THESIS ON CIVIL ENGINEERING F39

# Performance Measurement of a Road Network: A Conceptual and Technological Approach for Estonia

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

Kati Kõrbe Kaare /signature/

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# Teedevõrgu tulemuslikkuse mõõtmine: kontseptsioon ja tehnoloogiad Eesti näitel

KATI KÕRBE KAARE

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KIRJASTUS

# CONTENTS

# ABBREVIATIONS

| | |
|---|---|
| 3G | Third Generation |
| AADT | Annual Average Daily Traffic |
| Austroads | The Association of Australian and New Zealand Road Transport and Traffic Authorities |
| BAP | Battery Assisted Passive RFID-s |
| CAN | Controller Area Network |
| CDMA | Code Division Multiple Access |
| COST | European Cooperation in Science and Technology |
| CPI | Combined Performance Index |
| DB | Database |
| DCP | Dynamic Cone Penetrometer |
| EC2 | Amazon Elastic Compute Cloud |
| EMHI | Estonian Meteorological and Hydrological Institute |
| EPMS | Estonian Pavement Management System |
| ERA | Estonian Road Administration |
| ESRI | Environmental Systems Research Institute (USA) |
| EU | European Union |
| FCD | Floating Car Data |
| FHWA | Federal Highway Administration (USA) |
| FOSS | Free and Open Source Software |
| FWD | Falling Weight Deflectometer |
| GIS | Geographic Information System |
| GLONASS | Global Navigation Satellite System (Russia) |
| GPR | Ground-Penetrating Radar |
| GPRS | General Packet Radio Service |
| GPS | Global Positioning System |
| HDM | Highway Design and Management |
| HSDPA | High-Speed Downlink Packet Access |
| ICT | Information and Communications Technology |
| IDS | Integrated Database System |
| IoT | Internet of Things |
| IR | Infra-Red |
| IRI | International Roughness Index |
| IRIMETER | Road Roughness Measurement System |
| IT | Information Technology |
| ITF | International Transport Forum |
| KPI | Key Performance Indicator |
| LEF | Load Equivalency Factor |
| LIDaR | Light Detection and Ranging |
| LTE | Long-Term Evolution |
| LTPP | Long-Term Pavement Performance |
| M2M | Machine-to-Machine |
| MISP2 | Mini-Portals for Web Services |
| NRD | National Road Database |
| OECD | The Organisation for Economic Co-operation and Development |
| OS | Operating System |
| PHP | Hypertext Preprocessor |
| PeMS | Performance Measurement System |
| PMS | Pavement Management System |
| PSDA | Performance Measurement System Systematic Design Approach |
| RADAR | Radio Detection and Ranging |
| RDD | Rolling Dynamic Deflectometer |
| RDS | Radio Data System |
| REST | Representational State Transfer |
| RFID | Radio-Frequency Identification |
| RSS | Rich Site Summary |
| RTRRMS | Response Type Roughness Measurement Systems |
| SDE | Spatial Database Engine |
| SDK | Software Development Kit |
| SLC | Single Load Cell |
| SQL | Structured Query Language |
| SRD | System Reference Document |
| SSWiM | Slow Speed WiM |
| TAC | The Transportation Association of Canada |
| TMC | Traffic Message Channel |
| TRB | Transportation Research Board (USA) |
| VIP | Video Image Processing |
| WFS | Web Feature Service |
| WiM | Weight-in-Motion |
| WMS | Web Map Service |
| WSN | Wireless Sensor Networks |

- *If you don't measure results, you can't tell success from failure.*
- *If you can't see success, you can't reward it.*
- *If you can't see failure, you can't correct it.*

*D. Osborne, T. Gaebler [46]*

# INTRODUCTION

## Background

A country's level of economic activity, and its production of wealth, is for a large part dependent on its capacity to move people and goods. A nation's transportation infrastructure can either support or hinder its economic development. In Europe, over 75 % of ground freight and 80 % of passenger transport takes place by road [20]. Therefore, road networks are important lifelines for modern societies. A well designed, constructed and maintained road network, which allows for a high degree of mobility and accessibility to communities by road, is an essential factor in the economic development and prosperity of a nation.

Road agencies are responsible for the design, maintenance, repair and development of road networks under their jurisdiction in order to ensure required operational levels. In times of economic uncertainty, road agencies attempt to develop and deploy "optimal" maintenance and operational policies and actions [18]. As the quality of roads deteriorates over time from use and continuous impact from the environment, proper maintenance of the road system is necessary to preserve its serviceability and structural integrity, both of which are important for maintaining the effectiveness of transportation, safety of road users and economic development. Since roads are infrastructural assets with long lives, maintenance activities need to be viewed from a life cycle perspective if an optimal balance is to be obtained between benefits and costs. A life cycle perspective assists road agencies in providing appropriate levels of service to road users. When access to resources decline and ageing infrastructure deteriorates, the task of maintaining an efficient road network often becomes a challenge for the road agency.

Governments seek to provide programs and services to people that are affordable, and that respond to public needs focus on the condition of the pavement throughout its life cycle. This has a direct impact on road safety, driver satisfaction and the environment. Information management and information technology (IT) can be used assess the state of pavements on an ongoing basis. This information allows government agencies to streamline operations, improve levels of service and provide better information for decision making. To maximize the contribution of information and communication technologies (ICT) as a tool to improve the decision-making process the collected data needs to be reviewed, evaluated and analyzed. This can be achieved through a well-placed performance measurement system (PeMS) [57].

Performance is a term used in everyday life, in engineering, in economics and in many other areas. It can have a general meaning or a specific meaning. For the latter, and particularly for roads, performance must be a measurable entity. This is essential for assessing the current and future state of road infrastructure, as well as agency efficiency in service and safety provision for users, productivity, durability, cost-effectiveness, environmental protection, preservation of investment and other functions. The specification of performance criteria from the perspectives of both road users and road operators is a key prerequisite for the efficient design, construction and maintenance of road pavements.

Modern road management is performance based; both programming and implementation of maintenance and operational activities are driven by appropriately defined performance indicators. Performance indicators can be used in particular as target criteria in life cycle analyses within the context of pavement design and/or systematic road maintenance at the national and the European levels. Uniform performance indicators permit an evaluation of the effects of different design and maintenance strategies, but they can also be a basis for predicting road performance and for improving old and developing new prediction models. Performance indicators are thus an objective tool used in road construction and maintenance at various administrative levels, from the local to the national.

Performance indicators for road pavements could, however, also be used as inputs into pavement management systems (PMS) [42]. They can be used, for calculating maintenance needs and thus provide objective arguments for reinvestment in road pavements. Without maintenance, the pavement network would deteriorate to the stage where major expenditure would be needed and the residual value of the pavement or network would be very low. It is crucial to have continuous knowledge about the condition of the road network in order to plan maintenance work in an effective manner. To this end PeMS is necessary. The PeMS will enable agencies to assign priorities, and to compare maintenance outcomes based on the input of resources.

The increasing use of life cycle analyses as a basis for the selection of road pavement design requires an exact definition of the goals to be achieved and/or the performance criteria to be satisfied. The extent to which goals are reached or performance criteria satisfied can be quantified by calculating special indices characterizing the road pavement, which in turn permits an assessment of the efficiency of certain approaches from both a commercial and a macro-economic standpoint.

Road authorities collect and retain extensive datasets related to their services and the life cycle of their infrastructures. It is important to note, however, that proper collection, analysis, refinement and presentation of that data is a prerequisite for using them and for proper reporting to a broader audience. As such, development of appropriate PeMS, is required for linking transportation and infrastructure data to road management.

Organizations around the world, in the public and private sectors, have developed PeMS that corresponds to their specific needs. Yet many are dissatisfied with their solutions. In particular they are finding it difficult to develop cost-effective meaningful measures which drive performance improvement without leading to unanticipated negative consequences [48].

In the transport sector various organizations (OECD, ITF, COST, etc) have conducted studies [33; 42; 47] to develop guidelines for government agencies on how to define uniform performance indicators and indices for road pavements, taking the needs of road users and road operators into account. The quantitative assessment of individual performance indicators provides guidance regarding present and future needs in road pavement design and maintenance at both, the national and supranational levels.

A system can be formed by grouping these individual performance indicators into representative combined performance indices such as:

- functional performance indices (demands made on road pavements by road users);
- structural performance indices (structural demands to be met by the road pavement);
- environmental performance indices (demands made on road pavements from an environmental perspective).

Guidelines for performance measures can be developed centrally but cannot be implemented without adjusting them to the specific region or country. Every country has its own design guidelines, and its own geological and climactic conditions. Each county uses different construction materials commonly of local origin. By implementing a performance measurement system the data collected about pavement conditions and deteriorating effects can also be used to carry out long-term pavement performance (LTPP) studies. This LTPP monitoring programme can be used in order to produce pavement deterioration data that would be suitable for the development of pavement models.

The rapid growth of ICT including the Internet and other technological developments have introduced new possibilities for data collection. Crowd sourcing, machine-to machine (M2M) communications and the Internet of Things (IoT) are growing and offering new possibilities. These developments also include the road maintenance and management sector and can be used to collect data for the PeMS.

For forecasting future maintenance and funding requirements and road conditions, pavement deterioration models are essential. These pavement condition models are therefore the ‘heartbeat’ of any system that is capable of predicting the future network status and budget requirements. On the other hand these models cannot be designed without analyses and evaluations based on long-term performance data.

The geological history affects the make-up of the pavements in both the in situ layers as well as the constructed pavement layers. The influence of climate on the geology is significant enough that engineering geologists have established relationships between climatic conditions and the behavior of soils. Both these indicators are expressed in terms of climatic conditions such as rainfall, evaporation and the temperature. For engineering pavement, it is common to classify geological regions in terms of climatic conditions rather than only using geological formations classifications. The climate is therefore, a good moderator for the behavior of material [28].

Pavement performance studies in different countries have established the need to use some form of regionalization method in the design guidelines. Pavements will behave differently in different parts of a country even as small as Estonia, due to climatic and geological factors. The deterioration of Estonian roads is mainly caused by heavy loads and climatic factors. During the winter season 75 % of Estonians choose to use studded tires [60]. Furthermore, de-icing chemicals are used to improve road safety.

## Scope of the Research

Performance measurement is used in both the private and public sector. The public sector is different from the private sector and therefore a public sector organisation faced with a change in incentives will not necessarily behave in the same way as a private sector one. Accountability notions of effectiveness, efficiency and productivity are common in public sector agencies.

Three different levels of PeMS within a public sector are broadly identifiable [48].

- national (meta) level – assessing the performance of the national transport system;
- organization (macro) level – assessing the performance of the road authorities’ operations;
- project (micro) level – assessing the delivery of an individual construction or rehabilitation project.

In the road sector, performance can be measured from a number of different perspectives and for a number of reasons, especially to assess current and future conditions of road infrastructures [25; 33]. Agencies have instituted performance measurement processes for various reasons: to provide better information about the transportation system to the public and decision makers, to improve management access to relevant performance data, or to generally improve agency efficiency and effectiveness. Another important consideration is the desire to improve the link between resource allocation decisions, system conditions, and performance results.

The performance, involving the condition and serviceability of the road network can also be determined from the viewpoint of the maintaining agency, road users and society at large. The agency's viewpoint is technical, aiming at preserving and maintaining the technical condition of the roads. The road user experiences the serviceability of the road, which is related to the technical condition and the user's expectations of this service. From society's perspective, both the user's and agency's definition of condition are combined with various other objectives of transportation policies.

Road management involves a number of tools that include:

- policy formation: definition of standards and policies for the road sector; developing a strategic view of road network development and maintenance, targeted performance and resources required;
- overall network monitoring: knowledge of the network extent, conditions and traffic characteristics;
- needs assessment and planning: determination of projects with their required expenditures for management and operations;
- capital budgeting: appraisal and ranking of investment options, under budget constraints;
- project programming: programming of maintenance and improvement projects;
- monitoring and evaluation: monitoring the results and the impact of the project and comparing it to the strategic objectives defined during planning projects;
- monitoring operations: obtaining performance measures for operations [56].

These tools combined, aim for measuring the performance of road networks and planning their maintenance, comparing maintenance strategies against operational requirements, and for programming future maintenance, construction and improvement activities based on available resources [33].

This thesis focuses on *public sector micro-level PeMS in Estonia* and how such systems can contribute at the macro level and serve the interests of stakeholder groups. Consequently in this thesis the author addresses performance from *non-financial aspects* focusing on monitoring technical conditions, environmental impacts and performing *evaluations* during the *whole life cycle* of the road or road section.

## Problem Statement

Poorly maintained and badly constructed roads constrain mobility, significantly raise vehicle operating costs, increase accident rates and have impact on the environment and economy. Estonia, among other countries is facing financial constraints. This is restricting public spending on road mainteainance and development. Therefore it is important to gather knowledge about the technical performance of constructed roads. Long-term road condition monitoring programs and performance measurement systems can provide information to carry out detailed analyzes.

The pavement is affected by loads, due to traffic and climate, which will have an effect on the pavement condition and slowly deteriorate the structure. Every country comprises of several regions and is unique by its geology and climate, by its traffic volumes, soil mechanical characteristics, materials used for construction and also design guidelines. Therefore best practices in other countries cannot be benchmarked without detailed analyzes of suitability [15].

Estonia's 58 487-kilometre road network is a fundamental part of its everyday life. Estonia encompasses also the densest public road network in the Baltic and Nordic countries. The average traffic volume on national roads has increased by 26 % from 2002-2011 [1; 4]. Increased urbanization, economic cycles, and the use of ICT have all impacted on volumes and patterns of road traffic. Concomitantly, demands on and expectations regarding the road network are increasing. Because financial resources are limited government agencies must ensure in an effective and efficient manner that the road network meets legislative requirements and that road network development goals are achieved an optimal way.

Many road authorities, including the Estonian Road Administration (ERA) are facing an increased pressure to utilize their limited resources while still achieving the optimum road network development and maintenance outcome. The average roughness of main roads in Estonia is satisfactory but the average level of roughness of basic and secondary roads is still too high and the speed of improvement is insufficient [4]. For the user of basic and secondary roads that means less driving comfort and large indirect expenses. Road improvements bring immediate and sometimes dramatic benefits to road users through improved access to hospitals, schools, and markets; improved comfort, speed, and safety; and lower vehicle operating costs.

Currently in Estonia various data is gathered about the conditions of the road network and collected in the Smart Road (Tark Tee) Database. *The existing data collection and processing arrangement does not form an integrated system. Therefore it does not support the performance measurement of road conditions and networks on different levels* for the following reasons:

- systematic feedback about performance of pavements and road structures has not been implemented;
- key performance indicators (KPI-s) have not been determined;
- collected data is not systemized and linked to KPI-s;
- frequency of data collection is unsatisfactory;
- number of data acquisition points is insufficient;
- common use of different databases is limited.

The broader goal should be implementing performance measures in an integrated manner to set policy, allocate resources, measure and report results. Other researchers have claimed that 70 % of implemented PeMS experience failure [9;

32], therefore special focus should be put on developing mesures to avoid dysfunctional consequences. Performance measures alone will not affect agency decision making or the effectiveness of policy and resource allocation choices. To influence decisions, performance measures must be linked to objectives and integrated into the planning, management and decision making processes of an road agency.

## Methodology and Structure of the Thesis

- The thesis consists of 163 pages. In the review article two tables and 12 figures are introduced. In publications there are two tables and 23 figures.
- The references contain 62 sources.
- The thesis consists of the review article, abstracts in English and Estonian, references and a series of publications. These publications are referred to in the text by the Roman numbers (**I…VI**).

**I** Kõrbe Kaare, K., Koppel, O. Performance Indicators to Support Evaluation of Road Investments. – *Discussions on Estonian economic policy : Current problems in the EU Member States*, 2012, 2, 88-107.

**II** Kõrbe Kaare, K., Koppel, O. Improving the Road Construction Supply Chain by Developing a National Level Performance Measurement System : the Case of Estonia. – *International Journal of Social and Human Sciences*, 2012, 6, 225-231.

**III** Kõrbe Kaare, K., Koppel, O., Kuhi, K. Wireless sensing in road structures using passive RFID tags. – *Estonian Journal of Engineering*, 2012, 18(4), 314-323.

**IV** Kõrbe Kaare, K., Kuhi, K., Koppel, O. Tire and pavement wear interaction monitoring for road performance indicators. – *Estonian Journal of Engineering*, 2012, 18(4), 324-335.

**V** Kaare, K. K., Koppel, O., Kuhi, K. Use of smartphone accelerometers for winter road maintenance improvement in urban areas. – *Urban Transport XIX. Urban Transport and the Environment in the 21st Century. Southampton : WIT Press, 2013*. [Accepted for publication].

**VI** Kõrbe Kaare, K., Kuhi, K., Koppel, O. Developing Road Performance Measurement System with Evaluation Instrument. – *World Academy of Science, Engineering and Technology*, 2012, 72, 90-96.

In jointly published papers the author of the current thesis was the primary author and principal contributor, responsible for stating the problem, choosing the methodology and writing the conclusions under the supervision and guidance of Professor Dr. Ott Koppel.

This research work focuses on the *development and implementation of a balanced approach to performance measurement in road industry*. The long term goal is to have this research contribute to the development of knowledge to faciliate improved pavement design and road construction and reliable models of performance predictions. Data collection gives us possibilities to assess the current condition of the pavements and to evaluate the effect of maintenance techniques on the existing pavement capital.

Therefore, this work has the following technical and scientific objectives:

- the existing data used for pavement condition monitoring and pavement management system and the frequency of collection are analyzed;
- methodology for selection of indicators for structural performance measurement are defined;
- the indicators having the greatest impact on road deterioration are researched and mapped out;
- new effective technologies are analyzed and proposed to gather continuously necessary input data, for instance Radio-Frequency Idenfication (RFID) and participatory sensing technologies to expand the extent and increase frequency of data collection.

To achieve these objectives it is necessary to carry out the following tasks:

- establish preliminary data requirements to conduct a long term pavement performance study (**I…II**);
- propose methods, technologies and equipment for monitoring the condition of road pavements to acquire continuously pavement condition data as indicated in research papers (**III…V**);
- propose an effective PeMS that gathers various general and deterioriation data about the road network, specific roads and road sections (**VI**).

