system	Provide means for data security
Secure data and voice communication	Manage revenue and expenditures
Process collected data	Manage charge exceptions and discounts
Handle collection and management of data records	Provide means for protecting invasion of privacy
Calculate charge based on road usage	Provide facility for system maintenance
Identify violators	Provide facility for system monitoring and control
Provide means for system interoperability	Manage administrative operations

These basic functional requirements represent the minimum needed but should however always be adapted to the specific case.

BASIC SYSTEM FUNCTIONS

These identified functional requirements can be classified and transformed into a basic set of system functions that hence become the functional building blocks of GNSS-based road charging systems in general.

The functional building blocks for GNSS-based road charging systems presented in this paper are inspired from [1], [2], [3] and subsequently derived by taking into account the identified functional requirements related to both the charging process, the means for ensuring privacy and system security, the communication needed to exchange information and the requirements for system management and service that administers the entire system [9]. The resulting seven functional building blocks are given in Figure 1.

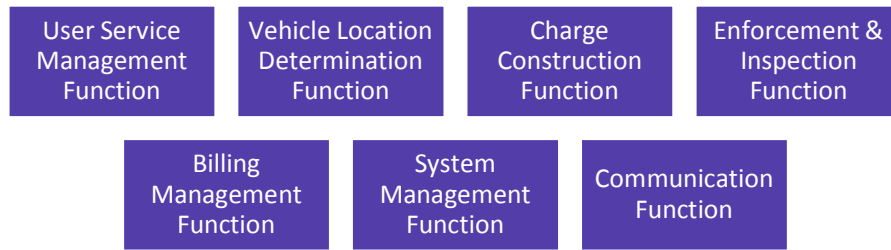


Figure 1: GNSS-based Road Charging System Functions.

These seven basic system functions form the generic foundation of any GNSS-based road charging system and hence form the basis for the high-level system architecture presented in the following.

SYSTEM FUNCTIONALITIES

The seven basic system functions determined in the previous can be further decomposed into several sub-functionalities that are necessary for a GNSS-based road charging system. This section presents the main functionalities of all the functional building blocks involved. The system functionalities are kept generic of all GNSS-based road charging system configurations [9].

The System Management Function

The system management function in a GNSS-based road charging system is responsible for the overall system functioning, which covers the accumulation of all functions, subsystems, methodologies and operations for the control and functioning of daily performance of the road charging system. The tasks to be satisfied by the systems management function can be categorized into four functional areas: accounting management, maintenance management, configuration management and security management.

The accounting function manages the system revenue and expenditures. It covers all the administrative operations and handles the revenue management according to the charging objective and policy. The maintenance function deals with continuous maintenance of the system components. The maintenance function requires continuous information on component health and service schedules and conducts reporting on system alerts, alarms and failures to keep all system components in repair. It also maintains system warranty, license and service organization details [3]. The configuration management focuses on establishing and maintaining consistency of the road charging system's performance with its requirements and design [14]. It includes activities (such as annual reviews and evaluations) to ensure that the system requirements are consistently being met in an effective and efficient manner. It focuses both on performance of the organization, the system functions and processes, level of

service and manages any necessary changes. In addition, the configuration management directs system adjustments and ensures interoperability. Security management is related to both physical security of the road users and human resource safety functions. The security management provides means for protecting invasion of privacy. It entails the identification of information assets and the development, documentation and implementation of policies, standards, procedures and guidelines in accordance with the legislation. These system management functionalities are classified into four sub-functions [9] given in Figure 2.



Figure 2: System Management Functions.

The system management function requires continuous reporting from the remaining functional blocks to ensure that the system satisfy the overall requirements. An effective management system is crucial to ensure a smooth functioning of all system functions, leading to system success, user acceptance and economic advantages.

