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Smartphone Based Measurement Systems for Road Vehicle Traffic Monitoring and Usage Based Insurance

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PETER HÄNDEL, JENS OHLSSON, MARTIN
OHLSSON, ISAAC SKOG, ELIN NYGREN

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School of Electrical Engineering
KTH, Royal Institute of Technology

Smartphone Based Measurement Systems for Road Vehicle Traffic Monitoring and Usage Based Insurance

Peter Händel, Jens Ohlsson, Martin Ohlsson, Isaac Skog, Elin Nygren

Abstract—A framework is presented to deploy a smartphone-based measurement system for road vehicle traffic monitoring and usage based insurance. Through the aid of a hierarchical data model to modularize the description, the functionality is described as spanning from sensor-level functionality and technical specification, up to the top-most business model. The designer of a complex measurement system has to consider the full picture from low-level sensing, actuating, and wireless data transfer to the top-most level including enticements for the individual smartphone owners; the end-users who are the actual measurement probes. The measurement system provides two data streams – a primary stream to support road vehicle traffic monitoring, and a secondary stream to support the usage based insurance program. The former activity has a clear value for a society and its inhabitants, as it may reduce congestion and environmental impacts. The latter data stream drives the business model and parts of the revenue streams which ensure the funding of the total measurement system, and create value for the end-users, service provider and the insurance company. Besides the presented framework, outcome from a measurement campaign is presented, including road vehicle traffic monitoring (primary data stream) and a commercial pilot of usage based insurance based on the driver profiles (secondary data stream). The measurement system is believed to be sustainable, thanks to the incitements offered to the individual end-users, in terms of a favorable pricing for the insurance premium. The measurement campaign itself is believed to have an interest in its own right, as it includes smartphone probing of road traffic with a number of probes in the vicinity of the current state-of-the art, given by the Berkeley Mobile Millennium Project. During the 10 month run of the project, some 4,500 driving hours / 250,000 km of road vehicle traffic data was collected.

Index Terms—Complex measurement systems, Smartphone based measurements, Usage based insurance (UBI), Mobile millennium, Insurance telematics, Moveo campaign, Pay how you drive (PHYD), Pay as you drive (PAYD)

I. INTRODUCTION

The number of cellular phones in the world grows steadily each year, with almost seven billion mobile subscriptions at the end of 2012; corresponding to some 96 percent of the

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P. Händel, M. Ohlsson and I. Skog are with the Department of Signal Processing, ACCESS Linnaeus Centre, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden. They are also with Moveo AB, Sveavägen 62, SE-111 34 Stockholm, Sweden.

J. Ohlsson is with the Department of Computer and System Sciences, Stockholm University, SE-164 40 Kista, Sweden, and with Moveo AB, Sveavägen 62, SE-111 34 Stockholm, Sweden.

E. Nygren is with Moveo AB, Sveavägen 62, SE-111 34 Stockholm, Sweden.

Corresponding author: P. Händel, ph@kth.se.

Fig. 1. Screen shot of aggregated road traffic data (that is, an example of primary data) during the pre-launch of the reported MOVELO campaign, March 2013. A part of the Greater Stockholm area is zoomed in. The figure illustrates the geographical concentration to the main roads of the gathered road traffic information.

world population [1]. Cellular phones are often referred to as feature phones and smartphones, where the former provides basic telephony and the latter provides flexibility by the use of software applications known as “apps”. The smartphone has become more and more popular, corresponding to one third of the cellular phones shipped out, or in absolute measures some 700 million units annually.

From an instrumentation and measurement point of view, we can foresee a revolution in the collection of data, since the smartphone is a ubiquitous device deployed on a large scale. The smartphone is factory equipped with a plurality of means for sensing and sounding out the environment, like radio receivers for a multitude of wireless cellular standards spanning from the second generation Global System for Mobile Communications (GSM), to the fourth generation Long Term Evolution (LTE); Wireless Local Area Network (WLAN) based on IEEE 802.11 standards; Personal Area Networks (PANs) like Bluetooth; satellite positioning systems like the Global Positioning System (GPS) and *Globalnaya Navigatsionnaya Sputnikovaya Sistema* (GLONASS); inertial measurement sensors like accelerometers and gyroscopes; electronic compasses or magnetometers; and audio-visual sensors like cameras and microphones. Accordingly, the smartphone provides a versatile probing device deployed on a large scale, enabling massive time- or location-based measurement campaigns.

A. Road Traffic Monitoring

Road traffic monitoring is an example of a complex smartphone-based measurement system; as illustrated in Fig. 1. State-of-the art research projects like the Mobile Millennium in the US provided a pilot traffic-monitoring system that used the GPS in cellular phones to gather traffic information, process it, and distribute it back to the phones in real time. Already in 2008, a traffic probing field campaign (known as the Mobile Century field experiment) was carried out which involved 100 private cars carrying GPS-enabled Nokia N95 phones [2], [3]. For the work reported in [2], real-time measurements were collected every third second while the vehicles repeatedly drove loops of 610 miles in length continuously for 8 hours on freeway I-880 near Union City in the San Francisco Bay Area, California. The successor, the Mobile Millennium project was launched in late 2008 and remained operational until the summer of 2010, with more than 2,000 registered users. The project demonstrated that the concept of infrastructure-free road traffic data collection is feasible [4]. In the perspective of a large-scale smartphone-based measurement system, the Mobile Millennium project highlighted some challenges that will need to be addressed before launching this kind of system, including a shift from procuring information rather than measurement probes, and the definition of the roles and business models for involved measurement collecting actors; challenges that are addressed in this work.