The author uses a PeMS Systematic Design Approach (PSDA) [27; 66], which is appropriate to achieve the objectives and tasks listed in previous paragraphs. Accordingly to the abovementioned methodology the following steps are presented: the stakeholders and objectives of the PeMS are defined (**I**), the objects being measured are described (**II**), technologies to perform measurements (**III…V**), and a PeMS is proposed taken into account various approaches of performance measurement (**VI**). The corresponding illustration of the structure of the theses is featured in Figure 1.

Research in the field of performance measurement and road condition monitoring in Estonia has been conducted by the following scientists. Professor Aavik has conducted research [3] on the evaluation of the structural strength of pavement in the Estonian Pavement Management System (EPMS). Professor Aavik with O. Talvik and P. Paabo have researched in detail the use of Falling Weight Deflectometer (FWD) measurements for pavement condition assessment and repair design [2; 3]. Professor Haldma from the University of Tartu has researched performance measurement and management in public sector institutions [31]. T. Kadak has created a model for designing and improving the performance management system of organizations [37].

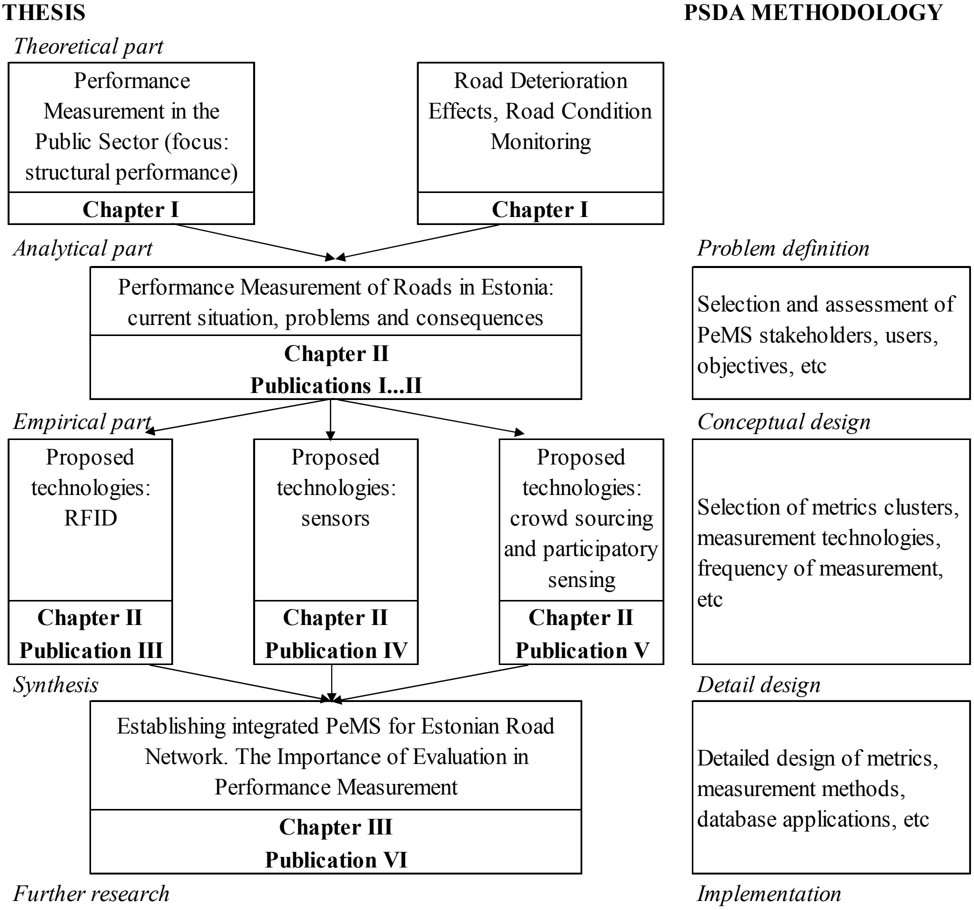

*Figure 1. PSDA methodology and structure of the thesis*

The scientific novelty and contribution of the research consist of the following. The author presents *a balanced approach to performance measurement in the road sector*. From different performance measurement techniques used in production, business administration, IT and public administration, suitable and applicable techniques for road sector are selected. Besides using traditional technologies for measuring structural performance the author proposes *to complement the existing*

*PeMS with real time data via crowd sourcing, floating car sensors and cross exploitation of government databases*.

This is the first research in Estonia *proposing an integrated long term road condition monitoring system that uses feedback for evaluation and analytical purposes*. The current shortcomings of condition monitoring – insuffi-cient rate and frequency, parts of network not covered, data about maintenance non-systemized and weak links to meta and macro levels can be resolved.

## Results approval

The full or partial results of this work were presented at:

- International Conference on Transportation and Logistics Engineering: ICTLE, 19-21st February, 2012, Kuala Lumpur (**II**);
- The 8th International Conference of DAAAM Baltic: Industrial Engineering, 19-21st April, 2012, Tallinn (**III**);
- 18th International Conference on Urban Transport and the Environment, 15-17th May, 2012, A Coruña (**V**);
- Twentieth scientific conference on economic policy: Economic policy in the EU member states – 2012, 28-30th June, 2012, Värska (**I**);
- 21st International Baltic Conference on Engineering Materials and Tribology: BALTMATTRIB, 18-9th October, 2012, Tallinn (**IV**);
- Think Tank on eGovernance Technologies: from applications to innovation, 31.10.2012, Shanghai;
- International Conference on Transportation and Logistics Engineering: ICTLE, 6-7th December, 2012, Penang (**VI**);
- 13th World Conference on Transport Research, 15-18th July, 2013, Rio de Janeiro (forthcoming);
- XXVIII International Road Conference, 26-28th August, 2013, Vilnius (forthcoming).

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# 1. PERFORMANCE MEASUREMENT IN THE ROAD SECTOR

## 1.1. Essentials of performance measurement

With the expectation that what is measured can be better managed, performance measurement is being implemented as a core component of management processes in public sector agencies. In the face of growing challenges, performance measurement is attracting growing interest from transportation agencies. They have long been using performance measurement as part of pavement management and bridge management systems. Now many agencies are extending the process to applications in construction and maintenance management systems, operations and safety programs, and administrative structures and processes.

Although many authors use the phrases of performance measurement and performance management interchangeably, they are different entities. Performance measurement is quantifying, either quantitatively or qualitatively, the input, output or level of activity of an event or process. Performance management is action, based on performance measures and reporting, which results in improvements in behaviour, motivation and processes and promotes innovation (see Figure 2). They also add a third strand of performance reporting – recording performance, possibly against a target or including analysis [53].

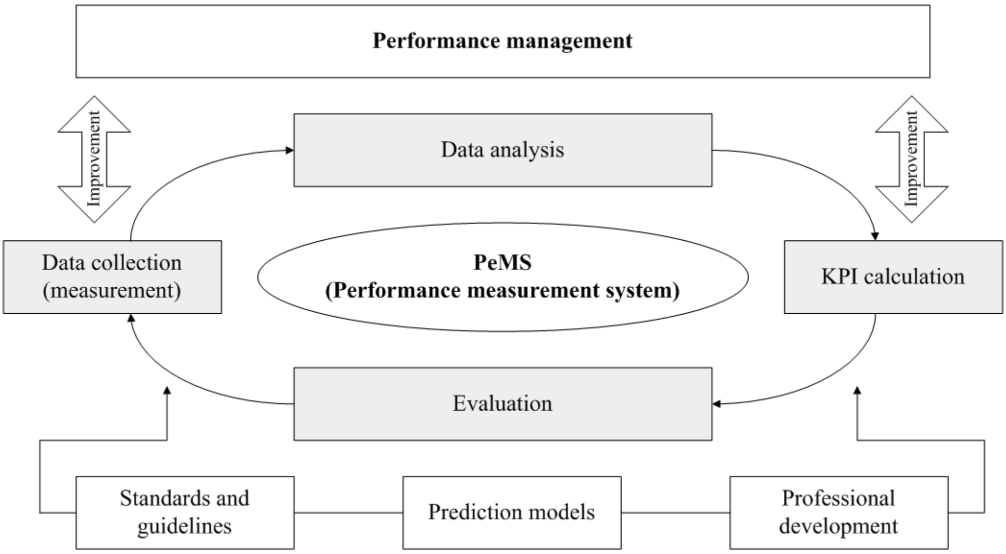

*Figure 2. PeMS in the performance management process [26]*

Performance measurement provides the means to assess the effectiveness of an organization's operations from different perspectives [11]. It is used to provide feedback at all levels – strategic, tactical or operational, project level – on how well strategies and plans are being met. Performance feedback provides the information necessary to improve decision making within the organization and further on government level, to enable proactive problem correction and to promote continuous improvement [57].

The four aspects of performance measurement are:

- deciding what to measure;
- how to measure it;
- interpreting and evaluating the data;
- communicating the results.

Performance measurement is a simple concept without a simple definition [41]. Performance is a term used in everyday life, in engineering, in economics, and many other areas. It can have a general meaning or a specific meaning. For the latter, and particularly for roads, performance should be a measurable entity. This is essential for assessing the current and future state of road infrastructure, as well as institutional efficiency in service and safety provision to users, productivity, cost-effectiveness, environmental protection, preservation of investment and other functions.

In the last two decades, interest has grown in the art and science of performance measurement, particularly as it applies to road and transportation systems. The topic is well documented in the literature with significant treatises from many organizations around the world, including the United States Federal Highway Administration (FHWA) and the Transportation Research Board (TRB), OECD, the Association of Australian and New Zealand Road Transport and Traffic Authorities (Austroads), the Transportation Association of Canada (TAC) and World Bank. The ultimate purpose of measuring performance is to improve transportation services for customers [49].

When developing performance measurement programs, the literature emphasizes that outcome measures should be included, where these relate the activities an agency undertakes to its strategic goals. Output and input measures, which reflect the resources that are dedicated to, and the products of, a program, may also be included in a performance-based management program. The number of measures included in a performance-based program should be limited to those that reflect the issues that are important to an agency.

Therefore, selecting a set of performance measures, it is important to recognize the distinction between input, output and outcome measures. Input measures reflect the resources that are dedicated to a program, output measures reflect the products of a program, and outcome measures look at the impact of the products on the goals of the agency. Outcomes can be more difficult to measure but are considered important to measure because they directly relate the activities an agency undertakes to its strategic goals [49].

The use of specific performance measures related to six outcomes:

- safety;
- transportation system preservation;
- sustainability and environmental quality;
- cost effectiveness;
- reliability;
- mobility and accessibility [25].

Particularly for roads, performance should be a measurable entity. Development of appropriate performance indicators is required for linking transportation and infrastructure data for road management. Performance indicators, are calculated from these measurement results, which indicate the present condition of the pavement. This present condition information together with pavement performance models, makes it possible to predict future performance of the pavement [24; 25; 47].

A performance indicator defines the measurement of a piece of important and useful information about the performance of a program expressed as a percentage, index, rate or other comparison which is monitored at regular intervals and is compared to one or more criterion. The use of performance indicators goes beyond simply evaluating the degree to which goals and objectives have been achieved.

The use of performance indicators by a road administration depends on the particular needs for development or improvement in performance [47]. Performance indicators can be applied to road project or programme evaluation, planning and organisation management in the following ways:

- in process management, to measure the success of individual processes or groups of processes;
- in management-by-results, to set targets and evaluate the achievement of goals and objectives;
- in benchmarking, to establish "best practice" or "superior performance" processes in order to improve performance of the road administration;
- to aid the development or improvement of the functions or specific engineering tasks of the road administration.

Performance indicators are an essential part of modern road asset management [25]. The basic rationale for having measurable performance indicators is that limited availability of resources makes it necessary to allocate these resources as effectively as possible among competing alternatives; moreover, that considerations of safety, capacity, serviceability and durability are explicitly recognized.

In developing performance indicators basic rationale should be considered in the comprehensive approach. A balance in use and reporting, efficiency and effecttiveness, a tie to transportation values, objectivity in the measurement used and the stakeholders involved in the development of a framework. Performance indicators should be tied to road administration agency's policy objectives and to implementation targets or minimum acceptable levels of serviceability [25].

There are different types of performance indicators and different ways to use them. This understanding is crucial in selecting indicators for an administration. Different indicators should be selected based on whether the intention is to improve [47; 54]:

- the internal efficiency of the road administration;
- the quality of the administration's products and services;
- the overall performance of the road transport system;
- a particular process of a specific engineering task.

In the process of choosing an effective indicator, it is essential to know:

- the assumptions regarding the indicator and the rationale for measuring it;
- the precision and accuracy of any measurements;
- congruence – many indicators are proxies, so it is essential that the indicator changes in line with the actual behaviour;
- whether a static measure (a value at a point in time) or a vector (a value and direction of change) is more appropriate whether a soft or hard measure is required;
- if the indicator is going to measure results or behaviour;
- what the likely intended and unintended consequences of the measurement system are [21].

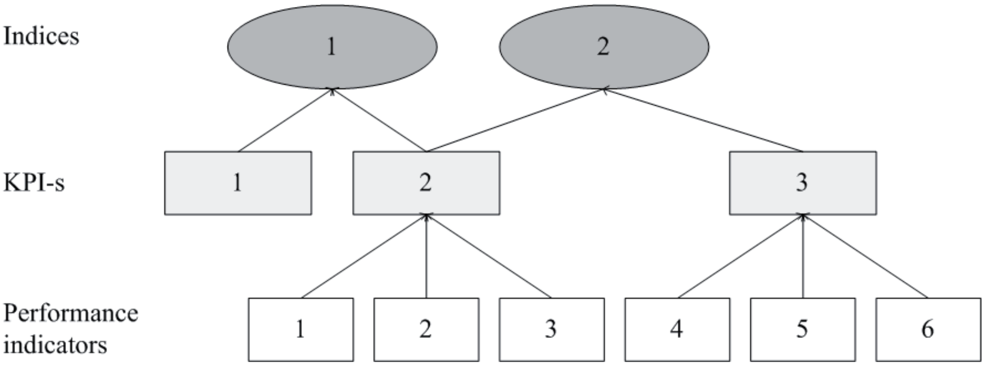

*Figure 3. Conceptual model for road performance indices [29]*

Performance indicators are defined for different types of pavement structures and road categories. In a first step several single performance indicators describing the characteristic of the road pavement condition are assessed. The next step is the grouping of these single performance indicators into key performance indicators and finally into representative combined performance indices (see Figure 3) as:

- functional performance indices (demands made on road pavements by road users);
- structural performance indices (structural demands to be met by the road pavement);
- environmental performance indices (demands made on road pavements from an environmental perspective) [42].

Finally, based on the combined performance indices a global (general) performance index is defined for describing the overall condition of the road pavements, which can be used for general optimization procedures [42].

For designing performance measurement systems data should be collected about various structural performance indicators about the road network and about characteristics having an impact on the deterioration of the road.

## 1.2. Causes of Road Deterioration

For the road network owners, the road represents their primary asset. The most vulnerable part of road structure is the pavement. The pavement is affected by loads, due to traffic and climate, which will have an effect on the pavement condition and slowly deteriorate the structure [14]. Pavement deterioration process is complex and involves not only structural fatigue but also involves many functional distresses of pavement. It results from the interaction between traffic, climate, material and time. Deterioration is used to represent the change in pavement performance overtime.

The ability of the road to satisfy the demands of traffic and environment over its designed life is referred to as performance. Without proper maintenance, the pavement and sometimes the road would deteriorate to the stage where major expenditure is needed to restore its condition to the original level and the residual value of the pavement would be very low. Timely and proper maintenance reduces this depreciation to the benefit of both the road owners and road users. In order to carry out repair work up-to-date information about the condition of the road network is required [52].

In the process of optimal selection and timing of the maintenance measures, the road owners should be supported by information and data from performance measurement and pavement management systems (PeMS and PMS) on appropriate performance indicators, measured by monitoring devices and stored in databases. This data together with road performance models can give to the road owner information concerning the behavior of the road in the long term.

Road deterioration is influenced by the following direct and indirect characteristics:

- climate: temperature, rainfall, freeze-thaw cycles;
- traffic loads;
- geology;
- ground water levels;
- soil mechanics;
- design, construction and maintenance guidelines;
- material characteristics used for construction;
- use of studded tires;
- deicing guidelines and agents [10].

Pavement deterioration in cold climates is significantly different from that in warmer climates. Climate change can have direct and indirect impacts on road infrastructure. The direct impacts are due to the effects of the environment; chiefly rainfall and temperature, indirect are safety and vehicle operating costs. The influence of frost causes large variations in roughness during winter and the spring thaw causes rapid deterioration during a rather short time. Cold climates are subjected to intense solicitation by traffic as well as climatic and environmental factors. In addition to normal wear caused by heavy trucks (vehicles) the three main factors contributing to pavement deterioration in cold climate are:

- thermal contraction and fracture in bound layers;
- volume change caused by frost heave;
- bearing capacity loss during spring thaw [16].

These factors are likely to reduce both the functional and structural levels of service of pavements.

Climatic factors also amplify traffic action by modifying the mechanical properties of pavement materials across the season. During spring, thaw penetrates into the pavement structure and releases the water accumulated in the interstitial and segregation ice. High water contents combined with lower densities are essentially responsible for the weakening of unbound pavement materials and subgrade soils. The strength is then progressively recovered as soils and materials consolidate (drain) over time.

St Laurent and Roy [17] have established that relative damage caused by given load during springtime is between 1,5 and 3 times higher than the annual damage. The weakening is a complex process, which is essentially a function of three major factors: the amount of water accumulated in the pavement system by frost heave, the rate at which the system is thawing and the rate at which the layer consolidates. Viscoelastic properties of asphalt bound make them susceptible to temperature variations. High summer temperatures can reduce significantly the stiffness of asphalt bound making them susceptible to permanent deformation while low winter temperature make them brittle and prone to cracking.

In the Northern hemisphere the geology has been influenced by the latest glacial period. Estonia is a country where the special problems with pavement deterioration in cold climates occur. Similar problems occur in other countries but vary with variations in temperature, geology and other condition as traffic configuration, pavement design practices, *etc*., roads in the cold climates of the Northern hemisphere are to a large extent located in areas which were reshaped by the thick layer of ice during the glacial periods. Therefore, ground conditions are often very inhomogenous and road behavior due to subgrade material difficult to predict in many cases.