User Service Management Function

The User Service Management manages the road user registrations and technical installations in the vehicles. Several road user registrations may be available depending on the charging scheme. In GNSS-based systems, OBU installations are required for regular, frequent road users, which then are linked with pay-per-use accounts [13]. The user service management function manages the necessary tasks for installation, repair and service of OBU in vehicles together with the road user registrations. Road user registration requires as a minimum enough information to identify and validate the vehicle in order to link it with an account. The road user registration is therefore closely connected with the billing management function that manages the pay-per-use accounts. These user management functionalities are classified into three sub-functions [9] given in Figure 3.



Figure 3: User Service Management Functions.

In general, the user service management function provides service to the road users before, during and after the road charging process. It assists the remaining functional blocks in providing information and assistance to the road users.

Vehicle Location Determination Function

The main objective of the Vehicle Location Determination function is to gather information on the vehicles' road usage by determining their position when driving by use of GNSS positioning systems (refer to [9]). Determining the position of moving objects is a fundamental task for many ITS applications such as autonomous navigation, collective traffic observation, and tracking of commercial vehicles. In road charging systems, the vehicle positioning is important for detecting the vehicles' driving and thereby determining their road usage. GNSS-based road charging systems can be either distinct or cumulative [10]. In distinct charging systems, vehicle positioning is applied to locate the vehicles in relation to specific roads or areas, while it is applied for continuous location determination in cumulative charging systems. In both types of charging systems, the GNSS location determination may be combined with additional measurements from cellular positioning or dead-reckoning sensors. In GNSS-based road charging systems, additional measuring may furthermore be necessary for automated classification of vehicle characteristics, depending on the scheme design. Additional measuring of vehicle characteristics may be performed by sensor systems either in the surface, roadside or overhead [11]. Inductive sensors embedded in the road surface can detect the presence of a vehicle, while roadside or overhead sensors can detect vehicle height, number of axles, shape of vehicle and gaps between vehicles to provide information on the number of vehicles crossing at a specified location. The scope of the vehicle location determination function also includes data reporting. The data reporting function collects and combines the measurement data from the positioning system and the additional sensors if applied. It selects the relevant information required and prepares data for subsequent communication to the charge construction process.

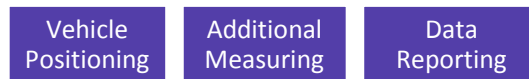


Figure 4: Vehicle Location Determination Functions.

The vehicle location determination functionalities are classified into three sub-functions [9] given in Figure 4.

Charge Construction Function

The main objective of the Charge Construction function is to calculate the charge based on the vehicle's road usage. The charge construction function is closely related to the vehicle location determination function and can either be integrated as an on-board function embedded in the vehicle's OBU or as a off-board function in a central server based system. The charge construction function receives the collected data from the vehicle location determination function and processes the data for charge calculations. The scope of the charge construction function also includes data processing and summarizing and sorting the location

data from GNSS or other sources available and converting the raw data into usable information for the charging process. Furthermore, it involves validating and storing data. Based on the collected location data, the charge construction function determines the vehicle's road usage. This is achieved by spatial analyses of data and different methods of charge calculation. The different charge calculation methodologies are in this paper classified into two overall categories: Distance-based charging based on the distance travelled as a measure of usage (i.e. kilometer) or distance-related charging based on the length of the road segments used.

The charge calculation in distance-based charging is based on summarizing the distances between the GNSS positions for every trip made, while the charge calculation in distance-related charging is based on relating the GNSS positions to the road network and summarizing the length of the road segments used. Depending on the scheme's level of charging detail (zone, segments etc.), different methodologies may be applied. Map-matching is a spatial analysis tool that based on an advanced algorithm, integrates the location data with the spatial road network on a digital map. The algorithm snaps the positions or trajectory to the nearest viable road and thus recreates the driven routes. Map-matching thereby enables the physical location of the vehicle to be identified on the map and is often used for navigation applications [9].

From the usage determination, the charge calculation determines the charge amounts to be paid corresponding to the vehicle's road usage. The charges are calculated by automated processes that for a given period (e.g. weekly or monthly) summarize the total charge to be paid. If the charge calculation is integrated in an on-board charging function, the calculated charges can be displayed to the vehicle users. The summarized charges are forwarded to the billing management function.