Other relevant road traffic monitoring projects include the Nericell by Microsoft, India [5]. However, the work in [5] does not address issues such as how to provide incentives for the participants. In general, the use of the sensors and processing capabilities of smartphones for vehicle applications is an emerging area with several recent publications [6], [7], [8], [9]. The case study presented in this article includes a smartphone probing of road traffic with a number of probes in the vicinity of the Berkeley Mobile Millennium Project, CA, USA, which is believed to have an interest in its own right.

B. Smartphone-Driven Usage Based Insurance

Insurance telematics refers to the technology of sending, receiving, and storing information from and to road vehicles for insurances purposes [10], [11], [12]. The market is expected to take off in some regions leading to a penetration of up to some 40 % share of total policies in 2020 [11]. Currently, the market penetration is low, with the Progressive Casualty Insurance Company in the US as the market leader with some 1.4 million customers in their program [12], and strong intellectual properties [13]. The measurement probe may be a fixed installation in the vehicle, semi-fixed installation using the power and data outlets, or a smartphone, as illustrated in Fig. 2. The probe monitors and transmits risk related information to the insurers such as the speeding, cornering, braking and accelerating habits, the time and date, and road conditions. The information collected by the measurement probe can be used by the insurers, to approve their risk assessment, thus through use of this data a particular driver's behavior can be assessed.

Fig. 2. Examples of measurement probes for insurance telematics: Progressive Insurance Snapshot probe for on-board diagnostic outlet (left); Probe for the cigarette lighter outlet (middle); Smartphone with UBI software (right).

As insurers can gain access to actual driving behavior data via the probe, the premium can be adjusted to reflect the driving habits of a driver and their related risk – so called, usage based insurance (UBI). As a result, the insurance premium can individually be adjusted according to the driving behavior and the likelihood of a claim related to that particular driver can be predicted. Insurers have long relied on factors such as the age of the driver and place of residence to calculate premiums. Insurance telematics has helped the insurers to use other variables in their risk calculation. By using telematics technology, the insurers can improve the pricing accuracy and sophistication, as well as attract favorable risks. As a result, the claims costs will be reduced, which in turn will enable lower premiums. The technology will help the insurers to increase their overall profitability.

For policy holders, there are numerous benefits related to a UBI program. Usage-based insurance will lead to premium discounts for the low risk end-users and they can enjoy value-added services such as teen-driver monitoring, emergency services, navigation and infotainment, stolen vehicle recovery, and vehicle diagnostics. In case of an accident, drivers can also use their profile of driving behavior to prove safe driving behavior to the insurer. In this paper, findings are presented from the first ever trial of a smartphone-based UBI, where the Smartphone is used as an advanced measurement probe in a complex measurement system.

C. Sustainable Large-Scale Smartphone Based Measurement Systems

The problem at hand is how to conceive, design, implement, and operate a complex measurement system as the one discussed, which performs reliably, efficiently, and predictably, and is manageable, controllable, and upgradeable. It must have a framework for a wide set of tasks including, but not limited to, computer power and wireless transmission resource allocation, software revision handling, incentive strategies for the voluntary end-users, and a business model that secures that the effort is profitable for the commercial actor. A rationale for this paper is that the system designer has to consider the full picture from smartphone low-level sensing, actuating, and wireless data transfer to the top-most level, including

Fig. 3. The triple helix providing the foundation for a sustainable large-scale measurement system based on a large number of smartphones as measurement probes. In the article, the primary data is data for road traffic monitoring of societal value. The secondary data includes the driving behavior parameters, or the risk profile, of the individual end-users, of commercial value for the insurer running a usage based insurance program. The individual car owners or end-users are offered incentives like discounts on the insurance premium.

incentives for the individual smartphone owners; as well as provide an attractive business model.

Simply providing a downloadable software measurement application (that is, an “app”) for individuals to download is not sufficient to build a large-scale smartphone-based measurement system. Incentives have to be provided to the signed-up smartphone owners, that is the “End-users” in Fig. 3. The cost for the collection of measured information scales with the number of probing platforms, and by a *large-scale measurement system*, we denote a data collecting system where the total cost for the target data (denoted as the “Primary data” in Fig. 3) is (much) higher than what the “Data collector” can afford. Accordingly, our approach assumes that the direct costs for the measurement probes (the smartphone and the corresponding subscription for wireless data transfer) are taken by the individual end-users. To motivate the end-users, sufficient incentives have to be provided by a commercial party. Our approach to construct a sustainable large-scale measurement system includes the involvement of a “Campaign sponsor” which supports the measurement campaign on a commercial basis, subject to access to some “Secondary data”, where the secondary data is a catalyst for novel revenue streams to the campaign sponsor.

D. Contributions and Paper Outline

A first contribution is a framework to conceive and design a sustainable smartphone-based large-scale measurement system, which is presented in Sec. II. In particular, in Sec. II a hierarchical model is introduced as a framework to modularize the system, spanning from functionality and technical specifications of the smartphone up to the top-most business model. The model modularizes the description of the measurement

system, and enables top-down as well as bottom-up design strategies.