Heavy loads cause structural distresses affecting the pavement courses including the subgrade soil. The most typical forms of structural distresses are fatigue cracking in bound courses and permanent deformation of bituminous courses, unbound layers and subgrade [42]. Excessive structural distresses usually occur at the end of pavement life, for properly designed pavements, or earlier for pavements where the number of load applications or the level of stress exceeds the assumptions made by the designer.

Climatic factors can also be the cause of specific pavement distresses. Bound materials are sensitive to temperature variations. As temperature drops, asphalt concretes tend to contract. In the absence of joints, the contraction is restrained and tensile stresses build-up in material. If the stresses exceed the strength of the material, a thermal crack is initiated. During winter, frost penetrates in pavement materials and subgrade soils. While processing in the pavement structure, frost causes interstitial water to expand and can also cause ice segregation to form in the unbound granular materials. When the frost front reaches frost susceptible subgrade soils, water is sucked toward the frozen fringe where ice lenses are formed. The frost heave phenomenon is rarely uniform [58].

Surface distortions have significant impact on the service level of roadways. Differential heaving also occurs as a result of snow accumulation on the pavement sides which affect the thermal regime and result in a greater frost penetration at the center of the pavement than the edge of the pavement. Transverse differential heaving can generate excessive tensile stresses and initiate longitudinal or meandering cracks. These resulting cracks can be highly detrimental to the structural performance of the pavement because they intercept running surface water [17].

Due to the great complexity of the road deterioration process (see Figure 4), performance models are the best approximate predictors of expected conditions. There are many parameters that need to be acquired to successfully predict the rate of pavement deterioration. Among others is annual average daily traffic, number of heavy vehicles, the axle loads, drainage, pavement thickness, pavement strength in term of structural number or value, mix design parameters and in Nordic countries also the temperature and freeze-thaw cycles. Pavement deterioration models are an integral part of PMS-s [28], which are used to forecast long-term maintenance needs and funding requirements on a road network.

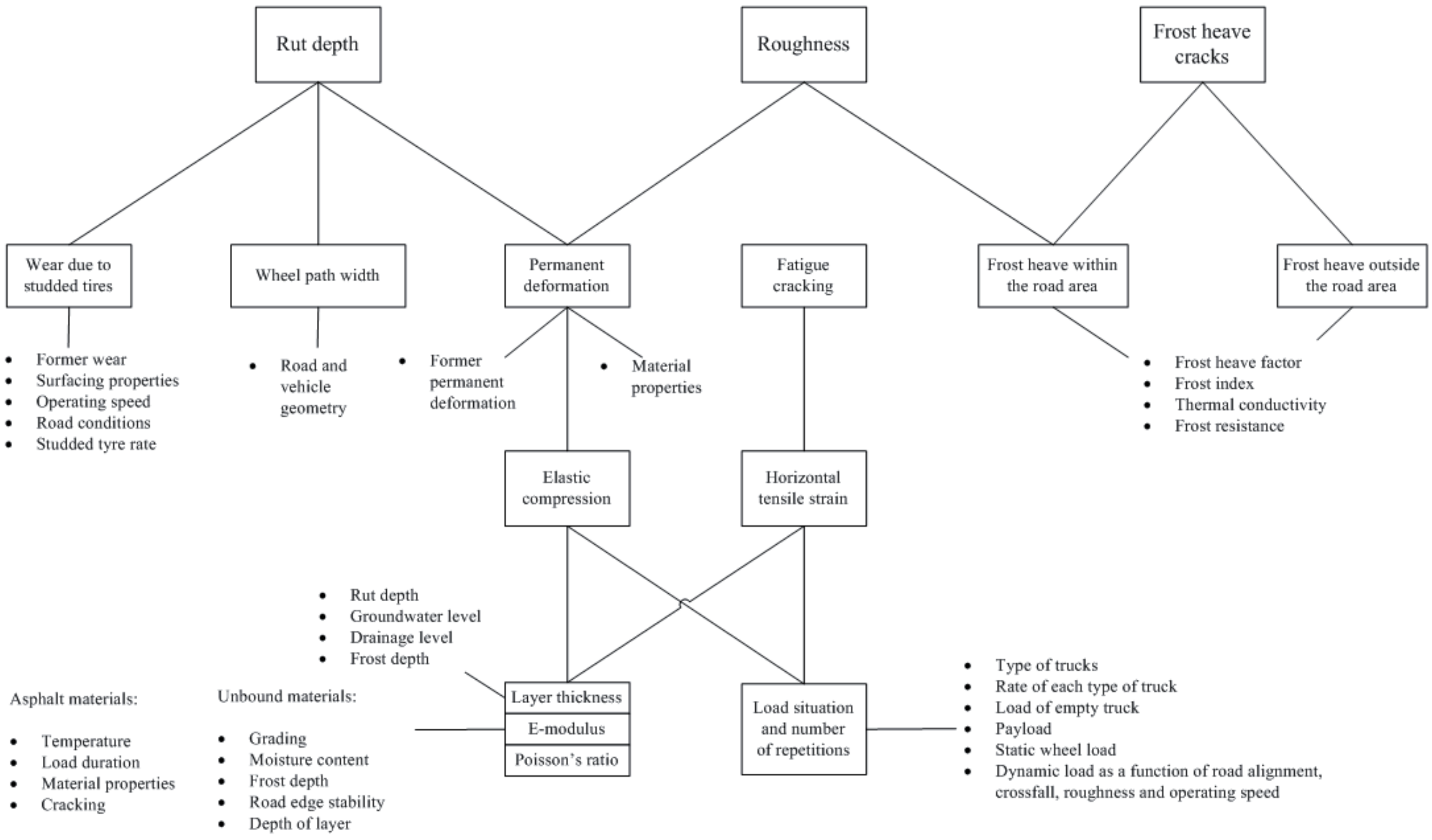

*Figure 4. Complexity of the pavement deterioration process [4]*

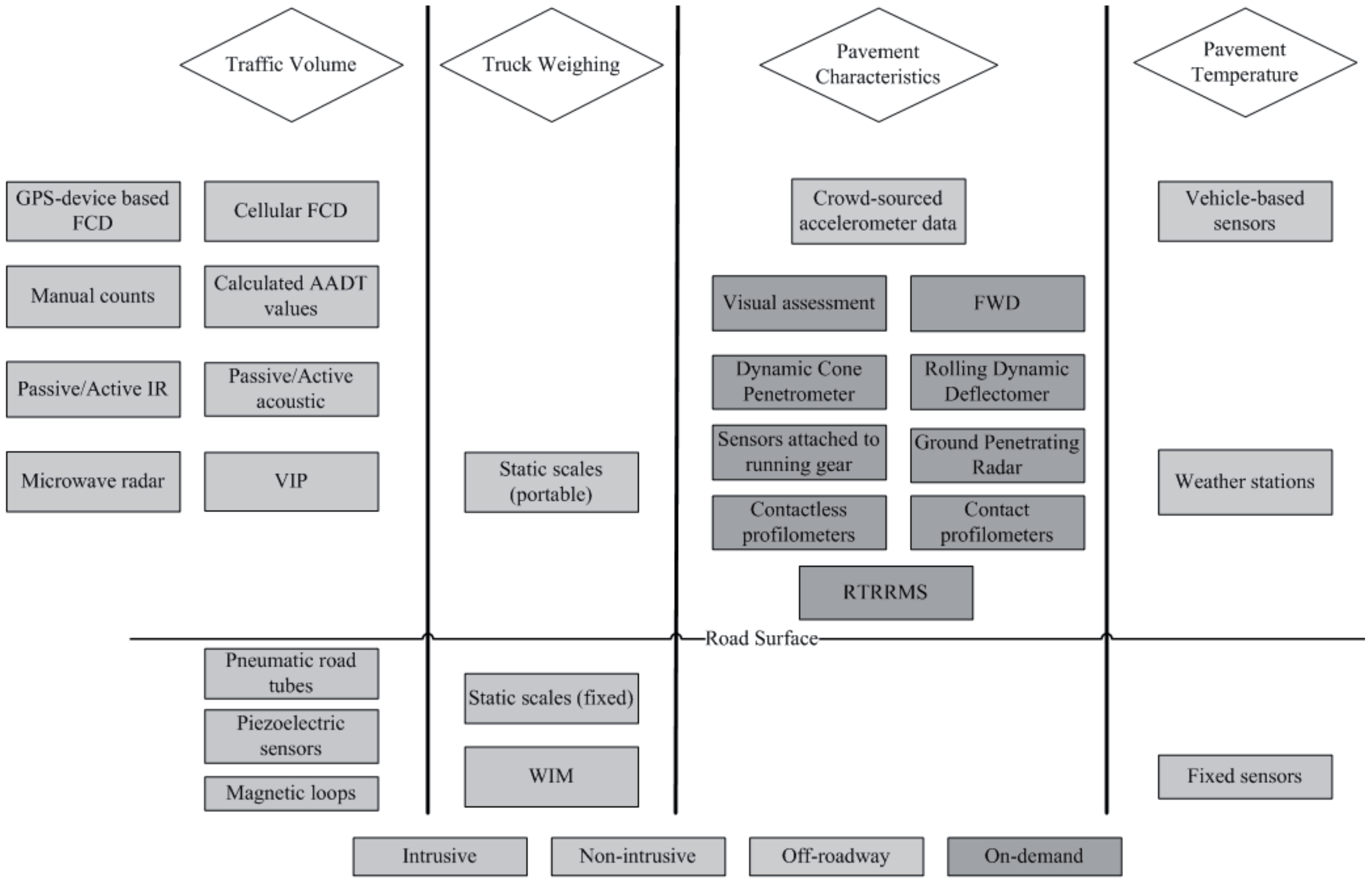

*Figure 5.* *Taxonomy of technologies for pavement condition monitoring*

## 1.3. Data Collection Technologies

During the road lifetime, several factors contribute to road deterioration. Among these factors, external influences, such as climate and traffic (both volume and loads), can be measured with various devices. Additionally, road condition can be monitored with several different techniques. This section describes some currently available technologies.

Due to technological advancements, data collection is becoming continuous, giving real-time insight to road conditions. Besides PeMS, this data is applied in several fields, including economic analysis, finance, legislation, maintenance and planning.

Monitoring technologies can be classified as follows:

- intrusive, e.g. inductive loops. Systems requiring installation inside the road structure.
- non-intrusive, e.g. road weather stations. Systems which are placed above road structure.
- off-roadway, e.g. floating car data. Systems which are not directly connected to road.
- on-demand, e.g. roughness measurement. This covers analysis performed on-demand basis.

In order to achieve comprehensive datasets, aforementioned technologies can be combined, thus minimizing errors. Overview of common technologies according to this classification is described on Figure 5. Common examples are described hereafter.

*Traffic volume*

As traffic volume is rather simple and straight-forward characteristic, all four technology classes have been employed.

- On-demand
    - ✓ Manual counts. While being the oldest, most traditional method, it still has advantages, such as determining vehicle occupancy rate. On the down side, it is the most labour-intensive, requiring trained observers. Therefore it is only performed on demand, usually when automated measurements are not applicable. Most common equipment used are tally sheets, mechanical count boards and electronic count board systems.

  - ✓ Calculated AADT values. As sensor networks do not cover whole road network, on other road sections AADT values are calculated using existing traffic data and inhabitance density around road sections.

- Intrusive. These technologies are widely used around the world. Common denominator is sensor system built into road structure, which detects vehicles. Exact detection method varies.

  - ✓ Pneumatic road tubes – elastic tubes are placed across the road. Any pressure applied to tube is recorded and processed. Downsides include limited lane coverage and sensitivity to weather conditions.
  - ✓ Piezoelectric sensors – this is similar to previous, but uses electricity generated by pressure as signal source, allowing measuring weight as well as speed.
  - ✓ Magnetic loops – most commonly embedded in roads, this solution measures differences in magnetic fields generated by its components. However, it is susceptible to damage from heavy vehicles.

- Non-intrusive. Less widely used, these systems rely on above-ground sensor network for detecting vehicles. Vehicle speed and size are measured via different radiations, such as:

  - ✓ infra-red (IR) – detects vehicles by IR signature;
  - ✓ microwave radar – uses Doppler radar to detect vehicle speed and size;
  - ✓ acoustic – similar to previous, uses sonar;
  - ✓ Video Image Processing (VIP) – using visible part of electromagnetic spectrum, detects moving objects in its view.

- Off-roadway. Traffic volume is measured off-roadway using Floating Car Data (FCD). Unlike other systems, no special devices or infrastructure is needed. Data is obtained from two main sources:

  - ✓ GPS-based – using either dedicated GPS (or other similar technology, such as Galileo, GLONASS or Beidou) device or GPS-capable smartphone, satellite-based positioning gives accurate data about location, speed and direction of travel;
  - ✓ cellular – using simple triangulation, data from cell towers gives approximate location. However, due to low accuracy, this is usable mostly in urban areas, where cell tower network is denser [38; 61].

*Truck weighing*

As the forces affecting road structure are directly related to vehicle weight, weighing heavy vehicles on road is rather common.

- Static scales. These are used both as portable (used on demand) and fixed (intrusive) solutions, which require the vehicle to be fully stopped on device. Depending on portability and purpose, size varies from wheel pads to full-width scales, allowing measuring the weight from single wheel to whole axle.
- Weight-in-Motion (WiM). This describes systems designed to measure vehicle weight without needing the vehicle to come to a full stop. Operating speeds and captured dataset varies among different systems, such as:

  - ✓ Single Load Cell (SLC);
  - ✓ bending plate;
  - ✓ Slow Speed WiM (SSWiM);
  - ✓ Lineas Quartz Sensor [35].

*Pavement condition characteristics*

As determining different characteristics of pavement is time-consuming and expensive, it is performed on demand. Following technologies are developed for analyzing deep structure of road construction:

- FWD – measures stiffness properties of the pavement layers through analysis of deflection data;
- Rolling Dynamic Deflectometer (RDD) – same as former, but allows measurements to be performed while in motion;
- Dynamic Cone Penetrometer (DCP) – estimates strength of soils and granular construction material;
- Ground Penetrating Radar (GPR) – uses radar to estimate dielectric properties on road construction layers [39].

As the road surface directly affects both road user costs and comfort, several techniques have been developed for measuring its condition:

- visual assessment – this is a traditional and proven way of determining road defects;
- profilometers – these systems compare cross-section of road surface to straight line and record all deviations;
- contact-device is in direct contact with road surface using a stylus;
- contactless-device uses remote sensing (RADAR, LIDaR) in order to map road surface;
- running-gear based systems – these systems, such as IRIMETER are attached to vehicle running gear and measure its movements;
- Response Type Road Roughness Measuring Systems (RTRRMS) – these systems measure the amount of work done by vehicle’s suspension [5].

In addition to that, with advent of accelerometer-equipped GPS-capable smartphones, these devices are showing potential with measuring road roughness. This gives a continuous data flow unlike other described techniques.

*Pavement temperature*

Data concerning temperature (and other weather-related variables) can be obtained from national or local weather forecasting agencies, but can also be collected on the road, giving higher precision. Data can be obtained from:

- sensors within road structure (intrusive);
- weather stations on or near the road (non-intrusive);
- sensors on vehicles traveling on road (off-roadway) [6].

The list above-mentioned technologies does not cover all measurement options and also due to innovative new approaches continuously expanding. The ones mentioned were chosen by the author either as most common and frequently used or with a potential to be applied in near future.

## 1.4. Conclusions of Chapter 1

The following primary conclusions can be drawn from Chapter I. *Performance should be a measurable entity, particularly for pavements and road structures.* Performance indicators are an essential part of modern road asset management. The basic rationale for having measurable performance indicators is that limited availability of resources makes it necessary to allocate these resources as effecttively as possible among competing alternatives; moreover, that considerations of safety, capacity, serviceability and durability are explicitly recognized.

The use of performance measurement to benchmark performance of one agency against another can be problematic and cause failure therefore every country should develop its own approach taking into account its requirements [49]. *In each case, the performance measures used must depend on the specific conditions of the agency and country, its goals, its resources, and its audience.* Appropriate PeMS can ensure efficiency, accountability and transparency for transportation agencies.

The most vulnerable part of road structure is the pavement. The pavement is affected by loads, due to traffic and climate, which will have an effect on the pavement condition and slowly deteriorate the structure [14]. Pavement deterioration in cold climates is significantly different from that in warmer climates. *Pavement deterioration process is complex* and involves not only structural fatigue but also involves many functional distresses of pavement. It results from the interaction between traffic, climate, material and time. For these reasons, while measuring performance of roads the focus is on collecting data about characteristics influencing pavement condition.

In the process of developing design and construction guidelines, deterioration models and while performing optimal selection and timing of the maintenance measures, *the road owners should be supported by information and data from performance measurement and pavement management systems (PeMS and PMS)*. Appropriate performance indicators should be measured by monitoring devices and stored in databases. This data together with road performance models can give to the road owner knowledge and information concerning the behavior of the road in the long term.

In the last years, the richness of road traffic data collection sources has grown substantially and we have grown from data poor to data rich societies. New types of data are available from traffic sensors, imaging technology, incident and event reports, and weather sensors. *The combination of traditional measurement technologies with floating car data techniques can provide high quality traffic data in real-time that can be utilised by all the transportation actors*.

# 2. DATA REQUIREMENTS FOR ESTONIAN ROAD NETWORK ASSESSMENT

## 2.1. Current situation

Estonia's 58 487-kilometre road network is a fundamental part of its everyday life. Estonia encompasses also the densest public road network in the Baltic and Nordic countries. The average traffic volume on national roads has increased by 26 % from 2002-2011 [1; 4]. Increased urbanization, economic cycles, and the use of ICT have all impacted on volumes and patterns of road traffic. Concomitantly, demands on and expectations regarding the road network are increasing. Because financial resources are limited government agencies must ensure in an effective and efficient manner that the road network meets legislative requirements and road network development goals are carried out.

Many road authorities, incl. ERA are facing an increased pressure to utilize their limited resources while still achieving the optimal road network development and maintenance outcome. Currently in Estonia the road conditions are deteriorating due to ageing and severe weather conditions. There is not a unified system gathering sufficient amount of data about the entire network The ERA is in charge of the maintenance and development of state roads and local government are responsible for the street networks in their jurisdiction.