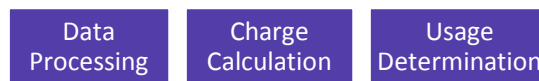


Figure 5: Charge Construction Functions.

The charge construction functionalities are classified into three sub-functions [9] given in Figure 5.

Enforcement & Inspection Function

The main objective of the Enforcement & Inspection function is to reduce the levels of unpaid charges, recover lost revenue and prevent fraud and sabotage to the system. According to KonSULT [12], the enforcement strategy needs to be based on three fundamental objectives:

- Ensuring that charging policies and payment rules are followed by all road users
- Informing and raising awareness of scheme requirements to prevent non-payment
- Ensuring that the fees are paid

This is achieved by inspecting the road users to identify violators and produce evidence of fraud and unpaid charges. The evidence is used in case of compliance or to apply the charge to the correct user account and thereby ensure that the fees are paid. This can be achieved by use of Automatic number plate recognition (ANPR) technology, tag and beacon technology or by police inspection and physical barriers. Police inspection is a means of preventing fraud, as being stopped by the police and having an immediate penalty is memorable for the violator. In a GNSS-based system, police inspection of the vehicles would mean verifying that the On-Board-Unit (OBU) is working correctly and that the GNSS positioning function is not obstructed intentionally. However, in a large scale road charging system police inspection is limited due to the expanse of resources and the costs associated. This makes their use on a continuous basis impractical, such that the probability of being stopped is likely to be low. Physical barriers can help to ensure that all vehicles passing through into a specific area have paid charges. With barriers, violators are identified immediately, as the barrier will not permit the violator to proceed. However, barriers also force the authorized users to slow to near-stop at the gates.

With the gathered evidence of road usage and fraud attempts, compliance can be processed in cooperation with the billing management function. The evidential processes rely on the accuracy of the evidence captured. Often a combination of the evidence extracted and associated information on time, date, vehicle location and positioning data are used to check whether an user account exists and whether the vehicle has been seen elsewhere [13]. The enforcement and inspection function thereby supports the vehicle location determination function in classification and identification of the vehicles. If the vehicle location determination function fails, road usage can be proven by use of the enforcement and inspection function and the charge can be estimated based on a combination of collected vehicle information.

The scope of the enforcement and inspection function also includes data verification, which is a very important process within GNSS-based road charging systems. Data verification takes effect as quality assurance of the charging process and features verification of the data collected, the road usage determined and the charge calculated and finally allocated. The data verification function includes database checks, process evaluations, and assessment of results.



Figure 6: Enforcement & Inspection Functions.

The enforcement and inspection functionalities described above, are classified into four sub-functions [9] given in Figure 6.

Billing Management Function

The main objective of the Billing Management function is to allocate charges to road users and manage the payment processes. When charges are calculated within the charge construction function, the charge data are forwarded to the billing management function, which hereafter correlates charges with user data and manages the invoice and payment processes. The billing management function manages and applies applicable discounts. In general, road charging systems can operate by prepay, post-pay, or a combination of both [13]. It is recommended that all vehicles are linked to an account, in order to provide a higher level of service to the road users. According to Burnham [2], billing for road charging systems is similar to the complexity of billing within telecommunications; the challenge is getting the accurate usage data, not in applying a tariff or handling user accounts.

These core functionalities are furthermore supported by functionalities that store billing details for producing reports of billing history, and maintenance road user information for resolution of customer issues and customer relationship management. In addition, the billing management function must handle road user complaints and is therefore closely related to the enforcement and inspection function, which verifies user data and produce the necessary evidence.



Figure 7: Billing Management Functions.

These billing management functionalities are classified into four sub-functions [9] given in Figure 7.