Then, design, implementation, and operating aspects of a sustainable large-scale measurement system are studied in Sec. III, which presents a road traffic probing activity denoted as the MOving VEhicle LOGger (MOVELO) campaign, including a pilot launch of a commercial private line UBI program. The contributions here include addressing the challenges identified during the Mobile Millennium project, that is the shift from procuring information instead of measurement probes, and the definition of a profitable business model.

The findings and outcomes of the MOVELO campaign are further discussed in Sec. IV. Opposite to tailored measurement platforms as shown in Fig. 2, the smartphone is primarily aimed for voice and data traffic, not to be a high-end measurement probe for events and data originating from a vehicle during high-dynamic movements. A contribution in Sec. IV is an in-depth discussion on data quality from a digital signal processing point of view. Further, the deployment, end-users’ experience, and issues like privacy are considered.

Finally, Sec. V concludes the paper.

II. SUSTAINABLE LARGE-SCALE SMARTPHONE BASED MEASUREMENT SYSTEMS

Hypothetic today, but a reality in the future, are large-scale measurement systems with millions or even billions of probes in terms of smartphones, or their future counterpart. In particular, we will consider smartphone based measurement systems that are independent of the telecommunication operators running the cellular networks; that is, they will not require any modifications to the existing cellular networks. With an operator independent system, the measurement campaigns will have maximum flexibility and the possibility to cover a particular geographical area or time period utilizing data traffic in all available cellular networks. In other terms, the coverage of active measurement probes, aka the success of the measurement campaign, will only be restricted by the tentative number of available smartphone owners residing in the desired time period or geographical location. The area of the work with independent end-users taking a role in the measurement campaign is sometimes referred to as participatory sensing [14].

Accordingly, by a *sustainable large-scale measurement system*, we mean a complex measurement system where the incentives for the individual end-users are supported by a campaign sponsor, who is motivated to provide the means for the end-users and support for the required infrastructure based on the secondary data collected during the measurement campaign. In other words, the campaign sponsor acts as a catalyst for a win-win situation, in which the end-users obtain benefits thanks to their measurement efforts; the data collector gathers measurement data for their own purposes supported by the campaign sponsor, and the campaign sponsor is provided with information in terms of secondary data that enables commercial benefits. With the large diversity of available sensors that can be embedded in a smartphone, the primary data may differ from the secondary data.

Fig. 4. The seven layer smartphone measurement system model employed for the process of conceiving and designing a sustainable large-scale smartphone-based measurement system for road vehicle traffic monitoring (primary data) and usage based insurance (secondary data).

We highlight that our definition of a large-scale measurement system differs from the definition used in [15], where a remote system with a large number of probing devices is considered, but the cost is affordable because of the low cost for the hardware and data transfer. The methodology proposed for managing such systems from a metrological point of view as proposed in [15] is, however, clearly applicable.

A. Smartphone Measurement System Model

In this Section, the smartphone measurement system model is introduced and defined; see Fig. 4. With the proposed model, the process of conceiving and designing a sustainable large-scale smartphone-based measurement system can coherently be described. One may note, that the lower levels of the model have several similarities with the participatory-sensing structure reported in [16], and the G-sense architecture in [17].

The model consists of seven layers, spanning from the physical smartphones and servers to the overall business model at the top layer; that is:

- Physical Layers:
 - 1) Smartphone Sensor and Actuator Layer,
 - 2) Smartphone Local Processing Layer,
 - 3) Wireless Transport Layer, and
 - 4) Central Storage and Data Aggregation Layer.
- Software Lifecycle Management:
 - 5) Implementation Layer.
- Management Layers:
 - 6) End-user Incentive Layer, and
 - 7) Business Model Layer.

The seven layers are described in some detail next. Afterwards, in Sec. III the layers are discussed in some detail regarding road vehicle traffic probing and UBI.

B. LAYER-#1: Smartphone Sensor and Actuator Layer

The sensor and actuator layer, LAYER-#1, defines the digital data transmission from the sensors, for example, position estimates at 1 Hz by the NMEA protocol provided by the GPS receiver, or accelerometer or gyroscope readings at 100 Hz

provided by the in-built inertial sensors. Actuators in current smartphones include internal actuators like the buzzer and loudspeaker, but also end-user feedback via the display, and external actions that can be set-up by a wireless or wired connection. The major function and service performed by the sensor and actuator layer is the establishment and termination of a connection to a sensor or actuator. These are signals operating over the physical cabling within the smartphone. Analog or digital means for direct cleaning of the sensor data are typically associated to this layer, for example noise reduction of a microphone signal.

C. LAYER-#2: Smartphone Local Processing Layer

The rationale for LAYER-#2 is the big data paradigm, cf. [18] with the role to structure and compress the voluminous amount of possible raw sensor data.

The major function and service performed by LAYER-#2 is the estimation of parameters related to the information gathered in the raw (or, enhanced) measurements, which is the compression of information into a set of Figure of Merits (FoMs), operating over the physical cabling within the smartphone. The local processing layer defines the digital processing of the sensor data from LAYER-#1 in combination with global information provided through LAYER-#3, such as information from neighboring measurement probes or centrally stored databases.