Key issues facing road transport system and road administration today in Estonia include:

- decreasing road budgets;
- ageing road network;
- demand for greater transparency in road administration performance;
- separation of the production and administration roles of road administrations;
- demand for greater efficiency in all operations, leading to better results and quality;
- demand for more co-ordination and co-operation across the transport sector;
- demand for performance improvements to be implemented more rapidly than in the past;
- new management aspects and the demand for an open and broad understanding of the mobility problems facing society;
- demand for more data and more efficient data management;
- demand for new design guidelines and deterioration models.

Countries needs long term performance analyzes of road conditions and detailed climate and traffic data to develop the best construction and maintenance guidelines and to develop models predicting deterioration. All Nordic countries including Estonia face challenges caused by freeze-thaw cycles and climate changes. Cold climate together with heavy vehicles are two of the most deteriorating effects to the condition of Estonian roads.

Every country is unique in its geology, climate, design guidelines and the characteristics of local construction materials therefore benchmarking and adopting best practices is not a suitable solution. For instance in Norway 1x1 km$^2$ grids are formed to gather climatic data about roads for maintenance and modeling purposes. The amount of heavy vehicles, their exact weight and especially their amount and weight during spring thaw are important inputs to conduct profound analyzes on their impact and also in developing new guidelines. The traffic data should ideally be available for all road sections. Regions develop very rapidly, as several external factors can change the traffic patterns dynamic information about traffic is necessary for evaluation, predictions and maintenance planning [7; 45; 51].

Different types of data are required for managing the road infrastructure. Data collection technologies and data needs vary depending on which infrastructure element is evaluated. In general terms, elements such as road inventory, pavements, structures and traffic require two types of data: inventory and condition. Inventory data describe the physical elements of the road system. These do not change markedly over time. Condition data describe the condition of elements that can be expected to change over time. During predictions and analyzes both inventory and condition data are required. The data collection and processing system cannot be too data intensive and too expensive to sustain. To avoid this situation, three guiding principles should be considered when deciding which data to collect:

- collect only the data you need;
- collect data to the lowest level of detail sufficient to make appropriate decisions; and,
- collect data only when they are needed [5].

PeMS-s need to be designed flexible. With the development of new technologies or changes in data needed or data frequency the implementation of changes needs to be possible in an efficient manner.

## 2.2. Data Collection and Processing

### 2.2.1. National Road Database

Estonian National Road Database (NRD) is for storing static data about roads in Estonia. Launched in its current form in 2005, it was initially meant for only state roads. However, since then it has been expanded to accommodate local and forest roads. NRD is built as attribute-based database with no direct GIS component. All spatial data is defined by linear referencing system, which allows mapping road data using GIS software and road axis data supplied by Estonian Land Board.

Its functions are defined in the Road Act, as are specified the datasets required for different road types. At this point, required data for all public roads is as follows:

- road name and number;
- road section number, name, length, administrative description;
- pavement and carriageway width, pavement type and construction date;
- required maintenance levels for summer and winter;
- intersections and railroad crossings;
- bridges, viaducts, culverts;
- bus stops;
- roadside lighting and walkways.

Additionally, on state roads, following data is required:

- pavement defects, roughness, load bearing capacity and rut depth;
- AADT;
- measurement devices on road – weather stations, traffic counters etc;
- static speed limits;
- traffic accidents – location, cause and type of accident.

Other various datasets are stored in database as well, such as pavement layer thickness. As it is not a requirement by law, the data is inconsistent. Same applies to non-public roads, whose data is usually present if the road has been a public road at some point of time. This implies to outdatedness of data. The NRD serves as a main data source for all analysis performed by ERA and its partners.

### 2.2.2. Estonian Pavement Management System

EPMS is used by ERA for determining and prioritizing upcoming road works. Its source data comes from NRD and consists of as follows:

- AADT;
- roughness;
- defects;
- E-modulus;
- rut depth.

Using AADT values and road classification, road network is distributed among four levels, which imply the required road condition (see Table 1). These levels determine the limit values for different characteristics, which in turn are used to calculate priority values – e.g. necessity of repairing current road section.

*Table 1. Road quality levels based on road type and traffic volume [2]*

| AADT / Types of roads | Below 500 | 500-3000 | 3000-5000 | Over 5000 |
|---|---|---|---|---|
| Main roads | 2 | 2 | 1 | 1 |
| Basic roads | 3 | 2 | 2 | 1 |
| Secondary roads | 4 | 3 | 2 | 1 |

Using AADT values, standardized reconstruction costs are calculated for all road sections. Using AADT and International Roughness Index (IRI) values, road user costs are estimated. With these two values, all road sections are given a feasibility index, which indicates feasibility during one year after road construction. As long-term feasibility studies are not in the scope of EPMS, these tasks are performed with HDM-4.

As a result, two lists are compiled – one for road sections with high and other for low traffic volume (separator is set at AADT value of 500). These lists are sorted by both priority index and feasibility index and presented to experts, who evaluate road section with highest indices in order to compile final plan for future road works.

### 2.2.3. Smart Road (Tark Tee) concept

Project Smart Road (Tark Tee in Estonian) was created to integrate various data sources related to ERA. Initial goal was to replace previous Road Information Centre applications with more complete and comprehensive approach, providing road users with on-time information about administrative regulations (such as road restrictions) and data gathered from road sensors, for example road weather stations. With future data analysis tools and dashboard applications in mind, gathered data is stored with timestamps and spatial attributes. This is part of a long term plan to become comprehensive tool for road network analysis and assessment.

„Tark Tee“ data center receives data from monitoring systems currently owned by or related to ERA (see Figure 6). Data acquisition is active, with data center connecting to external data sources at specified intervals and getting pre-determined datasets. These datasets are preprocessed by data source, for example, traffic counters provide averaged data for 15 minutes. System is designed to allow including other data sources as well, when deemed necessary. This includes sources currently not available due to not being affordable, such as RFID tracking and live telemetry from devices with accelerometers.

Currently, data is programmatically received from and preserved indefinitely from following sources:

- traffic counters;
- road weather stations.

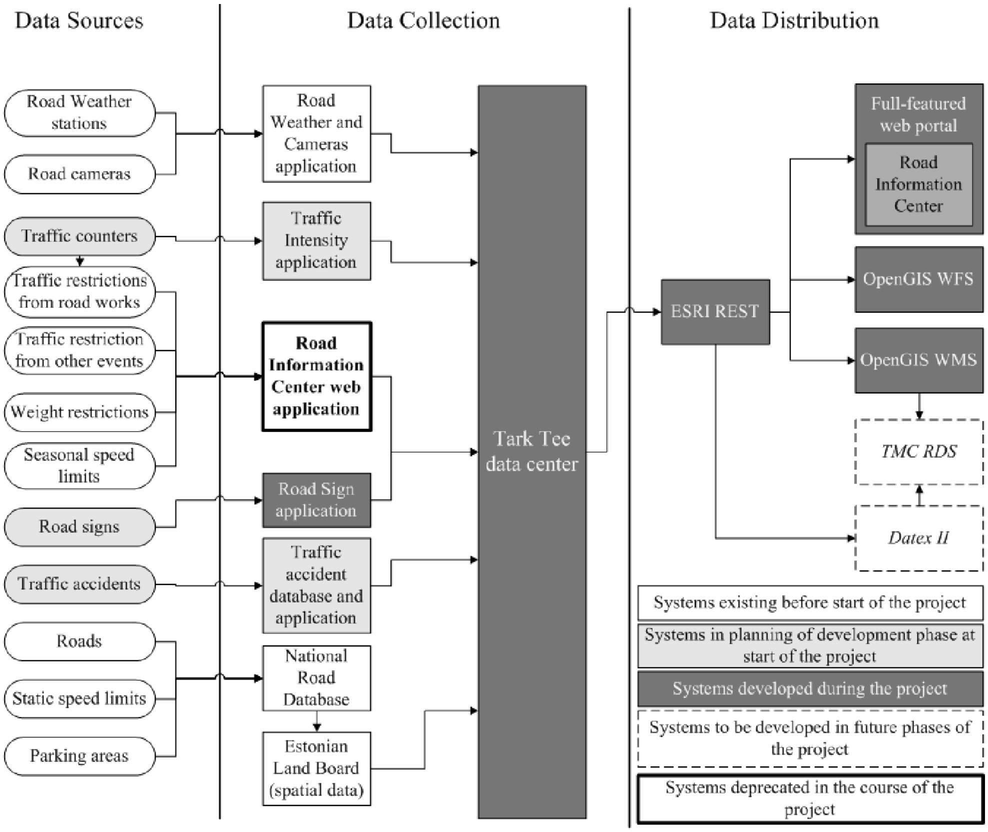

*Figure 6. Smart Road (Tark Tee) Database configuration*

Data is received programmatically, but not stored (only last values are kept), from following sources:

- road structure temperature sensors;
- truck stop mapping project of Transport Workers Union;
- road cameras;
- road maintenance vehicle GPS tracking.

Data is entered through dedicated applications (and stored indefinitely) from following sources:

- Road Information Center providing traffic restrictions;

- road workers gathering traffic sign data with smartphone application.

Additionally, road network spatial data is received annually from Estonian Land Board and static road data from NRD. This data is updated manually on on-demand basis.

Concerning analysis about road life cycle, following data could be imported to data center from NRD. This data is currently measured biannually on road sections with 100 meters of length:

- pavement defects;
- roughness;
- elasticity.

All data is made available in machine-readable form through well documented industry-standard platform, which provide source to public web portal and mobile applications. At this moment, data receives very little post-processing. For specific decisions, most data processing is done manually, for example using traffic counter data concerning seasonal speed limits [31].

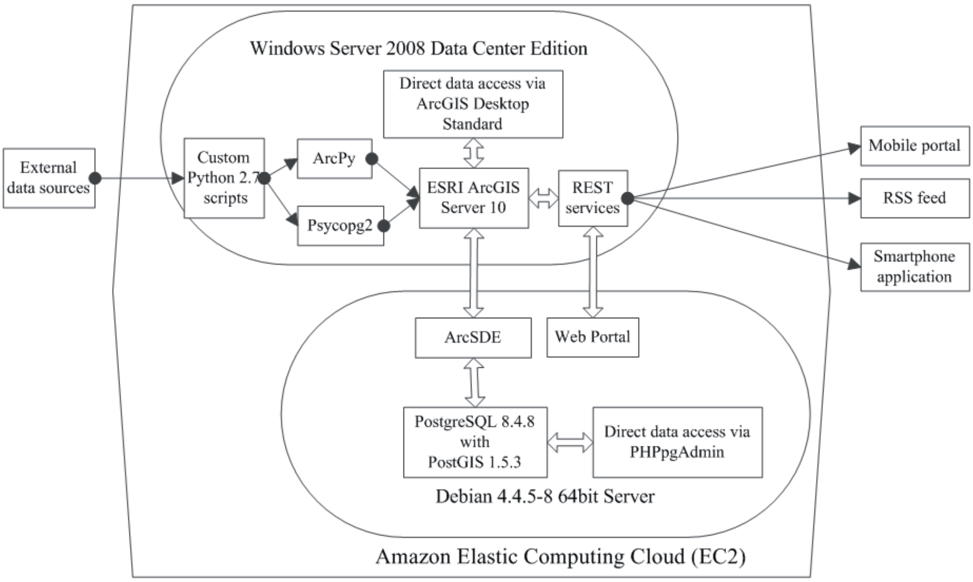

*Figure 7. Technical specification*

“Tark tee“ data center is based on ESRI ArcGIS Server 10 software, using open-source PostgreSQL 8.4.8 with PostGIS 1.5.3 as ArcSDE database (see Figure 7). Data import is performed by custom Python 2.7 scripts using ArcPy to communicate with ArcGIS and Psycopg2 to communicate directly with PostgreSQL database. Data output is performed by ESRI REST services, upon which there are currently working web portal built on Adobe (formerly Macromedia) Flash, custom mobile web app written in PHP and Android application built on Android SDK 8 and ArcGIS Runtime SDK for Android.

All hardware is virtualized and workload is distributed between two servers. FOSS software is run by Debian 4.4.5-8 64bit. Windows applications, such as ESRI ArcInfo Desktop (formerly ArcView) are run on Windows Server 2008 Data Center Edition. These virtual servers are hosted in Amazon EC2 environment [31].

In Estonia, data collection is distributed among several different government agencies. As substantial amount of it can be used in road performance measurement and deterioration modeling – such as data from law enforcement and weather services (e.g. EMHI) – an interoperability layer is needed.

## 2.3. Shortcomings in Existing System

At this point, there are number of different sources providing continuous flow of raw data. However, this data is mostly just stored and not used in analysis. This is due to lack of proven and widely accepted formulas of transforming data to comprehensive indicators. Other data is used, but only in specific analysis, which are used only in-house and not published.

Current system is lacking in feedback (see Figure 8). While road maintenance is required to fill out work journals, these are either paper-based or its digital analogue, being unusable for data analysis. Since maintenance works are divided among different authorities and executors, there is no common set of rules for data collection. Due to these reasons, all records of maintenance works are effectively nonexistent in context of data analysis. As the road elements are very heterogeneous and gradually aging, it is necessary to allocate important budgets, but also to look for agile models of technical, economic and administrative management.

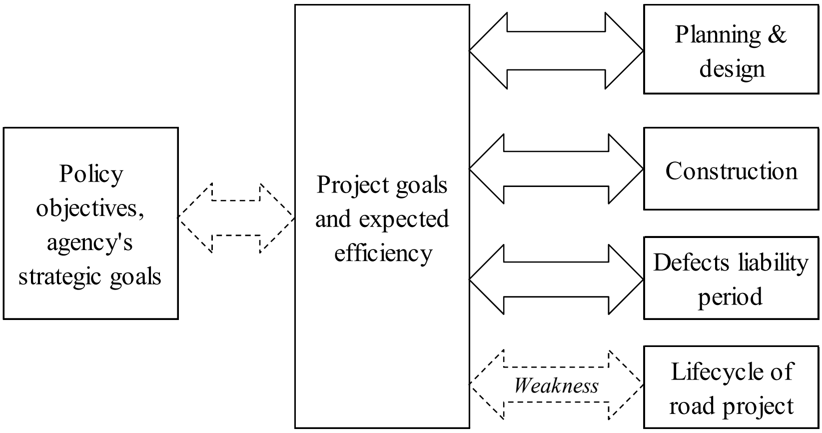

*Figure 8. Main weakness in Estonian road projects assessment*

ERA gathers data about IRI randomly with the interval of 1-3 years. Our climate requires an overall overview of the network twice a year – in autumns and after the sprint thaw – sometimes even more frequently. Today in Estonia, most analysis performed on road conditions are in essence, *post hoc* analysis. As limitations of time – for example, road defect detection can only be performed in small timeframe – and resources inhibit covering total road network, annual data gathering covers only half of it at best. This causes data collection frequency to be biannual or lower. While this is not an issue for long-term planning, time interval between collecting data and performing analysis contains several events affecting pavement condition, most importantly freeze-thaw cycles. Therefore, pavement degradation caused by aforementioned events on roads may go unnoticed until beyond event horizon.

However, there is large amount of sensor-based data – traffic volumes and weather conditions – collected by ERA and its contractual partners. This data is used for calculating AADT values and planning road maintenance, but not for other analysis.

Another issue is spatial distribution of data. While some sensors provide data flow which is indeed descriptive of whole country and can be interpolated along whole road network within reasonable margin of error, others do not. An example of the former is Road Weather Station system, which is rather evenly distributed. For the latter, Traffic Counter system provide real-time data mostly for main roads, which have highest traffic volume, but are less that 10% of state road network. Other systems, such as WiM sensors have too few data points to adequately assess the impact on whole road network. This issue is caused by both legacy and budget reasons.

In addition to that, 61% of public road network is not managed by state, but consists of local roads, managed by local governments. This means over 200 interested parties within wide range of capabilities in resources and know-how. There are no incentives for maintaining local road data in NRD, other than road names and lengths. Therefore all other datasets are incomplete.

Along with differences in spatial distribution, temporal distribution is just as various. Data from aforementioned sources is effectively real-time, while other data is gathered through procurements annually. While combining these data sources, it is imperative to account for dynamics between different measurements.

Estonian X-Road project is an example of best practice in the field of such interoperability layer between different parties. It was based on innovative and resource-saving idea of using unified set of user interfaces for communicating with different data sources. It is currently connecting over 100 databases, serving both public and private sectors. Its technical solution does not necessitate mirroring all data into centralized database, but creating a standardized data endpoints at every connected database. These endpoints can be Secure Servers for data exchange or Mini-Portals for Web Services (MISP2). Access to different databases requires authorization via national ID Card or e-banking and personalized approval from database owner [30].

As the X-Road project focuses on mostly personalized or otherwise sensitive data, all connections are strongly encrypted. While this is absolutely necessary for privacy and security, it does inhibit performance in terms of bandwidth. As road data does not require such security (as it is already public), but – due to sheer volume of raw data – has high requirements for bandwidth. Therefore directly integrating Smart Road and Road PeMS with X-Road is not suitable.

However, as the X-Road exchange layer requires standardized output, it can be used as a model for new exchange layer, which could be oriented for performance instead of security. This allows cross-referencing several data sources without data redundancy, for example determining exact road conditions during traffic accident or visualizing all events on road during its life cycle.

## 2.4. Upcoming Developments

The data acquisition should stay true to current principles in the near future. Data volume and speed are expected to rise, but within the frames currently existing. Instead of current situation that only covers the state roads, data should be acquired from all roads and geographical reach should be expanded to include neighboring countries, possibly the whole EU. Also, data acquisition should be expanded to sources currently unused.

Compared to current situation, output should be vastly different. With smarter cars, on-time information is crucial. Whether this information is received by the car directly or through the drivers smartphone is of little relevance. The main issue is, that drivers receives information instead of unprocessed data. For instance, drivers should be informed not only about traffic incidents or weather conditions, but also given suggestion, what would be appropriate reaction. Thus should be possible to alleviate traffic jams by routing cars through different streets/roads, depending on how many cars have already been sent to those directions.

So the end-user output should be operative and simple. For the in-house users, there should be at least three different approaches.

- Decision-making. All data is highly processed, so that output is figuratively traffic light, color coded. It should be overly simplified, as it is for people with little knowledge of exact details.
- Experts. While preserving decision-makers simplified view, it should also give some access to source data, as experts are familiar with its acquisition and processing and can improve on the initial decision.
- Research and development. Full access to any and all source data with no limitations must be available. For instance, combining an average headway on state roads with road camera picture brightness should be made effortlessly and quickly accomplishable.