Communication Function

The scope of the Communication function covers the distribution of information to the road charging system components in the form of voice, data and video information. This is achieved using various communication methods. In GNSS-based road charging systems, the data collected needs to be communicated regularly from the vehicles to a central site in order to process charging of the vehicles. In general, the communication function provides connectivity and information transfer between road users, infrastructure and charging system

providers that are both internal and external to the road charging system. In this paper, the communication function is not decomposed into sub-functionalities as the communication function is very dependent on the system design.

HIGH-LEVEL FUNCTIONAL SYSTEM ARCHITECTURE

The defined functional blocks and their related sub-functions are presented in a generic high-level functional system architecture illustrated in Figure 9.

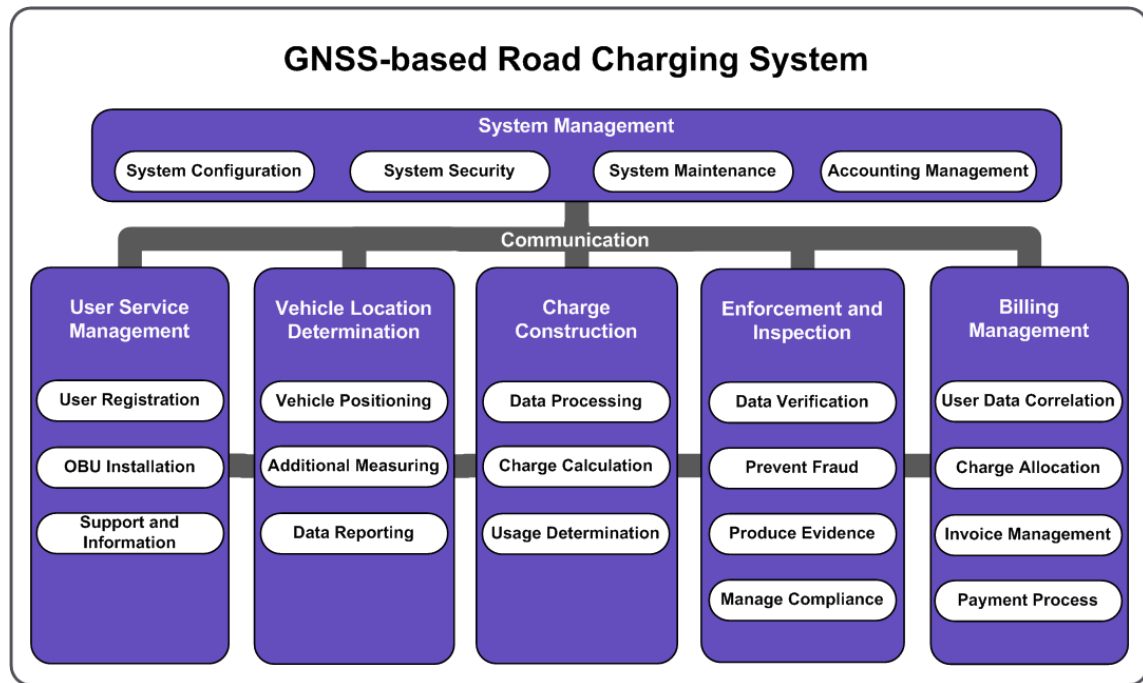


Figure 9: High-Level Functional Architecture.

This high-level functional system architecture presents the system functionalities independent of specific system design and is defined as the overall functional framework for any GNSS-based road charging systems [9]. This architecture may within future GNSS-based road charging systems be further decomposed and adapted to the specific case, and hence become a central part for all entities involved in understanding and defining the overall project. In these complex systems where user needs and technology is continuously changing, this high-level architecture helps to maintain the conceptual framework that defines the important concepts and basic functions of GNSS-based road charging systems.

SUMMARY

This paper has presented a high-level functional architecture for GNSS-based road charging

systems based on the system engineering methodology. A set of functional requirements were transformed into seven basic system functions for which the sub-functionalities was defined. Based on these functionalities, a high-level functional architecture was presented, which can serve as a common reference framework that helps to keep focus of the important concepts and basic functions of GNSS-based road charging systems.

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