D. LAYER-#3: Wireless Transport Layer

The functionality of LAYER-#3 is the wireless transport in the up- and down-link of information between the smartphone and the backbone infrastructure. The popularity of smartphones has created a demand for reasonably priced mobile internet connections, because a handset without internet connection has no real use for most users. Accordingly, the end-users typically have a fixed priced connectivity up to some limit on the transmitted data size. This means that the smartphones are mostly connected to the internet 24/7 and provide the means for data transportation.

For the design of a large-scale smartphone-based measurement system, it is important to consider that the network is not always accessible and that the instantaneous data rate may vary. The consequence is that real time information is not always possible to send, and that the protocols used must manage latency. In addition, a solution must not use too much of the users paid bandwidth, which has to be considered both in the design of the measurement functionality including information coding and pre processing, as well as for the design of protocols. Standard Internet protocol (IP) layers are available in the smartphones and servers connected to the internet. The application protocol can be chosen from existing protocols like FTP or HTTP to use existing client/server software libraries, but better adapted protocols may be considered as well [19].

E. LAYER-#4: Central Storage and Data Aggregation Layer

The major function and service performed by LAYER-#4 is the central storage and data aggregation. This layer defines the

TABLE I
EXEMPLARY DEPLOYMENT PROCESS (LAYER-#6).

a)	Awareness: inform the potential end-users.
b)	Registration: collect the end-users for the campaign.
c)	Qualification: measurements for a first remuneration (short period).
d)	Quote: committing the serious end-users.
e)	Policy period: main measurement campaign with dedicated end-users (long period).
f)	Retention: for attainability and long-term operation.

central storage and data aggregation. The aggregated data can be divided into primary data and secondary data, but also, for example, feedback data streams (broadcasted to all end-users, or transmitted to an individual one) are included. These are signals operating on the physical cabling of the cloud.

F. LAYER-#5: Implementation Layer

This layer handles the software lifecycle management including technical specifications, software revisions, and version distribution. Many theoretical and/or practical methods exist for the lifecycle management of software and system development. The iterative agile methods usually suit the type of development used for the kind of systems where the requirements are not fully understood at the beginning, or they change over time as more is learned about the utilization of the system. Combined with methods and systems for configuration management and distribution, a quality assured lifecycle is maintained.

G. LAYER-#6: End-User Incentive Layer

The major function and service performed by LAYER-#6 is the description of the incentive-driven deployment process, that is the enabler for a successful large-scale distribution of the software to the individual end-users. An example process is summarized in Table I, where a multi-step strategy is employed. In the first phase, the end-users get a first remuneration, that period is configurable in terms of length and time period. After a predetermined qualification period, the end-user can request a quotation for a reward during a policy period.

A key issue is the motivation of the individual end-users to accept the role of being the host for a mobile measurement probe. The remuneration for the end-users has to gain more value for them than the effort it takes to host and take responsibility for the required actions during a measurement campaign.

Depending on the actual scenario, categorization of the end-users may enable more focused incentive programs, for example a classification according to Tab. II, where:

- “The dedicated” is the most attractive category of end-users to enable a successful launch of a measurement campaign.
- “The forgetful” category is dedicated, but has a habit to forget to activate the probing software application. Typically, their performance can be significantly improved by simple means, for example, by providing them with

TABLE II
EXEMPLARY CATEGORIZATION OF END-USERS (LAYER-#6).

a)	“the dedicated”	the most attractive end-user
b)	“the forgetful”	attractive, but must be triggered
c)	“the fraudulent”	unwanted

additional (low-cost) gadgets. An example, adopted from the MOVELO campaign reported in Sec. III, is to equip this category with such a simple gadget as a buzzer equipped mobile phone battery charger for the vehicle’s cigarette lighter outlet, eventually with the functionality that it automatically triggers the start of the application [20]. In a low-cost configuration, the battery charger just reminds the car’s driver to activate the measurement application once the ignition is turned on and the engine has started. In addition, it will remind this category of individuals to charge their cellular phones, which has a clear added value. A combination of a sensor equipped mobile phone battery charger and a smartphone is another approach to enhance the measurement activities of the forgetful end-users; See Fig. 2. Other means from the MOVELO campaign include the use of an automatic enabling of the measurement application by near field communication (NFC) tags mounted on a phone cradle or directly on the panel of the vehicle.

- Finally, “the fraudulent” is harder to handle, and is typically not a demanded customer segment for a campaign.

H. LAYER-#7: Business Model Layer

For a cross-disciplinary project, an easy to understand business model ontology is required. Osterwalders business model ontology was evaluated against other business model ontologies and was chosen because of its contemporary characteristics such as its capabilities and suitability for ICT dominant business models and because of its communicative capabilities. The business model ontology defines nine building blocks for business models, as summarized in Fig. 5. [21], [22]

The first building block is the value proposition, which is defined as an overall view of a campaign sponsor’s bundle of products and services that are of value to the customer, that is, the end-users. The second building block is the target customer, which is defined as a segment of customers a company wants to offer value to, for example, the low-risk and safe driver for an insurance company. The third building block is the distribution channel, which is defined as the means of getting in touch with the customer. The fourth building block is the customer relationship, which is defined as the description of the kind of link a company establishes between itself and the customer. The fifth building block is the value configuration, or key activities, which are defined as the arrangement of activities and resources that are necessary to create value for the customer. The sixth building block is capabilities, which can be defined as the ability to execute a repeatable pattern of actions that are necessary in order to create value for the customer. The seventh building block is partnership, which can be defined as a voluntarily initiated cooperative agreement

Fig. 5. The business model ontology by Osterwalder.

between two or more companies in order to create value for the customer. Finally, the last two building blocks relate to the financial aspects of a firm: the cost structure, which is defined as the representation in money for all the means employed in the business model; and the revenue model, which is defined as the way a company makes money through a variety of revenue flows.