If these developments can be implemented obvious improvements will follow. First the whole Estonian road network is united into one Integrated Database System (IDS). Secondly the collected data can be processed into information.

## 2.5. Conclusions of Chapter 2

At this point, *road network is monitored at a level that is insufficient in both temporal and spatial scale*. As there are no clearly set performance indicators and data is only used for occasional analysis, *actual speed of road deterioration is unknown*. Database interoperability and FCD should complement existing data collection. It is important to establish guidelines for feedback and evaluating the quality of design and construction of new roads and maintenance of existing network.

In order to overcome these problems, following steps are necessary:

- data acquisition must be expanded to cover whole road network;
- data acquisition should be intensified where possible, so data collection frequency would match the speed of road deterioration;
- models and formulas have to developed for transforming raw data into KPIs;
- comprehensive feedback system has to be implemented for calibrating those models;
- issues with jurisdiction are to be alleviated and entire road network should be monitored in unified form, using Smart Road Database as a foundation.

Using existing data for performance measurement gives semi-real-time insight to road condition. Its benefits include, but are not limited to:

- quick response to degradation events;
- due to quicker response, less repairs are needed;
- in longer term, large-scale data collection can be replaced with smaller collection for calibration purposes.

In order to maximize the benefits and alleviate the shortcomings of aforementioned systems, following is suggested:

- improve monitoring on road network with additions to current sensor network and using currently unused resources, such as crowd sourcing;
- all data should be combined in order to provide KPI-s, allowing using them for financial planning and policy making.

The objective of long term pavement monitoring is to facilitate the better understanding of pavement behavior under Estonian conditions and practices. Specific goals related to this objective include:

- to increase understanding of road condition measurements and condition data. Given the accuracy of measurements currently being undertaken, the data set lends itself towards being a benchmark for investigating most data measurements and statistical characterization aspects;
- to provide the required condition performance data for on-going pavement model development. There are a number of models still to be developed and others that need further refinement work which is only possible with more data. increased use of data in the Smart Road Database;
- to use the data in research and development of new innovative technologies such as pavement design and materials;
- with the availability of the data, transportation industry, agency and policy goals could be supported.

Even if not all goals are reached, *current situation offers several low-cost opportunities of improvement with require little effort*. These improvements, most notably KPI-s on existing data and implementing participatory sensing, will bring improvement to most of listed areas.

- *Measurement alone does not yield good data . . .it requires rigor.*
- *Data alone is not information . . . it requires interpretation.*
- *Information alone is not knowledge . . . it requires context.*
- *Knowledge alone does not yield results . . . it requires action.*

*H. Kassoff [34]*

# 3. SYNTHESIS AND DISCUSSION

## 3.1. Performance Measurement System Configuration

As the funds available to road maintenance and construction are limited, it is imperative to monitor the construction phase and the conditions affecting the road in its public usage phase. These conditions include underlying geology, traffic loads, climate and technologies and materials used in construction. This is especially important in Estonia due to general lack of resources and severe climate conditions. The basic rationale of using performance indicators is allocating limited resources for road infrastructure efficiently, choosing optimal solution among competing alternatives and getting feedback to avoid unsuitable techniques and approaches.

Comparing the data from distinct sensors and locations enables identification of correlations between as-constructed properties of pavements in databases and field performance of pavements to quantify the link between material quality, traffic flow, climate and performance. By comparing traffic data and wearing of several lanes gives for data users feedback about the impact of traffic load and tire type on that particular pavement. Further on with more test locations long-term performance of pavements and road structures can be evaluated.

A conceptual model (see Figure 9) can be developed that enables analyzing and predicting more precisely future pavement deterioration based on road utilization. By adding dynamic climate data to the traffic model, prediction of the approximate timeline for probable maintenance needs of pavements will become possible for Estonian conditions. In condition monitoring it is important to gather detailed locations and information about defects, repairs and maintenance history including de-icing frequency and agents used. Several countries including Estonia have outsourced road maintenance from different operators via public tenders. Therefore there needs to be a system supporting unified data collection procedures.

The delivery of a PeMS is affordable, accessible and responsive to the needs of the organization can be achieved only if road sector managers are able to obtain effective feedback provided through a profound approach to data collection and quality. Such feedback provides the information needed for the organization to establish and sustain excellence in program and service delivery to the public.

Proposed PeMS architecture and data collection system is such that information will be provided to consumers dynamically as they request it. Sample usage scenario in Estonia may be a driver starting to drive from Tallinn to Tartu requesting road condition information from the system – the car will subscribe to the road condition information on the route, receiving it directly and incrementally in real time from the server as the car proceeds on the route. Similarly the police may request information on traffic loads on different roads or locations receiving it from the sensors in the location. Other potential beneficiaries are:

- internal and external security forces (police, criminal police, customs, border guard authorities, defense forces);
- road maintenance and construction authorities;
- transportation companies;
- road authorities in developing design and construction guidelines and planning road maintenance.

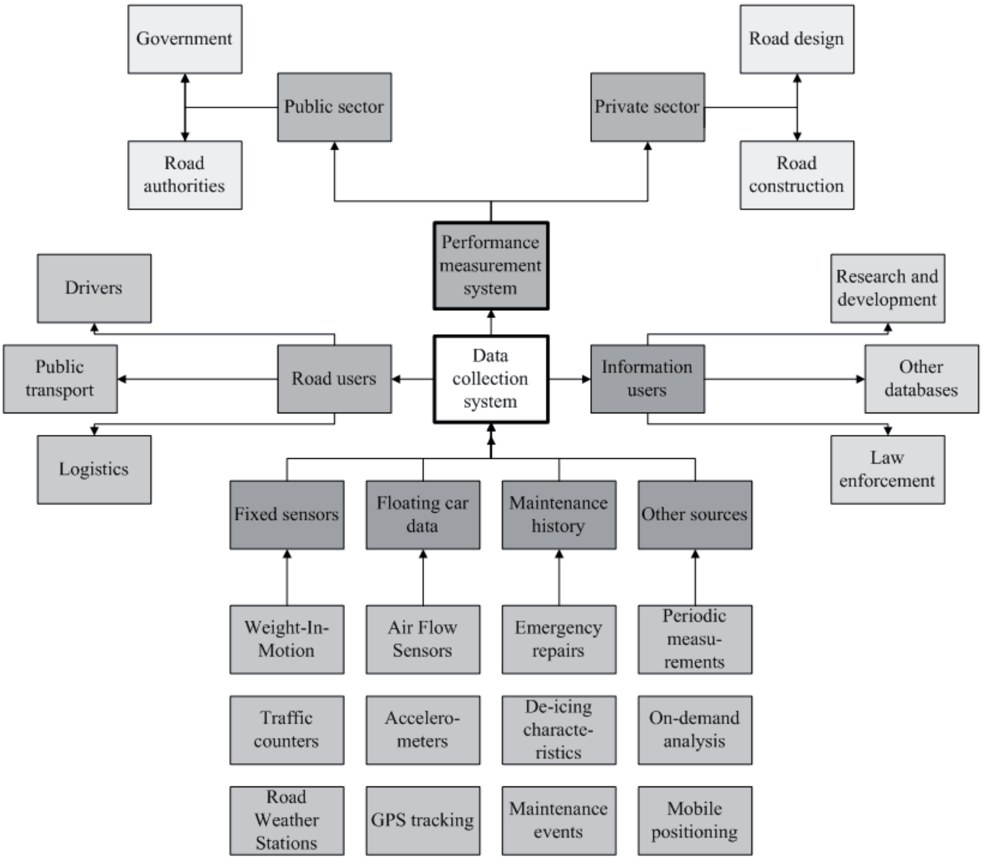

*Figure 9. PeMS configuration for Estonian road network*

Further on, based on long term performance monitoring results a model can be developed to predict the development of deteriorating effects to pavements and road structures based on climate, traffic and road data.

## 3.2. New Technological Solutions for Road Network Data Assessment

### 3.2.1. Sensor Equipped Radio Frequency Identification

The RFID technology is a means of uniquely identifying an object with a wireless radio link, allowing data to be stored on an RFID tag and retrieved in remote application at a later point of time [8]. Wireless sensors incorporated in RFID systems are important in several industrial, consumer and logistics applications. By extending RFID tags to sensing applications the products become smarter and RFID sensor network applications are emerging and becoming more accessible [12; 13].

The climate of Estonia, comprising of several freeze-thaw cycles even per day in winter makes it particularly important from the sustainability point to have knowledge about temperature changes and the amount of water moving through pavement and in different layers of the embankment. Cracking of pavements related to low-temperature frost action and freeze-thaw cycles is a well-recognized problem in most northern countries. Premature deterioration of road pavements is related to high frequencies of freeze-thaw cycles, primarily where subgrades are composed of fine-grained, saturated material. Once in a pavement or embankment water plays a primary role in giving shorter service life, service-ability and increasing the need of rehabilitation measures. In order for a road to be sustainable it is necessary to: consolidate well the earthworks; have good sub-base drainage; keep the water-table low; preventing the moisture content of the sub grade increasing; avoid failures due to binder stripping; and not to allow water to remain on top of the surface course weakening the surface due to hydraulic pressure. If improperly canalized, water can also cause soil erosion and a breakdown of pavement edges.

The way to acquire data about temperature and water content in different layers of road structure is still costly, difficult and time consuming. In this research an idea is presented and preliminary laboratory tests are carried out to use passive and Battery Assisted Passive (BAP) RFID-s with sensors in road structures to measure continuous data about significant parameters throughout the designed lifecycle of the road. The estimated lifetime and durability of suggested technologies are more close to lifetime of the road than other low-power wireless technologies such as Wireless Sensor Networks (WSN) and Active RFID Sensor Tags. Therefore they do not require intrusion to road structures for data acquisition and maintenance reasons. The results of these tests proved that RFID tags can be read through different layers and depths of road construction materials. The idea of using passive RFID tags to gathered data about temperature and water content in different layers of road structures for road performance measurement systems is proposed.

### 3.2.2. Road Section Based Data Collection

For performance measurement of specific roads, or road sections it is important to gather data about different key performance indicators and how they change during the life cycle of the road. Flexible pavements deteriorate under traffic loads and climate effects. The road wear from the traffic will be exposed to road pavements, and depending on the ability of the pavement materials and design the pavement will develop distresses over time. These effects differ depending on the technology and materials of the specific road but the greatest effects depend on traffic loads, their volumes and climate. Integrating a dynamic measurement station in every constructed road or road section is presented as a concept of input data collecting for road performance measurement system.

While planning a new road, this kind of measuring point should be designed at the beginning of every road section as a part of the road construction project. During the life cycle of the road the collected data gives possibilities to analyze the results from various angles – environmental impact, technical sustainability, wearing of the road, etc. With new developments in technology or new requirements the measurement system is flexible to integrate new data collection.

Emphasis of this research was put on finding effects of traffic volume, axle load and tire type on pavement wearing, but also proposing solutions of measuring tire wearing. For pavement design, but also to determine the pavement wear effect of different tires, wear effects of different axle loads have to be determined. Generally this is described by a load equivalency factor (LEF, also equivalent axle load factor), where an axle load is said to be equivalent (producing equal pavement wear) to a number of applications of a reference (standard) axle load. The most well-known LEF is so called "fourth power law" which is expressed mathematically as shown in Formula 1:

$$\frac{N_{ref}}{N_x} = \left( \frac{W_x}{W_{ref}} \right)^4, \tag{1}$$

where:

$W_x$ and $W_{ref}$ - axle loads;
$N_x$ and $N_{ref}$ - corresponding numbers of load applications.

The use of a fourth power relationship predicts that e.g. 7.3 % increase in allowable loading for a single axle will result in a 33 % increase in pavement wear, and consequently road authority can expect a 33 % increase in the length of pavement rehabilitation required per year.

The results are input measurement for performance measurement, allowing also to determine the pavement wear effect from different tires and axle loads. With time the pavement will develop described distress modes in various degrees until the pavement reaches an unacceptable condition and will be rehabilitated by resurfacing and possibly strengthening.

### 3.2.3. Participatory Sensing

As mentioned before currently existing systems do not fulfill the constraints imposed of Estonian roads today. There is a need to reduce specialized and expensive equipment. Developing low cost solutions that involve participatory sensing or crowdsourcing is one of the solutions that is gathering recognition and vast implementation. In this research using smartphone and tablet accelerometers for pothole detection is well suited for initial and real time road surface condition monitoring.

Due to the increasing demand of the transportation authorities for rapid, accurate data acquisition about the road pavement, a mobile mapping system has been developed primarily for road surface detection. Road roughness is measured in different ways, using IRI as an indicator to describe it.

IRI is essentially a computer based virtual response type system that summarises the roughness qualities, that impact vehicle response and is most appropriate when a roughness measure is desired that relates to overall vehicle operating cost, overall ride quality, dynamic wheel loads and overall surface condition. The IRI measurement has m/km (sometimes mm/m) or in/mi units. The determination of IRI can be easily done from the intersected surface points; only the longitudinal profile has to be used [35].

Within the transportation technology industry, there has been an increasing interest in road surface monitoring and in finding easier ways to map and monitor potholes.

There are several vehicular sensing systems for pothole and roughness detection, particularly [19; 22; 35; 43; 44; 50; 59]:

- BusNet system developed at University of Colombo;
- tri-axis accelerometers in an embedded Pothole Patrol system together with GPS receivers developed at Massachusetts Institute of Technology;
- mobile devices as a surrogate traffic sensing and communication systems like Nericell and TrafficSense developed at Microsoft Research India;
- a system developed at National Taiwan University what is using motorcycle-based mobile phones;
- a pothole detection approach in the context of offline data mining, proposed at University of Jyväskylä (Finland);
- a mobile sensing system for road irregularity detection using Android OS based smart-phones developed at University of Latvia;
- photogrammetry-based road roughness measurement system developed at Budapest University of Technology and Economics (Hungary);

- different laser scanners;
- Englo road roughness measurement system IRIMETER.

A mobile monitoring system can be installed on a series of service vehicles or buses, capable of acquiring, elaborating and transmitting data in real time. The instrumented vehicles can be designed to capture the road surface temperature by the use of contactless IR-sensors and various others sensors can be integrated that can perform analysis of textures, crack detection, surface details such as grooving, and others.

## 3.3. Modelling Pavement Performance

### 3.3.1. Estimation of Missing or Incomplete Data with Probabilistic Graphical Models

Pavement PeMS-s are to help decision makers to reach reasonable decisions. If the data that the decisions are based on is old or incomplete then the decisions suffer. The state of the pavement of a road section is often uncertain because the observations about it are partial. Only some aspects of the causes of the pavement deterioration process are observed or the observations are noisy given the exact time moment. When using deterministic models the uncertainty of the pavement state is not visible thus applying the deterministic models are more likely to give false diagnosis.

Traditionally, probability is defined for a random event as the relative frequency with which an event occurs in a set of repeated trials. However, in the case of missing maintenance and recovery history, unknown parameters do not originate from random experiments. Instead, there is uncertainty arising from having insufficient information and not from randomness. As a result, traditional probability concepts are not suitable for addressing this particular problem. To deal with such problems, Bayesian statistics interpret uncertainty as a result of insufficient information and interprets probability as the apparent validity of a hypothesis based on the state of knowledge [55].

In the past decades, researchers have developed various infrastructure deterioration models varying from simple linear regression models to complicated Markov Chain models by using empirical, mechanistic, or mechanistic-empirical approaches. However, these models are limited in two aspects. First, the traditional deterministic models are inadequate to model the uncertainties associated with pavement deterioration processes. Although various stochastic models, such as Markov Chain models, have been developed to capture the stochastic characteristics, these stochastic models suffer from such limitations as the assumption that pavement deterioration is a stationary process. Second, most of the traditional performance models do not consider pavement deterioration as a dynamic process. In other words, most of the previous performance models are static in nature. Moreover, these models focus on developing deterioration models based on historical data, where updating the developed models with new inspection data is generally neglected [40].

Based on modeling approaches, pavement deterioration models can be classified into three groups: mechanistic, empirical, and mechanistic-empirical. Historically, pavement behavior was studied using the mechanistic approach based on the physical principles such as the soil mechanistic theory, mechanical property of pavement materials under load, and multilayer structural analysis techniques. Most of these studies were conducted under limited experimental conditions.

Therefore, they need to be validated and calibrated to the full range of real situations before implementing the developed mechanistic models. In addition, most of these models are still simple and only represent the material or structural responses in limited situations. Even though the mechanistic approach is regarded as the best to characterize the deterioration process, the development of reliable and acceptable mechanistic models is still at its early stage and requires a significant amount of time and effort for continuous studies [40].

The empirical approach employs statistical techniques to explain pavement deterioration with its explanatory variables. Although this approach has the capability to link the pavement performance with their causal variables, the explanatory variables taken are only based on their availability and statistic values. Consequently, this approach suffers from the limitations associated with the scope and range of the available data [40].

The mechanistic-empirical approach is the combination of the above two approaches. The mechanistic approach assists in determining pavement responses, structuring the explanatory variables and functional forms of empirical models. The final relationship between the response variables and pavement performance is developed with the statistical techniques adopted in the empirical approach. The coherent combination utilizes the advantages of both approaches and is expected to attain better performance models than the empirical approach only [40].

Keeping up to date the technical parameters (e.g. using crowd-sourcing) is not possible in case of each type of parameter. To display the more reliable pavement performance index with the probability indicator by the road section to the PMS end user, the mechanic-empirical COST354 modeling can be combined with probabilistic graphical models that estimate the missing or improve the outdated technical parameter measurement values.

The research [37; 55] shows that by applying very simple probabilistic concepts together with the state of similar road sections data, also historical planning and build information, the accuracy of the estimation of the repair need of the road section is very high. Those techniques theoretically are applicable to technical parameter approximation.

The observations in Estonian Smart Road (Tark Tee) Datacenter case are done in very different time intervals varying from minutes to years. To find probable state of the pavement of a road section we need to consider also the time passed from the last given observation. This requires the dynamic nature of the probability modeling (e.g. using Hidden Markov Models and Dynamic Bayesian Networks).

Some of the currently missing values can be derived from other measurements and similar historical cases. Some can be approximated and still used in the performance calculus giving indication to the end user of the probability of correctness.