III. THE MOVING VEHICLE LOGGER CAMPAIGN

The MOVELO campaign was initiated to deploy a sustainable large-scale smartphone-based measurement system for road traffic probing, independent of any kind of fixed road traffic monitoring infrastructure. Stockholm, the capital of Sweden, has been identified as the fifth most congested city in Western Europe [23]. Currently, some 1,000 taxi mounted probes are collecting traffic data, known as the Mobile Millennium Stockholm project [23], which clearly is insufficient to provide high resolution traffic monitoring to reduce congestion, environmental impact, accidents, and costs. With a required 2-3 % penetration of probes [2], [4], [3] on occupied roads, the implication is that a large number of active probes have to be available to cover a major metropolitan area. More specifically, a large number of probes is required to obtain fine resolution in time and space at less trafficked road segments.

This paper includes a 10 month (October to August) case study of implemented traffic probing based on the methodology presented herein. The MOVELO campaign was initiated in early 2012. After development efforts and initial tests and verifications, the first end-users were activated in mid October, 2012. The campaign was combined with a commercial UBI pilot to make it sustainable. Exemplary data is illustrated in Fig. 1. In the figure, geographical coverage is shown for downtown Stockholm, Sweden, during a 10 day period in March 2013, based on some 500 individual vehicle trajectories (pre-launch tests).

Next, we take a top down approach and describe the implementation of the campaign in some detail starting from LAYER-#7.

A. LAYER-#7 Innovative Business Models in Practice

To facilitate the triple helix in Fig. 3, a legal entity was founded outside of academia (that is, MoveLO AB) to take the role of data collector. A starting point was to design an innovative business model based on an ideal design of the theoretical framework presented above; see also Fig. 5. Step one was to identify a suitable campaign sponsor, which had

commercial benefits out of the campaign via the secondary data, and had resources to market and distribute the mobile application to their current and potential customers, and make them use the application on a regular basis. The ideal case would be if the end-users benefited from using the application every time they drove their car, thus creating a clear value proposition to the firm's customers. After some investigation, a company in the insurance industry (If Skadeförsäkring AB) was proven to be the most relevant campaign sponsor, the market leader in the Nordic Countries with some 3.6 million customers.

With reference to Fig. 5: From a financial perspective there are some costs related to the fifth building block – key activities and the sixth building block – key resources. Examples of these costs are server costs and administration of the servers and applications. The revenue model that would finance these costs is revenue shared with the campaign sponsor. For the insurance company, the benefits would be lowering risks and obtaining more information on driving behavior and statistics. An added benefit for the insurance company is them getting a new customer channel and improved customer relations via the smartphone (see building block three and four in Fig. 5) with possibilities to communicate to their customers via smartphones, for example, to inform customers about dangerous road segments and traffic conditions that can affect their safety. By collecting information on driving behavior, customer segmentation will also be improved; for example, identifying “the dedicated” ones.

Another example could be forecasts of traffic flow and congestion. The insurance company also gains new possibilities to innovate their business model to cooperate with new key partners; examples of such companies are companies with customers who are car bound, for example gas retailers.

B. LAYER-#6 Usage Based Insurance

Since the value proposition is focal in a business model, a relevant value proposition has to be designed. The appropriate value proposition designed was a combination of *Pay As You Drive* (PAYD) and *Pay How You Drive* (PHYD) [24], [25]. In short, the value proposition designed is based on giving incentives to selected customer segments, building block number two in Fig. 5. In practice, the incentives and value proposition to the motor insurance customer consists of giving discounts on their premiums. If the customer drives safer and in a more economic manner, they will receive discounts on their insurance premium, which in the considered campaign were in the interval of 0-30 %.

In the MOVELO campaign, the value proposition is a two-stage proposition, as summarized in Tab. I. In the first phase, the end-users qualify during a period of typically two weeks for a discounted insurance premium based on an achieved “safety score” (that is, the most important part of the secondary data). The obtained discount is valid up to a period of one year. This first phase is configurable in terms of length and time period. During this period, the end-user uses the smartphone as much as possible to gain the maximum discount on the premium. The length of the drive is compared with initial and

final readings of the mileage from the odometer [26]. After the qualification period, the end-users can request a quotation. During the following policy period, activation of the “app” is encouraged by added valued services.

C. LAYER-#5: Implementation Layer

For the MOVELO campaign, we followed a pragmatic life-cycle where internal and external requirements were collected continuously by all the people involved and then collected by the project manager and broken down to verticals; that is, distributed tasks for the development team. Time estimates for the different actions are instrumental for the project steering, where “go or no-go” decisions are taken by the project management. The verticals with their tasks are scheduled in one to two week sprints. All source code and configuration are stored using Apache Subversion (SVN) with a configuration management system based on tags. Before the release, the critical code is peer reviewed; subsystems go through automated regression testing and final release candidates are tested by internal and external test groups. The applications are written in Objective C for the iOS, and Java for Android.

Distribution of the tested subsystems depends on the platform. The MOVELO campaign uses Amazon (AWS) for all server systems because of the flexibility of configurations and easy upgrade/downgrade of hardware to suit the specific needs on a day-by-day basis, with Ubuntu 12.04 LTS as server operative system. The number of devices that can be handled depends on the AWS server, eg. m1.small about 8 requests/sec and m1.xlarge instance can handle about 70 requests/sec over HTTPS.

For commercial use, the probing apps are distributed through the regular channels for each platform and sideloaded for test purposes using iPhone authorized internal distribution and Android sideloaded from external sources. For these distribution methods, the measurement system, denoted as the Real-time UBI software suit (RUBI), uses an in house system that emails the users links to new versions. Old versions can be invalidated remotely through the user authentication methods implemented in the system.

D. LAYER-#4: Central Storage and Data Aggregation Layer

We process and store data according to the business use (secondary data) and traffic monitoring use (primary data), but some fine resolution data (raw data) storage is on occasion also possible for future use. For traffic monitoring, data is stored in relational databases transferred from file storage when server processing load is low. The primary and secondary data are first processed locally in the smartphones (that is, LAYER-#1 and LAYER-#2) to enhance quality and reduce the amount of redundant information, and further processed centrally at storage time and managed in a relational database. This approach enables fast access to relevant information used for business. Employing a relational model provides easy access to data utilizing different pre defined criteria, but still gives the possibility to access it in sets that have not been predefined. Recording and storage of raw sensor data can centrally be turned on and off at a device-by-device level. Raw data is stored in a file system that enables it to be batch processed.

E. LAYER-#3 Wireless Transport

The measurement system is based on the standard IP using HTTP as the application layer. On top of that, XML-RPC is used for low rate transmissions because of its availability on most platforms [27]. For higher rate communications, the probing application uses HTTP PUT/GET file transfers of compressed files in a proprietary format.

In general, the primary data (traffic flow data) is uploaded in real-time subject to the availability of a wireless connection, whereas the secondary data (insurance telematics related FoMs) is uploaded at the end of each drive. A rationale for uploading the secondary data at the end of the drive is not only an increased robustness against link failures, but also so that many of the FoMs can be calculated more accurately using batch-processing, such as the map matching used to check if the driver has been speeding, or not.

F. LAYER-#2 Figure of Merits Processing

Locally processed FoMs include metrics for acceleration, braking, smoothness, cornering, swerving, and speeding. Detection of speeding where the comparison between the actual speed of the vehicle and the speed limit is monitored is often denoted as intelligent speed adaptation (ISA) [28]. For ISA, NAVTEQ maps, OpenStreetMap [29], and the Swedish National road data base (NVDB) by the Swedish Transport Agency [30] were all tried out. NAVTEQ maps were finally selected for the considered campaign due to a favorable price/performance metric. In addition, an eco-driving score [31] is monitored, as well as basic data like location, time, and traveled distance. One may note that for eco-driving related FoMs, the gear shift may be detected by the sensor data [6]. Every calculated FoM is continuously compared against a configurable threshold to detect events that are considered dangerous driving behavior and a threshold used to warn the driver (see Fig. 7 for exemplary driver feedback).

There are several challenges involved in using smartphones for detection of rapid events like heavy braking, because of the low data sample rate, the high occurrence of outlier data, and the loss of data, for example, due to non-line of sight, towards the GPS satellites. During a road test (an 1 hour and 15 minute run) using seven different smartphones mounted in the windshield of a vehicle, the satellite based positioning reported a coverage in the interval of 60 % to 99.7 % for the individual smartphones. Using a reference system connected to the vehicle’s on-board diagnosis outlet, six heavy braking events were detected during the run. Without any preprocessing of the smartphone data, the number of heavy braking-detections by the individual smartphones varied between 28 and 58, which is clearly different from the number of actual events. To combat the imperfections in the detection, model based data enhancement and outlier rejection were included in LAYER-#1, which improved the detection significantly. Calculated over the individual smartphones, the mean number of heavy braking-detections was 6.6, with a standard deviation of 1.7; yielding detector performance sufficient enough for insurance telematics applications. More details can be found in [32].

Fig. 6. Example of the clock jitter in the sampling of the GPS-receiver data in an Iphone 4.

G. LAYER-#1 Sensor Data Enhancement and Driver Feedback

For the MOVELO campaign, the main source of sensor information is the location information provided by the GPS or the GLONASS receiver, although some FoMs rely on sensor fusion incorporating accelerometer or gyroscope data, as well as information from digital road maps.

To monitor the quality of the GPS/GLONASS position and velocity, the data is (recursively) fitted to a model of typical vehicle dynamics. If the discrepancy (on sample level) between the measured data and values predicted by the vehicle dynamics model deviates too much, the data is rejected. Because of the significant clock jitter of position and speed readings provided by contemporary smartphones, data is, in practice, non-uniformly sampled, which has to be handled by the digital signal processing, typically leading to the use of time-variant digital filters. Rejected samples are straightforwardly handled in such a framework. See Fig. 6 for an example of the clock jitter in the GPS data of an Iphone 4.