### 3.3.2. Performance Indices

PeMS is suitable for monitoring the performance of the entire road network in Estonia. The roads managed and supervised by the ERA have a better capability to implement the system. The system is designed to collect measurements of the pavement condition, climatic conditions, traffic load and volume and also maintenance records. After modeling, analyzing and evaluating the outcomes of the gathered data it is possible to make suggestions to the design guidelines, construction guidelines and to optimize repair strategies for pavement rehabilitation and maintenance.

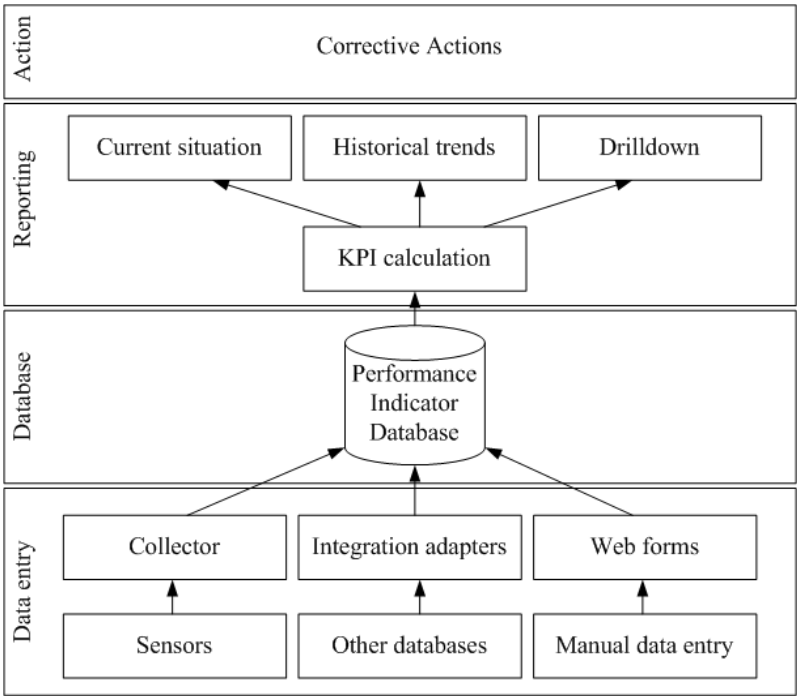

*Figure 10. PeMS architecture*

Besides valuable information about how to design and construct sustainable roads the system (see Figures 10 and 11) enables to develop and successfully implement a proactive approach for prioritizing, preserving, rehabilitating, and maintaining existing pavements. The process includes technology and implementation planning, software application configuration, database implementation, interfaces to internal applications, testing, training, data conversion, end user and technical documentation, project management, and post-implementation check-up and annual evaluation, development and support.

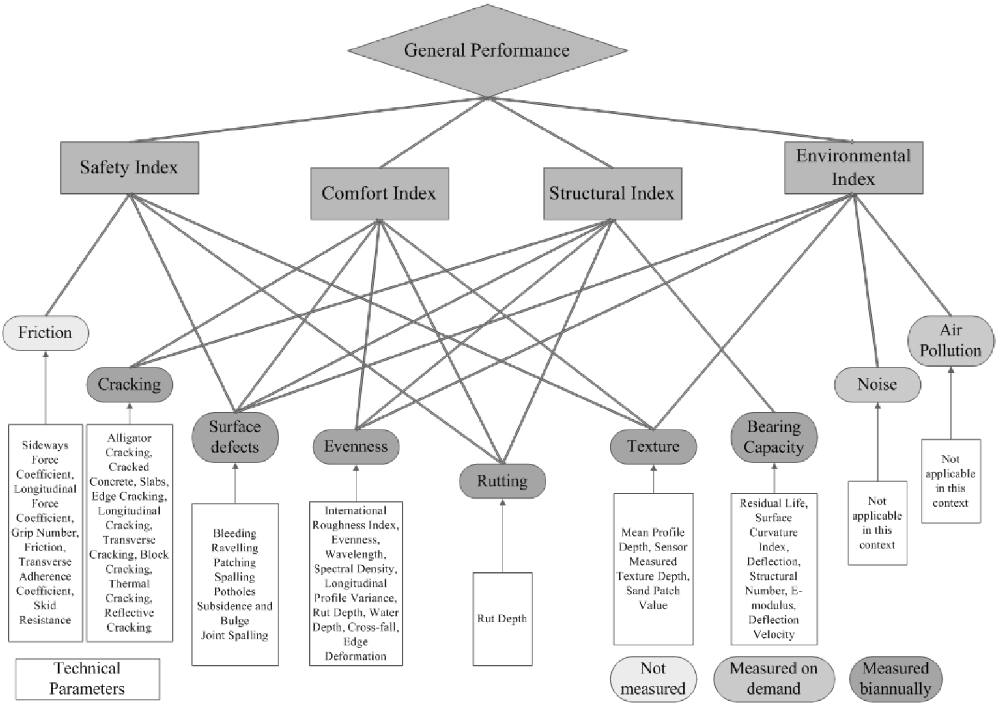

*Figure 11. Combined performance indices as proposed by COST354 [42]*

The primary objectives of developing a PeMS are the following:

- create the ability to provide a secure method to assure data integrity and access to all vested and interested parties which will lead to improved communication and help optimize the investment in maintenance activities;
- allow for importing of data from other databases to create a single source for pavement data to improve the network and project decision making process;
- provide a single source of reports for internal and external stakeholders to improve the decision making process;
- provide timely and accurate information executive management to improve the daily decision making process;
- create the ability to prioritize pavement projects based on objective distress and condition indices leading to optimized investment and long-term cost avoidance;

- monitor pavement segments, sections over time to see the change in the pavement condition to optimize the timing of maintenance decisions leading to long-term cost avoidance;
- create predictive models for assisting in optimizing the planning and programming of future projects leading to long-term sustainability and cost avoidance;
- provide the ability to centralize and standardize the tracking of history through integration of key data sources to facilitate optimization of the investment in maintenance and rehabilitation activities;
- provide pavement performance and history of activities at any project location within the network to facilitate optimization;
- provide the ability to determine a level that will support a defined pavement performance level focused on extending the service life by applying preservation treatments early instead of having to rehabilitate the pavement later leading to long-term cost avoidance.

Common way of combining different parameters is defining indicator as weighted sum of different measured values. These weights must be calibrated after according to road network conditions, giving higher weights to more descriptive items.

For example, technical parameter for cracking describes the severity and spread of pavement cracks. As different crack types are described differently, e.g. longitudinal cracking is measured as length, while alligator cracking is measured as area, formulas (e.g. Formula 2) are to distinguish and combine collected values based on their spatial properties.

$$TP_{cr} = Min\left(100;\ Min\left(100;\ \frac{1}{A_{ref}} \cdot \sum\nolimits_m \left[W_m \cdot \sum\nolimits_i \left(S_{cr,a,i} \cdot A_i\right)\right] \cdot 100\right) + Min\left(100;\ \frac{1}{A_{ref}} \cdot \sum\nolimits_n \left[W_n \cdot I_{width,l} \cdot \sum\nolimits_j \left(S_{cr,l,j} \cdot L_j\right)\right] \cdot 100\right) + Min\left(100;\ \frac{1}{A_{ref}} \cdot \sum\nolimits_o \left[W_o \cdot I_{area,k} \cdot \sum\nolimits_k \left(S_{cr,E,k} \cdot E_k\right)\right] \cdot 100\right)\right), \tag{2}$$

where:

$TP_{cr}$ - technical parameter cracking;
$A_{ref}$ - reference-area;
$E_{ref}$ - total number of referred elements (e.g. number of concrete slabs);
$I_{area,k}$ - standard area of elements with cracks (e.g. area of concrete slab);
$I_{width,l}$ - standard influence width of linear cracks (e.g. 0,5 m);
$S_{cr,a,i}$ - severity of crack type $_i$;
$A_i$ - cracked area of crack type $_i$;
$L_j$ - cracking length of crack type $_j$;
$S_{cr,l,j}$ - severity of crack type $_j$;
$E_k$ - number of elements with cracks of type $_k$;

$S_{cr,E,k}$ - severity of cracks on an element of crack type $_k$;
$W_m$ - weight of cracked areas;
$W_n$ - weight of cracked length;
$W_o$ - weight of cracked elements.

Similar formulas are developed for all technical parameters (see Table 2). COST354 provides two possible ways to create combined performance indices upon these parameters.

*Table 2. Technical parameters for KPI-s in Estonian road PeMS: compiled by author based on literature [42]*

| Indicator | Description | Technical parameters |
|---|---|---|
| Friction | Measure of the frictional properties in pavement surface | Sideways force coefficient, longitudinal force coefficient, grip number, transverse adherence coefficient, skid resistance |
| Rutting | Measure of rut depth on pavement surface | Rut depth |
| Cracking | Weighted sum of different types and dimensions (area, linear, numbers) of cracking in reference to the investigated area | Alligator cracking, cracked concrete, slabs, edge cracking, longitudinal cracking, transverse cracking, block cracking, thermal cracking, reflective cracking |
| Surface Defects | Weighted sum of different types and dimensions (area, linear, numbers) of surface defects in reference to the investigated area | Bleeding, raveling, patching, palling, potholes, subsidence and bulge, joint spalling |
| Evenness | Longitudinal Evenness is the deviation of the profile from a straight reference line | International roughness index, wavelength, spectral density, longitudinal profile variance, rut depth, water depth, cross-fall, edge deformation |
| Texture | The Macro-texture of surface is formed from the aggregate particles | Mean profile depth, sensor measured texture depth, sand patch value |
| Bearing Capacity | A measure of the structural performance of the pavement | Residual life, surface curvature index, deflection, structural number, e-modulus, deflection velocity |
| Noise | Noise caused by traffic on current road section | N/A |
| Air Pollution | Air pollution caused by traffic on current road section | N/A |

Alternative 1 (see Formula 3) considers the mean value of the weighted single performance indices other than the maximum weighted single performance index influenced by a factor $p$.

$$CPI_i = min\left[5;\ I_1 + \frac{p}{100} \cdot \overline{(I_2, I_3, \dots, I_n)}\right], \qquad (3)$$

where:

$I_1 \geq I_2 \geq I_3 \geq \dots \geq I_n$ and $I_1 = W_1 \cdot PI_1; I_2 = W_2 \cdot PI_2; \dots; I_n = W_n \cdot PI_n$.

Alternative 2 (see Formula 4) considers the second largest weighted single performance index influenced by a factor p. All other performance indices which are less than the second largest weighted single performance index are not taken into consideration.

$$CPI_i = min\left[5;\ I_1 + \frac{p}{100} \cdot I_2\right], \qquad (4)$$

where:

$I_1 \geq I_2 \geq I_3 \geq \dots \geq I_n$ and $I_1 = W_1 \cdot PI_1; I_2 = W_2 \cdot PI_2; \dots; I_n = W_n \cdot PI_n$.

Alternative 1 is the preferred combination procedure for the calculation of Combined Performance Indices (CPIs) because it takes all relevant input values into consideration. However, alternative 2 can be useful for specific applications.

As the sensor network covers mostly main roads, initial indicators should also cover main road network, which carries over 50 % of traffic volume on state roads while constituting only 10 % of total length of state roads [4]. With sensor network expanding, those indicators can be extended to whole road network. Possible performance indicators are as follows.

- *Freeze-thaw degradation.* Combining freeze-thaw cycle data from road weather stations with traffic volumes from thawing periods shows possible damage caused by vehicles while pavement is more susceptible to damage than usual. In longer term, these values can be calibrated against actual measured degradation values.
- *Average speed compared to speed limit.* In Estonia, it is common to keep traveling speed close to posted speed limit. If average speed is significantly lower than speed limit, it could indicate problems with road itself.
- *Weather effect on speed.* Combining average speed data with weather conditions gives insight to whether vehicles are travelling slower than usually in similar conditions, indicating problems with road construction, for example drainage.

### 3.4. Importance of Evaluation

In road network performance measurement, evaluation should complement and support the system (see Figure 12). Evaluation studies and performance measurement are highly complementary forms of knowledge production. Evaluation and performance measurement share many of the same features with regard to structuring and planning, obtaining data, analyzing and evaluative judgment. Evaluation tools can remedy a number of the shortcomings of performance measurement and also contribute to research-based policy development. Improved technology enables monitoring and reporting systems to collect outcome data on a regular basis and thus measure performance in a more balanced and focused way.

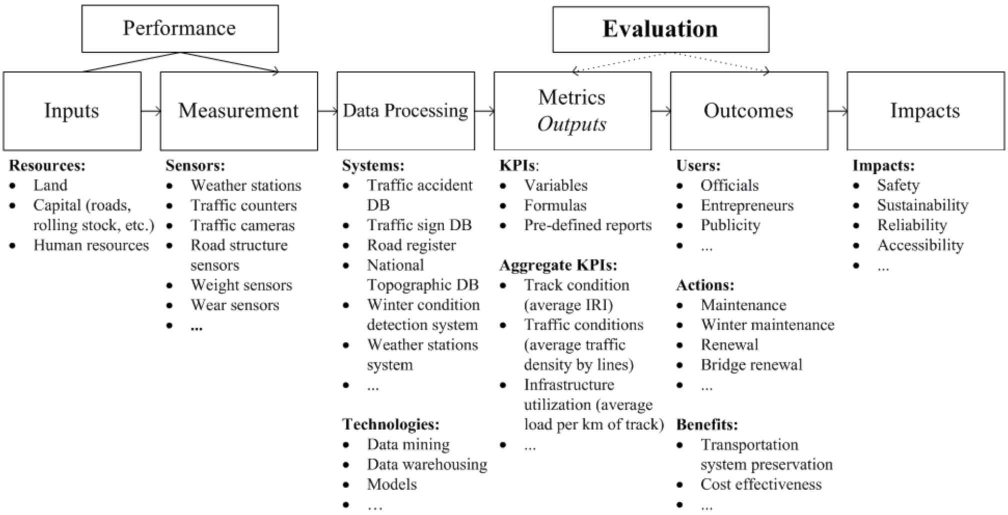

*Figure 12. Evaluation mechanism in PeMS for Estonian road network*

Institutions sometimes draw conclusions from performance indicators and implement changes based on raw observations and output measurements and lead to unwanted outcomes. This automatic transformation into performance information has caused many PeMS-s to fail [47] and therefore it is important to involve data analyzes and evaluation process into performance measurement.

Failure of PeMS is often described from organizational point of view. Bourne [40] has stated that there are three main blocking factors to implementation of the measures that refer to the road network performance measurement:

- the effort required;
- the ease of data accessibility through the IT systems;
- the consequences of measurement.

The measures may therefore prove inaccurate and these cannot be used to track the pathway to strategy execution. Information from performance assessment that should necessitate adjusting activities, do not bring this effect. Even improvement activities are undertaken these are not based on the facts collected by the system. [40].

Contrary to performance measurement, evaluation can question the very relevance and appropriateness of the development, program, project or solution and as such identify unintended as well as expected and planned results. It can further explore the reasons for the documented results. In this sense, evaluation has a deeper heuristic and penetrating nature than performance measurement.

As has been stated, performance data feeding back into the program organization needs to be analyzed in order to identify the contextual evidence that may explain good or poor performance. It is thus important that performance data is reported on the basis of balanced assessment. Evaluation audits are a tool to help in creating such assessments.

## 3.5. Conclusions of Chapter 3 and Further Research

During this research the following was done.

- *A new conceptual model for public sector PeMS that focuses on structural performance of road network, is introduced*. This proposed system enables analyzing and predicting the behavior of pavements and road structures. It is suitable for Estonian conditions, but applicable also in other regions with similar climatic and geological conditions.
- *New PeMS architecture and data collection system for Estonian road network has been proposed* focusing on monitoring of technical conditions, feedback, environmental impacts and life cycle evaluation.
- *New technological solutions for more frequent and real time road network data collection have been analyzed*, allowing further developments of Smart Road (Tark Tee) Database.
- Novel pavement performance models to estimate missing or incomplete data with probabilistic graphical models have been elaborated.
- Novel performance indicators, forming KPI-s, and performance indices for PeMS architecture have been introduced.
- *New evaluation mechanism for road network PeMS has been proposed* to eliminate failure and dysfunctional impacts before reporting results and implementing corrections.

In this research work a proposed system of data gathering for performance measurement is introduced. The current research concerns road PeMS with restrictions and the topic calls for further research. *Further research should be conducted on the implementation aspects of the proposed system*, including development of measuring technologies, constructing deterioration models and combined performance indicators and integration of financial and non-financial measures.

Key recommendations for future research are as follows:

- *More data about conditions within the road structures* will give a faster and better understanding about impending problems. Early discovery allows corrective actions even during the construction phase in order to solve quality issues. Wireless Passive or Semi-Passive Sensors with energy harvesting power supply built into road structure are insufficiently covered as a topic. Further research should be carried out to understand the different possibilities of data harvesting from sub-surface structures using RFID. The research should continue on buried passive and semi-passive wireless sensors and energy harvesting of their power supply units in order to get more exact data of pavement structure environmental variations and deviations.
- Precise data regarding technical parameters is measured with sufficient time intervals on main roads. Other parameters and total network coverage can be achieved by *applying participatory sensing principles*.
- *Some values need approximation based on the existing data using probabilistic models or other modern learning algorithms*. The analysis needs to determine which techniques and algorithms to use on different parameters to alleviate the inexactitude of the data at specific time. After improving data collection and correction, it is easy to calculate the KPI-s and indices for a road section together with the reliability assessment. Further research is needed on the implementation aspects of the root cause analysis drill down functionality to enable the lifecycle analysis of road section. Also, the gap analysis needs to be performed with the existing system in order to identify the work packages and create the implementation plan of PeMS in Estonian Smart Road (Tark Tee) Database context.
- ICT is becoming more common in various industry verticals. Automotive industry is one of the leading implementers. Today, a multitude of sensors such as accelerometers, temperature sensors, relative humidity sensors etc. are used in the vehicles. This data is published through CAN bus or its equivalent and becomes available to different devices in the same vehicle. At the same time the M2M communication platforms are evolving and it becomes economically feasible to connect the cars to the Internet using wireless data communication technologies (GPRS, CDMA, HSDPA, 3G, LTE). By connecting those two trends, and taking the security aspect into consideration, *using the car sensor data for pavement condition and climate monitoring becomes possible*. This gives the PeMS a more reliable alternative as a data source besides Smart Phone data. The further research in this field gives answers like which sensor data should be exploited in the PeMS, what would be the best technical solution for data transfer from car to System Refernce Document (SRD) and what security aspects need to be considered in order to connect SRD with car sensors.