The experience from the MOVELO campaign is that the quality of the GPS/GLONASS data varies quite significantly between smartphone makes and models, and in the production of the secondary data for the campaign sponsor (i.e., the insurance company), some percentage of the data has to be rejected. By combining the GPS/GLONASS data with the accelerometer and gyroscope data into a so called GPS-aided inertial navigation system [33], the amount of data that is rejected due to low quality could be further reduced.

Feedback to the driver may be provided by the smartphone. Variations of touch and feel were studied, spanning from no real-time feedback (as used in the launched campaign later on), to the extended dashboard appearance displayed in Fig. 7. It is worth observing that the processing of real-time driver feedback typically differs compared with the risk calculations performed after a trip. The latter typically includes off-line calculations considering the data from the full trip to improve the risk scoring.

IV. DISCUSSION

Sustainable large-scale smartphone based measurement systems have numerous application areas, both future and present ones. Road vehicle traffic probing in larger metropolitan areas driven by UBI programs is merely one out of many tentative applications, where the purpose (sensed by the primary data)

Fig. 7. The smartphone used as an extension of the vehicle's dashboard for real-time driver feedback. The real-time feedback includes measures of acceleration, smoothness, braking, cornering, speeding (with respect to the actual speed limit), and swerving. In addition, a measure of the eco-ness of the drive, and the elapsed distance are shown.

is to model, predict, and control the traffic flow, and where the commercial value is provided by a UBI program (driven by the secondary data). Here, the smartphone owner allows data collection by monitoring the vehicle status; for example, the time of the day, the speed, and location. The smartphone owners get an incentive to collect data by way of a reduced vehicle insurance premium, where the rebate can be substantial.

Some further issues are discussed below.

A. Data Quality

In-car positioning and navigation have been killer applications for GPS receivers, and a variety of electronics for consumers and professionals have been launched on a large scale. These navigation aids (that is, “black box”) are designed to support the driver by showing the vehicles current location on a map and by giving both visual and audio information on how to efficiently get from one location to another, fleet management, usage based insurance, etc. Road vehicle positioning and navigation technologies based on stand-alone GPS receivers are vulnerable because of the low signal levels and requirement of line-of-sight, and thus, have to be supported by additional information sources to obtain the desired accuracy, integrity, availability, and continuity of service [33], [34].

Using the smartphone as a measurement probe increases the complexity of data quality assurance, because the smartphone is mainly designed to be used as a hand held terminal for voice and data traffic. Accordingly, the performance as a measurement probe is expected to be inferior compared to a tailored black-box due to consideration during the design of the radio receivers and transmitters, antennas, etc. Further, the mounting or location of the smartphone within the vehicle is not predetermined and may vary significantly between different users as well as between different trips. As reported in Sec. III-F during a trial with 7 smartphones mounted in

Fig. 8. Illustration of the obtainable performance using sensor fusion to improve accessible sensor data. The performance of three generations of black-boxes (#1–#3, solid line), unfiltered smartphone data (dashed line), and smartphone data after sensor fusion (dashed-dotted).

the windshield, the GPS-coverage spanned 60 % to 99.7 % for an exemplary run. On the other hand, the smartphone is a main driver for the sensor industry, so every new smartphone generation is equipped both with additional sensors as well as with sensors of higher quality than the replaced generation.

The quality of sensor output (QoS) is illustrated in Fig. 8. The more or less continuous improvement of the smartphone platforms results in the fact that the smartphone as measurement probe over time outperforms the black-box, which has a significantly longer expected time of operation; despite the fact that the smartphone's performance is limited by the aforementioned design constraints and possibly unfavorable location during vehicle trips.

Sensor fusion is a key tool to enhance data quality [35]. By looking at the vehicle probing problem from an information source perspective, we find basically four different sources of information available: (1) GPS and other radio frequency based navigation systems, (2) sensors observing vehicle dynamics such as gyroscopes and accelerometers, (3) road maps, and (4) mathematical models of vehicle motion [33], [34]. The GPS receiver and vehicle motion sensors provide observations to estimate the state of the vehicle. The vehicle model and road map put constraints on the dynamics of the system and allow past information to be projected forward in time and to be combined with current observation information [36]. Therefore, in practice, the available sensor output can be improved by sensor fusion technology resulting in performance close to the ideal performance given by full access to raw sensor outputs. This quality improvement by means of software is illustrated in Fig. 8.

B. End-User's Experience, Penetration and Privacy

After initial development and testing, the deployment of the measurement system started on a small scale in a first, second, and third Call for Probing End-Users (CFPs). These calls invited some 200 end-users in total, out of which some 64

Fig. 9. Cumulative covered distance and hours of recorded data for road traffic monitoring.

% downloaded the application. Besides general testing of the application, the end-users had the possibility to run a 2 week and 200 km qualification period to earn an insurance premium discount, where the discount was based on a combination of driving behavior and actual usage of the smartphone during the qualification period [37]. By questionnaires, it was found out that a large majority of the drivers who used the application were positive or very positive about the concept. The results analyzing the initial CFPs indicate that sufficient enticements need to be provided to ensure a sustainable measurement system. Consequently, a larger number of end-users were invited, and the campaign went public with a press release and awareness through the internet and social media. The actual number of recorded data is reported in Fig. 9. At the end of the project, some 10 months after the first probe was activated, some 4,500 hours of traffic data covering a total distance of 250,000 km had been collected. As indicated in Fig. 9, the effects of new end-users invited in CFP #1–#3 are clearly visible in the slope of the reported data. Christmas break between CFP #2 and CFP #3 led to a reduced activity and less data coverage. The effect of the public launch is clearly visible, but also the fact that the public relation activities were more or less concentrated to the time period of the launch. The campaign was officially closed for new end-users in August, 2013.