- One area of further research is *development of a vehicle-mounted device* tasked with the following areas of application:

  - ✓ texture measurements for PMS including safety investigations;
  - ✓ quality control measurements for new pavement for certifying whether the pavement meets contract specifications for texture and aggregate segregation limits;
  - ✓ texture and surface detail measurements (wear, grooving, tinning);
  - ✓ longitudinal and transversal planarity of the road surface;
  - ✓ faulting at joints and cracks;
  - ✓ joint and crack measurement summarized over a section of pavement;
  - ✓ records of repaved surfaces;
  - ✓ road pavement defects and roadmarking analysis.

Most of these things should be achievable through the combination of a series of laser displacement sensors, LIDaR scanners, accelerometers, digital image processing (Wisecrax, Alparysoft, etc.) and other devices or software implementations for error compensation and calibration. For an exact positioning however, GPS data quality and precision lacks reliability, therefore an optical shaft encoder should be used for linear referencing.

In addition the following areas can be brought out for further research:

- the suitability of introducing COST354 performance model needs to be assessed and its shortcomings alleviated;
- development of Bayesian probabilistic network models is necessary in order to predict the discrete pavement state probability of the single road section given the historical planning and construction information and also the current state of similar road sections. The ultimate goal would be estimating the discrete pavement performance indices (safety, comfort, structure, environmental impact) on the road sections where the technical parameters are either not collected or are collected less frequently than required by the state of the art performance models;
- other modern learning algorithms need to be tested on the collected data and the performance of different algorithms evaluated to predict different values in the COST354 model with the perspective to design auto-calibration system for the model.

With this technical and theoretical further research *the PeMS can be complemented in time making it more effective and efficient.*

# ABSTRACT

A country's level of economic activity, and its production of wealth, is for a large part dependent on its capacity to move people and goods. A nation's transportation infrastructure can either support or hinder its economic development. In Europe, over 75 % of ground freight and 80 % of passenger transport takes place by road. Therefore, road networks are important lifelines for modern societies. A well designed, constructed and maintained road network, which allows for a high degree of mobility and accessibility to communities by road, is an essential factor in the economic development and prosperity of a nation. Road agencies are responsible for the design, maintenance, repair and development of road networks under their jurisdiction in order to ensure required operational levels.

As the quality of roads deteriorates over time from use and continuous impact from the environment, proper maintenance of the road system is necessary to preserve its serviceability and structural integrity, which are important for the effectiveness of transportation, safety of road users and economic development. Since roads are infrastructural assets with long lives, maintenance activities need to be viewed from a life cycle perspective if an optimal balance is to be obtained between benefits and costs, and to assist road agencies in providing appropriate levels of service to road users. Therefore, when access to resources declines and ageing infrastructure deteriorates, the task of maintaining an efficient road network often becomes a challenge for the road agency.

*Modern road management is performance based*; both programming and implementation of maintenance and operational activities are driven by appropriately defined *performance indicators*. Performance indicators can be used in particular as target criteria in life cycle analyses within the context of pavement design and/or systematic road maintenance at the national and the European levels. Uniform performance indicators permit an evaluation of the effects of different design and maintenance strategies, but they can also be a basis for predicting road performance and for improving old and developing new prediction models. Performance indicators are thus an objective tool used in road construction and maintenance at various administrative levels, from the local to the national.

Currently in Estonia various data is gathered about the conditions of the road network and collected in the Smart Road (Tark Tee) Database. *The existing data collection and processing arrangement does not form an integrated system* therefore not supporting performance measurement of road condition and networks on different levels because of below mentioned reasons:

- key performance indicators (KPI-s) have not been determined;

- collected data is not systemized and linked to KPI-s;
- frequency of data collection is unsatisfactory;
- number of data acquisition points is insufficient;
- common use of different databases is limited.

Performance measures alone will not affect agency decision making or the effectiveness of policy and resource allocation choices. *The broader goal should be implementing performance measures in an integrated manner to set policy, allocate resources, measure and report results*. To influence decisions, performance measures must be linked to objectives and integrated into the planning, management and decision making processes of a road agency.

The thesis consists of review article, abstracts in English and Estonian, references and series of publications. *This research work focuses on the development and implementation of a balanced approach to performance measurement in the road industry*. Long term goal following this research is to develop knowledge, relationships and models to facilitate improved pavement design and reliable performance predictions. Data collection gives us possibilities to assess the current condition of the pavements and to evaluate the effect of maintenance techniques on the existing pavement capital.

*Therefore, this work carried out had the following technical and scientific objectives*:

- reviewed the existing data used for pavement condition monitoring and pavement management system and the frequency of collection;
- defined the indicators for road network performance measurement;
- mapped out the indicators having the greatest impact on road deterioration;
- new effective technologies are proposed to gather continuously necessary input data covering the entire road network, for instance RFID and participatory sensing technologies to expand the extent and increase frequency of data collection.

To achieve these objectives following tasks were carried out.

- *A new conceptual model for public sector PeMS that focuses on structural performance of road network, is introduced*. This proposed system enables analyzing and predicting the behavior of pavements and road structures. It is suitable for Estonian conditions, but applicable also in other regions with similar climatic and geological conditions.
- *New PeMS architecture and data collection system for Estonian road network has been proposed* focusing on monitoring of technical conditions, feedback, environmental impacts and life cycle evaluation.
- *New technological solutions for more frequent and real time road network data collection have been analyzed*, allowing further developments of Smart Road (Tark Tee) Database.

- *Novel pavement performance models to estimate missing or incomplete data with probabilistic graphical models have been elaborated.*
- *Novel performance indicators, forming KPI-s, and performance indices for PeMS architecture have been introduced.*
- *New evaluation mechanism for road network PeMS has been proposed* to eliminate failure and dysfunctional impacts before reporting results and implementing corrections.

In this research work a proposed system of data gathering for performance measurement is introduced. The current research concerns road PeMS with restrictions and the topic calls for further research. Further research should be conducted on the implementation aspects of the proposed system, including development of measuring technologies, constructing deterioration models and combined performance indicators and integration of financial and non-financial measures.

# KOKKUVÕTE

## Teedevõrgu tulemuslikkuse mõõtmine: kontseptsioon ja tehnoloogiad Eesti näitel

Eesti teedevõrgu kogupikkus on 58 487 kilomeetrit, millest seisuga 01.01.2012 on 16 443 kilomeetrit ehk 28,1 % riigimaanteid. Eesti teedevõrk on Põhjamaade üks tihedamaid, ning seega ka üks kallimaid üleval pidada. Selle strateegiliselt olulise infrastruktuuri õigesti projekteerimine, ehitamine ja haldamine tagab inimeste ja kaupade liikuvuse, millest omakorda on sõltuvuses majanduse areng ja elanikkonna rahulolu.

Eesti geograafilisest asukohast tingitud põhjamaine kliima koos lumetõrje vajaduse, mitmete külmumis-sulamistsüklite ja kevadise sulaga tingib kõrgendatud nõuded projektidele, tee-ehitusele ning -hooldusele. Eesti erinevate piirkondade (nt rannikuala *vs* sisemaa) temperatuurid, pinnasevee tasemed ja külmumis-sulamistsüklite arvud aastate kaupa erinevad märkimisväärselt ning vajavad seetõttu erinevat käsitlust projekteerimisnormides.

Mida ulatuslikum on teedevõrk, seda olulisem on omada teede kohta võimalikult täpset andmestikku, seda nii teede seisukorra kui ka seda mõjutavate tegurite kohta. Sellise andmestiku abil on võimalik saada informatsiooni analüüsideks, mille alusel on võimalik koostada Eesti erinevate piirkondade eripäradega arvestavaid projekteerimisnorme ja prognoosida teede seisukorra muutumist nende elutsükli jooksul. Täiendavalt võimaldab nimetatud andmestik teede seisukorda jälgida ning vajalikke investeeringuid võimalikult kuluefektiivselt planeerida.

Kaasaegne juhtimine keskendub üha rohkem lühi- ja pikaajaliste eesmärkide integreeritusele. Infovajaduse määramisel on otstarbekas lähtuda strateegilise juhtimise ja tulemuslikkuse mõõtmise süsteemidest. Erinevaid tulemuslikkuse mõõtmise süsteeme on nii era- kui avalikus sektoris viimastel aastakümnetel juurutatud mitmeid, sh ka teehoiuga tegelevates organisatsioonides. Maailmas ei ole kindlalt välja kujunenud arusaama, milline peaks olema tulemuslikkuse mõõtmise süsteem teatud ettevõttes või organisatsioonis. Üks peamisi eesmärke, mida erinevad osapooled infosüsteemidelt ootavad, on väljastatava informatsiooni olulisus. Kui selline informatsioon on infosüsteemist kättesaadav, võime öelda, et infosüsteem on efektiivne.

Organisatsioonides esineb tihti olukordi, kus on kogutud palju töötlemata andmeid ja vajalik info ikkagi puudub. Parim tulemuslikkuse mõõtmise süsteem organisatsiooni jaoks on selline, mis kindlustab teda järjepidevate mõõtmiste abil asjakohase informatsiooniga organisatsiooni kontrollimiseks, planeerimiseks ja juhtimiseks. Iga organisatsioon valib välja enda jaoks olulised nähtused, mida mõõta. Andmeid ilma analüüsi ja hilisema kasutuseta ei ole mõttekas koguda. Kirjanduses rõhutatakse, et mõõdetavad näitajad peavad olema seostatud strateegiliste eesmärkidega. Käesoleva töö *eesmärgiks on esitada Eesti teede seisukorda ja seda seisukorda oluliselt mõjutavate näitajate kogumiseks ja süstematiseerimiseks sobiv tulemuslikkuse mõõtmise süsteemi kontseptsioon*.

Asjakohaste nähtuste mõõtmise abil

- saadakse operatiivne ülevaade teedevõrgu kohta;
- selgitatakse välja kohad, kus teatud tehnoloogilised lahendused töötavad ning kus ei tööta, saades nii tulevikus vigu vältida;
- saadakse võimalus prognoosida tee seisukorra muutumist elutsükli jooksul;
- saadakse võimalus prognoosida kavandatavate investeeringute kulu-efektiivsust;
- saadakse võimalus paremini planeerida nii remondi- kui ka ehitustöid;
- saadakse võimalus modelleerida erinevate lahenduste sobivust enne nende rakendamist;
- saadakse ülevaade kliima ja liikluskoormuse mõjudest tee seisukorrale.

Teeseadusest lähtuvalt on kõigi avalikult kasutatavate teede kohta andmete kogumiseks, töötlemiseks, säilitamiseks ja avalikustamiseks asutatud riiklik tee-register. See veebipõhine avalik andmebaas sisaldab andmeid nii riigimaanteede kui ka kohalike teede kohta. Riikliku teeregistri andmeid täiendatakse ja sinna lisatakse uut teavet pidevalt, võttes aluseks teetööde vastuvõtudokumendid ja lisainventeerimise tulemused. Maanteeameti ja Maa-ameti koostöös on kasutusel Eesti põhikaardile tuginev riigimaanteede kaardikiht, mis aitab andmete kogumisele kaasa näiteks süsteemse GPS-põhise andmete kogumise abil. Ka samalaadse kohalike teede kaardikihi loomine on jõudnud lõppetappi. Teeregistri andmete visualiseerimiseks kaardil on Maa-ameti geoportaalis (*X-GIS*) olemas Maanteeameti kaardirakendus, kus käesoleval ajal kuvatakse riigimaanteede andmeid.

Teede seisukorda kajastavate andmete kogumine on toimunud juba pikka aega. Alates 1995. aastast on riigimaanteedel mõõdetud teekatte tasasust (*IRI*, ingl. *International Roughness Index*) ja inventeeritud teekatete defekte. 1996. aastast on mõõdetud tee konstruktsiooni kandevõimet dünaamilise koormusseadme (ingl. *FWD*) abil ja 2001. aastast teekatte roopa sügavust. Need neli teekatte seisukorra näitajat koos liiklussagedusega on EPMS-i (ingl. *Estonian Pavement Management System*) põhinäitajad. Uuendusena on 2011. aastast alustatud koos teekatte tasasusega makro- ja megatekstuuri mõõtmist. Teekatte seisukorra andmed on riikliku teeregistri andmebaasi kaudu kõigile vabalt kättesaadavad. Teekatte seisukorra analüüsimiseks (seisukorra pingerida, remondivajadus, tasuvusarvutused jne) kasutab Maanteeamet kahte arvutitarkvara: EPMS ja HDM (*Highway Design and Maintenance*)-4.

Kuigi andmeid teede seisukorra kohta on kogutud juba kaks aastakümmet, on Eesti teede seisukorra planeerimine teaduspõhiselt astumas alles oma esimesi samme. *Autori poolt tuvastatud probleemid senises töökorralduses on järgmised*:

- puuduvad ühtsed alused ja mõõdikud teedevõrgu seisundi hindamiseks;
- olemasolev andmestik ei kata kogu teedevõrku;
- teehooldus on killustatud – puudub ühtsetel alustel digitaalkujul hooldetööde dokumenteerimise süsteem;
- valminud teeobjektide seisukorra kohta puudub tagasiside kogumise ja analüüsimise süsteem;
- teekatte ja katendi erinevate kihtide temperatuuri ja veesisalduse kohta kogutavad andmed on ebapiisava ruumilise tihedusega;
- veokite kaalumispunkte on liiga vähe (2013. aasta jaanuarikuu seisuga kolm), et teha täpsemaid analüüse;
- andmebaaside ristkasutus on puudulik;
- tee seisukorra hindamine ja teekatte tasasuse mõõtmine on tellimuspõhine ja jooksvat seisukorra monitoorimist ei toimu.

Käesolev doktoritöö keskendub *tulemuslikkuse mõõtmise süsteemi oluliste komponentide väljaselgitamisele ja uute tehnoloogiate leidmisele*, mis aitaksid tõhustada andmete kogumist teeseisundit mõjutavate oluliste näitajate kohta.

Tulemuslikkuse mõõtmise süsteemi olulisteks komponentideks on andmed, valemid ja mõõdikud. Kui andmed peavad olema täpsed ja valemid kõikehaaravad, siis mõõdikud peavad olema lihtsad ja selged ning kergesti mõistetavad, kuid jäädes samas tee seisukorda ammendavalt kirjeldavaks. Mõõdikute süsteem peab muutma võrreldavaks kogu teedevõrgu, olles samas võrreldav iseendaga erinevatel ajahetkedel. Nii on võimalik teedevõrgus leida nii probleemseid lõike kui ka identifitseerida sündmusi, mis eelnevad teede seisukorra halvenemisele. Nende sündmuste tuvastamine loob eelduse teede seisukorra halvenemise ennetamiseks tulevikus. Selle põhjal on võimalik tulevikus suunata investeeringuid sinna, kus nad annavad parima sotsiaal-majandusliku tulemuse.

Käesoleval ajal on andmeanalüüs valdavalt ühekordse iseloomuga ja nõuab rohkelt inimtööjõudu. Kuna juba praegu laekub suur osa andmestikust automaatselt – tulevikus seda enam –, siis peab muutuma automaatseks ka analüüs. Õigeaegse reageerimise eelduseks on info kiire liikumine ja töötlemine. Lisaks on vaja juurutada süsteem, kuidas need andmed ja analüüsid teehoiukava koostamisel arvesse võetakse, st milline on teehoiukava iga-aastase ülevaatamise protsess, kuidas toimub õigeaegne projekteerimisprotsessi algatamine jne. Sellega seoses on vajalik tihe koostöö Maanteeameti, kohalike omavalitsuste, tee-ehitajate, teehooldajate jm huvigruppide vahel.

*Praegu on Eestis eeldused teedehoiu tulemuslikkuse süsteemi loomiseks olemas, kui*

- täiendada olemasolevat automaatmõõtmise võrku;

- viia alusandmestiku kogumine ühtsetele alustele;
- rakendada uusi tehnoloogiaid ja tööprotseduure andmete kogumiseks;
- *kasutada RFID-põhiseid sensoreid, mis mõõdavad teekatte temperatuuri ja niiskusesisaldust*;
- koguda rahvahanke (ingl. *crowdsourcing*) abil *aktseleromeetriandmestik, mis põhineb nutitelefonirakendustel ja spetsiaalsetel mõõteseadmetel* (nt IRIMETER);
- *juurutada statsionaarsed teesektsioonipõhised mõõtmissõlmed*, mis annaksid teetemperatuuri kohta infot, kaaluksid veokeid, tuvastavad rehvitüübi.

Pärast Eestile sobilike näitajate väljavalimist on võimalik luua andmete kogumise süsteem. Kogutud andmete töötlemise tulemusena saame indikaatorid, millest omakorda võtmenäitajad. Tulemuslikkuse mõõtmise süsteemi abil kogutud info analüüsimise teel on võimalik saada piisavad andmed, et välja töötada Eesti oludele sobivad projekteerimisnormid ning kasutada tulemusi erinevate juhiste ja ennustusmudelite koostamisel. *Analüüsi abil, kasutades sobivaid hindamismeetodeid ja pidevat tagasisidestamist, on võimalik jälgida teede vastupidavust ja kvaliteeti kogu nende elukaare jooksul*. Analüüsides seoseid erinevate näitajate vahel, on võimalik tuvastada konkreetse piirkonna jaoks parimad sobilikud projektlahendused, elimineerides samas ebasobivad.

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## PUBLICATIONS

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| I | Performance Indicators to Support Evaluation of Road Investments. |
| II | Improving the Road Construction Supply Chain by Developing a National Level Performance Measurement System: the Case of Estonia. |
| III | Wireless sensing in road structures using passive RFID tags. |
| IV | Tire and pavement wear interaction monitoring for road performance indicators. |
| V | Use of smartphone accelerometers for winter road maintenance improvement in urban areas. |
| VI | Developing Road Performance Measurement System with Evaluation Instrument. |

# PUBLICATION I

Kõrbe Kaare, K., Koppel, O. Performance Indicators to Support Evaluation of Road Investments. – *Discussions on Estonian economic policy : Current problems in the EU Member States*, 2012, 2, 88-107.