To ensure a high level of privacy, the interested end-users were only required to provide an (possibly anonymous) email address to enter the campaign. In such a way, a foundation for general statistics was provided. To enter the qualification period, the end-users actively agreed that monitored data was used to calculate a (strictly positive) discount on the insurance premium, and for no other use. Processing of personal data was handled according to the Swedish Personal Data Act, which is

based on common rules decided within the European Union.

V. CONCLUSIONS

The smartphone has entered the scene as a versatile probe for large-scale measurement campaigns with a substantial number of probing devices. In the current work, we have provided a cross-disciplinary multi-layer model to conceive and design a sustainable large-scale measurement system. The model has been a fundamental tool in the development of the reported MOVELO campaign. Designing, implementing, and deploying a sustainable large-scale smartphone-based measurement system for road traffic monitoring and UBI is a reality thanks to the mobility and connectivity of the measurement probes, cloud-based storage, data aggregation, and the technology advances in processing data. In addition, social media is used to spread the word, and end-user incentives are provided. The campaign ran for 10 month and resulted in not only some 250,000 km of recorded road vehicle traffic data, but also new customers in a commercial test of UBI where the individual end-users were able to cut their vehicle insurance premium up to 30 %. To the authors knowledge, this is the first trial of a commercial smartphone-based UBI, where the app installed in the smartphone is used not only as a customer acquisition tool, but also as an advanced measurement probe where the inherent shortcomings of the measurement platform are combated by advanced digital signal processing including time variant system models, data outlier rejection schemes, and matching to digital maps by modeling vehicle trajectories, to mention a few strategies. These findings may boost the deployment of UBI programs in general, and smartphone-driven UBIs in particular, from today's level of some two million only UBI customers globally, in a handful of UBI programs [12].

As pointed out in [38], combining the technology trends: connectivity/mobility, cloud, social media, and big data, "magic happens". All the mentioned trends are present in sustainable large-scale smartphone-based measurement systems. We have applied the reported methodology to road vehicle traffic monitoring, which enables high resolution traffic monitoring to reduce congestion, environmental impact, accidents, and costs. We have successfully demonstrated an approach where information has been procured instead of measurement platforms, and where a commercial actor provides incentives to the individual smartphone owners, making the system not only of commercial value, but also sustainable.

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Peter Händel (S'88-M'94-SM'98) received the Ph.D. degree from Uppsala University, Uppsala, Sweden, in 1993. From 1987 to 1993, he was with Uppsala University. From 1993 to 1997, he was with Ericsson AB, Kista, Sweden. From 1996 to 1997, he was a Visiting Scholar with the Tampere University of Technology, Tampere, Finland. Since 1997, he has been with the Royal Institute of Technology KTH, Stockholm, Sweden, where he is currently a Professor of Signal Processing and Head of the Department of Signal Processing. From 2000 to

2006, he held an adjunct position at the Swedish Defence Research Agency. He has been a Guest Professor at the Indian Institute of Science (IISc), Bangalore, India, and at the University of Gävle, Sweden. He is a co-founder of Movelo AB. Dr. Hndel has served as an associate editor for the IEEE TRANSACTIONS ON SIGNAL PROCESSING.

Jens Ohlsson received the MSc in Computer and Systems Sciences, Stockholm University, 1999. In 2004, he obtained an additional BSc in Communications-Pedagogy, Stockholm University. Between 1999 and 2011, Mr Ohlsson worked with business development at companies like SAP, Aptus Consulting, and IDS Scheer. In March 2011, he joined Movelo AB as CEO. Since 2011, he also holds a position at the Department of Computer and System Sciences, Stockholm University.

takes the role as CTO.

Martin Ohlsson holds an MSc in Computer Science from the Royal Institute of Technology KTH, Stockholm, Sweden. Mr Ohlsson has been active in the ICT area some 20 years as entrepreneur and systems architect. Projects include the augmented reality game Ghostwire which was awarded the 1st prize in Nokias N-Gage Mobile Games Innovation Challenge 2008, and the Swedish award Guldmobilen within the category Entertainment Service of the Year, 2009. In 2009, he co-initiated the project that later become Movelo AB, where he currently

KTH coordinating the KTH Insurance Telematics Lab.

Isaac Skog (S'09-M'10) received the BSc and MSc degrees in Electrical Engineering from the Royal Institute of Technology KTH, Stockholm, Sweden, in 2003 and 2005, respectively. In 2011, he received the Ph.D. degree in Signal Processing with a thesis on low-cost navigation systems. In 2009, he spent 5 months at the Mobile Multi-Sensor System research team, University of Calgary, Canada, as visiting researcher and in 2011 he spent 4 months at the Indian Institute of Science (IISc), Bangalore as a Visiting Scholar. He is currently a Researcher at

Elin Nygren received the MSc degree in Business and Economics, Stockholm University, School of Business, Sweden, in 2012. She has been with Movelo AB since 2012, where she currently is a Marketing Coordinator.