# PERFORMANCE INDICATORS TO SUPPORT EVALUATION OF ROAD INVESTMENTS

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## Abstract

Transportation planning recognizes the critical links between mobility and other goals of society. Strategies supporting infrastructure investments lead to substantial public interest because they relate to public expenditures. Decision processes related to transport projects involve considerations on environmental, economic, technical and safety issues, and are characterized by many actors and multiple objectives in feasibility studies.

This paper compares performance measurement approach in road management and compares them with current practice in Estonia emphasizing the importance of feedback from previous projects. The need to compare predicted inputs, outputs, costs and benefits with actual performance is brought up. Lifecycle approach performance measures are presented that allow government and transportation agencies to consider road construction and rehabilitation strategies more effectively.

**Keywords:** transport policy, infrastructure investments, feasibility studies, road network, performance indicators

**JEL Classification:** O18, R42

## Introduction

A modern transport system must be sustainable from an economic, social and environmental viewpoint. The performance of the transportation system affects public policy concerns like economic development, safety, and security, air quality, consumption of other environmental resources, social equity, land use, and urban growth. Transportation helps shape an area’s economy and quality of life being a major component of economic activity, both in itself and as an input factor to most other sectors.

Transport systems need to be reliable and sustainable to support economic growth. Freight and passenger services strongly support international trade. Infrastructure investments are a key determinant of performance in the transport sector. Governments’ ability to provide infrastructure is limited by the availability and scarcity of resources. Precisely because of these resource limitations, the pursuit of efficiency – i.e. the best possible use of available resources – is at the core of the decision regarding which project to finance (Haas *et al*, 2009).

Due to the social impact, determining role in economic growth and the scale of these investments the risk of errors in judgment should be minimized. During the last decade performance measurement systems have been studied particularly as it applies to road and transportation systems to avoid transport investment risk. Several factors have encouraged this trend toward using performance measures in transportation planning and programming, including:

- desire to increase the accountability of public expenditures;
- need to communicate results to public and to get their support for investments by focusing on results in the face of reduced resources;
- responsiveness of state and municipal statutes (Performance..., 2006).

In this paper the authors have reviewed practices of performance measurement in road construction in different countries, what the appraisal methods for road investments like and how feedback is gathered. Based on the results of other countries practices a set of performance indicators are presented to be considered for evaluation of the road network condition and feedback.

In the United States, United Kingdom, Australia, Canada, Belgium, Denmark, Finland, Hungary, Japan, Netherlands, New Zealand, Portugal, Sweden and Switzerland transportation agencies have conducted research as to why performance measurement in road construction is important, how it should be undertaken, and what is typically measured. This has led to developing and implementing performance measurement indicators for road agencies to evaluate their whole road networks (Performance..., 2001; Transport…, 2008).

These implemented performance measurement systems focus on agencies strategic goals and the outcome of individual road construction projects cannot be identified. Over the past decades, pressures (axle load, number of vehicles, traffic frequency) on the road networks have increased. This has resulted in accelerated road damage and increased demand to develop and upgrade the road network. There is a need to report and communicate how public funds are used to maintain and develop the system and the effect of expenditures upon it.

The ability to perform life-cycle economic analysis associated with infrastructure assets is important to long-term sustainability. To be able to identify if finalized development projects have met estimated financial, environmental and social indicators as predicted is essential to that process. The ability to measure the success of finished projects can help governments or road agencies to use their limited resources more effectively. Performance measures offer a powerful tool for setting objectives, focusing resource allocation decisions, measuring results and improving accountability. This paper aims to emphasize the importance of continuous performance feedback from transportation projects throughout the lifecycle due to the rich support of decision process it can give to new transport projects and development of policies.

## 1. Transportation Policy and Planning

Transport policies arise because of the extreme importance of transport in virtually every aspect of national life. Transport is taken by governments of all types as a vital factor in economic development. Transport is seen as a key mechanism in promoting, developing and shaping the national economy.

Transportation policy planning is a cooperative process designed by the governmental or local agencies to foster involvement by all users of the system such as the general public, the business community, community groups, environmental organizations, the traveling public and freight operators through a proactive public participation process (Rodrigue *et al*, 2009; Litman, 2011) This co-operation and input from all interest groups results in developing and implementing a regional or state transportation policy (see Figure 1).

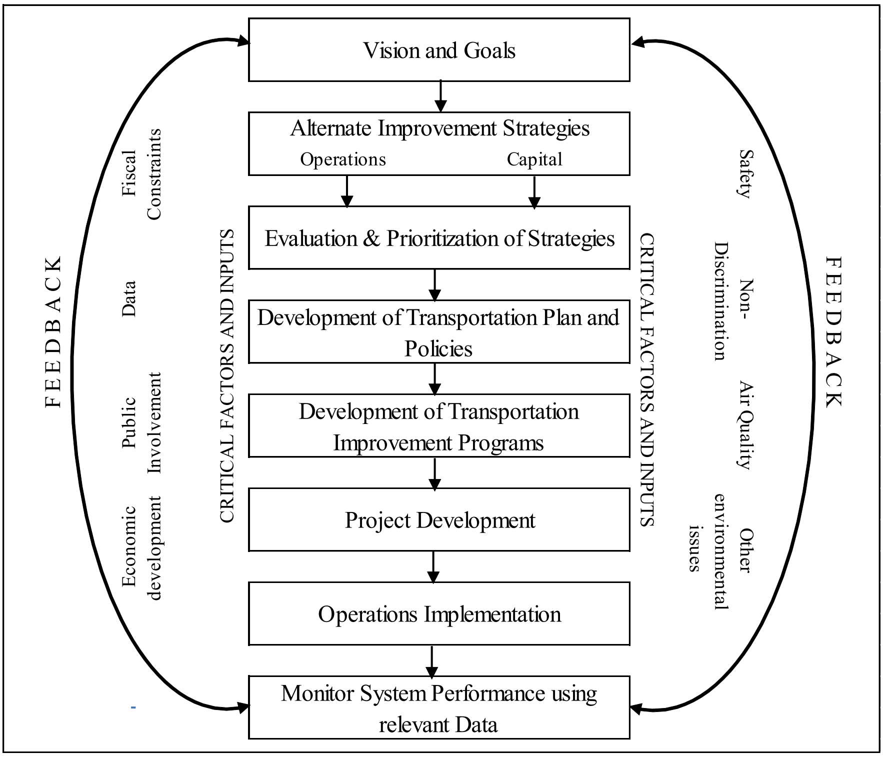

**Figure 1.** The transportation policy-making and implementation process (Adapted from The Transportation..., 2007).

Transport policy is the development of a set of constructs and propositions that are established to achieve particular objectives relating to social, economic and environmental development, and the functioning and performance of the transport system. Transport planning deals with the preparation and implementation of actions designed to address specific problems. A major distinction between the planning and policy is that the latter has a much stronger relation with legislation. Policies are frequently, though not exclusively, incorporated into laws and other legal instruments that serve as a framework for developing planning interventions (Rodrigue *et al*, 2009).

Transportation policy should state the government's primary goals for transport system investments. Four key goals are recommended to be set by national transportation policy, all of which are critical to the national interest, require state level leadership and action and are intrinsically of national nature:

- Economic Growth – producing maximum economic growth per monetary unit of investment;
- Metropolitan Accessibility – providing efficient access to jobs, labor, and other activities throughout metropolitan areas;
- Energy Security and Environmental Protection – integrating energy security and environmental protection objectives with transportation policies and programs;
- Safety – improving safety by reducing the number of accidents, injuries and fatalities associated with transportation (Performance…, 2009).

International experience indicates that diverse problems of transport sector are closely related with each other as they have similar causes and do not necessarily depend on the peculiarities of a transport mode. The main obstacles to the sustainable development of transport arise from one of the following four issues:

- Inadequate planning;
- Inadequate infrastructure quality;
- Issues of safety and security;
- Adverse environmental effects (Campbell *et al*, 2008).

Consequently, transportation policy needs to be performance-driven, directly linked to a set of clearly articulated goals and accountable for results. If a transportation policy has lost direction and a clear sense of purpose, it has substantial costs to collective prosperity, security, environment, and quality of life. In many countries the extensive investments into highway networks, begun more than 50 years ago, that are now nearing or beyond their intended lifespan. Existing systems are dated, in many cases strained to (or beyond) capacity, and increasingly fall short of delivering transportation services at the level of quality, performance, and efficiency the public demands. Current funding mechanisms are not sufficient to maintain existing infrastructure, let alone provide the investments needed to expand and modernize the transportation systems. The broader fiscal outlook is suggesting that public resources will be more constrained than ever in the years ahead. Available resources cannot be distributed without a strong sense of national priorities, and recognition of the link between transportation investments, energy, and climate (Performance…, 2009).

For example, in the United States the importance of performance measurement in transportation projects was clearly stated in 2009 during the development "The New

Performance Driven Vision for U.S. Transportation Policy". Previously there was no federal requirement to optimize returns on public investments, and current programs were not structured to reward positive outcomes, or even to document them. Without clearly articulated goals, there was little accountability for the performance of most federal transportation programs and projects to that date. The result had been an emphasis on revenue sharing and process, rather than on results (Performance…, 2009).

However, as the pre-existing problems on the list, is placed in the centre of the need to learn from past projects carried out in order to avoid irrational spending of resources. The same questions can be posed whether and how to develop a performance measurement system for road transport and to carry out the investment follow-up audit linkage with formal decision-making procedures, incl. use of appraisal methods.

## 2. Interaction between feasibility studies and performance measurement systems

### 2.1. Appraisal methods for road projects

Investment appraisal is an important issue in transport planning and policy. The investments are usually long lasted, practically irreversible, costly and may at the same time have great impact on people's lives and the development of communities and regions. The evaluation of projects should identify key consequences of proposed project and provide quantitative information about them. The various types of effects should then be made comparable, so that a choice can be made in the typical case where different project alternatives would score better on different criteria, and no strictly dominant alternative is available. Investment decisions should therefore be well thought trough, and various alternatives should be compared carefully before making final choice.

Public sector investment appraisal has to take into account externalities generated by proposed transport projects. The range of effects that have to be taken into account with the investments of a road is wide (see Appendix 1). The wide range of effects may make it very difficult for policy makers to decide whether a project is worthwhile to undertake, or to rank competing projects. A skillfully performed projects appraisal will structure the information. The rise in the development of appraisal techniques for transport projects came in the late 1960s and early 1970s. Cost-benefit analysis (CBA) is the common bases for most appraisal networks (Grant-Muller *et al*, 2001).

CBA offers a framework for evaluating all social costs and social benefits of an investment project - including externalities. CBA essentially compares the projected future stream of benefits from project with its initial and future costs. It thus allows a ranking of several competing projects or project variants, or a decision not to undertake any of these. Investment decisions on transport investment are usually made by public authorities, often motivated by infrastructure's "public good" character. Two major weaknesses often mentioned are the unavailability of accurate estimates of shadow prices for various effects, and the method's assumption that different types of effects can be regarded as they can be traded off on "dollar to dollar bases" (Nijkamp *et al*, 2002). As a consequence several complementary approaches have been deployed, such as cost effectiveness analysis, planning balance sheet methods and shadow project approaches. Multi-criteria analysis (MCA) is often seen as competing with CBA, even though there is no fundamental reason why these two approaches may not be used in an entirely complementary manner within an overall framework (Grant-Muller *et al*, 2001).

Therefore, investments in road infrastructure development may not be evaluated using only traditional appraisal methods such as the Net Present Value (NPV), Internal Rate of Return (IRR), Accounting Rate of Return (ARR), Payback Time etc. This is due to the fact that road infrastructure comes with other social and economic benefits that are difficult to quantify in monetary terms. Development projects impose a series of costs and benefits on recipient communities or countries. Those costs and benefits can be social, environmental, or economic in nature, but may often involve all three. Public investment typically occurs through the selection, design and implementation of specific projects to achieve the goals of policy (Adu, 2009).

An international effort to develop improved road investment appraisal methods was undertaken in 2001 by the British Overseas Development Administration, the Asian Development Bank, the Swedish National Road Administration, The Inter-American Federation of Cement Manufacturers, and the World Bank. Since then the Highway Design and Maintenance Standards Model (HDM-III), developed by the World Bank has been used to combine technical and economic appraisals of road investment projects, and to analyze strategies and standards (Archondo-Callao, 2008).

HDM-IV broadens the scope of such models beyond traditional project appraisal, providing a powerful system for the analysis of road management and investment alternatives. A completely new software package was developed and associated documentation which will serve as the primary tool for the analysis, planning, management and appraisal of road maintenance, improvements and investment decisions that will supersede HDM-III. The HDM-IV model is based on the concept of pavement life-cycle analysis and uses three sets of models: a) road deterioration - which predicts pavement deterioration; b) works effects - which simulate the effects of road works on pavement condition and determines the corresponding costs; and c) road user effects - which determine costs of vehicle operation and travel time (Gerbrandt and Berthelot, 2007).

HDM-IV simulates total life cycle conditions and costs for an analysis period under a user-specified scenario of circumstances. The primary set of costs for the life cycle analysis include the costs of capital investment, maintenance, vehicle operation, travel time, and accidents as an option. The cost of environmental pollution is not currently included, but will be added in a later release. The broad concept of the life cycle analysis is illustrated in Appendix 1. Interacting sets of costs, related to those incurred by the road agency and those incurred by the road user, are added together over time in discounted present values. Costs are determined by first predicting physical quantities of resource consumption and then by multiplying these quantities by their unit costs or prices. Economic benefits are then determined by comparing the total cost streams for various maintenance and construction alternatives with a base case (do nothing or do minimum alternative), usually representing minimal routine maintenance.

In the infrastructure project economic evaluation, two project alternatives are evaluated: a "without project scenario" and a "with project scenario". Annual road agency and road user costs are computed for both alternatives over a defined evaluation period, and total costs to society are compared for the two scenarios. It is desirable that more than two project alternatives can be evaluated per project, which permits the economic comparison of the project alternatives and the recommendation that the project alternative that maximizes the project's NPV can be implemented.

Hereby project analysis of road investments is concerned with the evaluation of one or more road projects or investment options. The application analyses a road link or section with user-selected treatments, and associated costs and benefits, projected annually over the analysis period. Economic indicators are calculated for the different investment options. Project analysis may be used to estimate the economic or engineering viability of road investment projects by carrying out the following (Kerali et al, 1998):

- Life cycle predictions of pavement performance;
- Estimation of maintenance and improvements effects and their costs;
- Calculation of road user costs and benefits;
- Prediction of environmental effects;
- Economic comparisons of project alternatives.

The primary effects are reduced vehicle operating and capital costs, reduced journey time, changes in road maintenance costs, changes in accident costs, increased travel, environmental effects, change in value of goods moved. Secondary effects are changes in agricultural output, changes in services, industrial output changes, changes in consumer behavior, change in land values. Benefits from road investments are changes in transport costs which occur because of lower road roughness, shorter trip distance, faster speeds, reduced chance of impassability, reduced traffic ability problems, change in mode (Hine, 2008).

## 2.2. Performance measurement in road management

Measurement of performance and productivity has gained significant interest recently among both academics and practitioners. Much progress has been made on establishing performance management systems (PMeS-s) which include a portfolio of measures aimed to balance the more traditional, single focus view on profitability. In this article the following definitions are used (Neely *et al*, 1995):

- Performance measurement can be defined as the process of quantifying the nature of operation;
- A performance measure can be defined as a metric used to quantify the nature of operation;
- A performance measurement system can be defined as the set of metrics used to quantify and qualify the nature of operation.

Performance measurement describes the feedback or information on activities with respect to meeting strategic objectives. They are used to measure and improve the efficiency and the quality of the production processes, and identify opportunities for progressive improvements in process performance. Traditional measures, however, are usually ineffective barometers of performance because they do not isolate non-value-added costs. In addition, most measures overlook key non-financial performance indicators (Wegelius-Lehtonen, 2001).

The traditional distinction of good and poor project performance focused on the meeting of cost, time and quality criteria, which has been described as the iron triangle (good-fast-cheap) of project management. Using the iron triangle as a measure has led the construction industry to witness examples of poor performance. Since 1980 other measures of performance have been developed, with the redefining of what constitutes good and poor project performance. Performance is now rather measured using various criteria, by different groups of people, at different stages in a project’s life, which has been described as a multi-dimensional and multi-observational approach (Shenhar and Dvir, 2007).

According to literature contemporary PMeS should meet the following criteria: support strategic objectives; have an appropriate balance; have a limited number of performance measures; be easily accessible; consist of performance measures that have comprehensible specifications (Tangen, 2004). Other issues that should be considered selecting performance measures to evaluate a road network include forecast ability, clarity, usefulness, ability to diagnose problems, temporal effects and relevance (Performance..., 2006).

Generalizing previous authors argue that the factors that definitely should be PMeS-s for Road Management to consider are: the purpose of the measurement; the level of detail required; the time available for the measurement; the existence of available predetermined data; the cost of measurement.

Performance measures are classified in several ways in the literature. Measures are grouped, for example, into improvement and monitoring measures. Improvement measures are vital when starting new development and cooperation projects. The need for that kind of measures is obvious: if you do not know your current practices, you can not develop your operations further effectively.

The second group of measures consists of monitoring measures. These measures are needed for screening and controlling every-day actions continuously. Commonly the literature treats only these measures. There are several very good examples of PMeS amongst road agencies, which all monitor the existing network and give feedback about the conditions but do not give any feedback to the appraisal models in order to improve the decision making process (Wegelius-Lehtonen, 2001).

Performance measures are often described as input, output or outcome measures too. Input measures look at the resources dedicated to the project, output measures look at the product delivered, and outcome measures look at the impact of the products on the goals of the agency. Although outcome measures are generally preferred, transportation agencies need to consider data availability, cost and validity when developing their system measures. Some agencies are trying to implement performance measures in an integrated manner to set policy, allocate resources, and measure and report results. Thus, as transportation planning becomes more closely related to broadly defined policy goals, there needs to be greater participation by numerous disciplines in defining terms and in designing measurement approaches.

Over the past two decades, transportation agencies worldwide have developed various highway asset management systems such as pavement, bridge, maintenance, safety, and congestion management systems as analytical tools to help them make cost-effective investment decisions. In general, each road management system generally performs the following tasks:

- establishing highway system goals and performance measures;
- monitoring the performance of physical highway assets and system operations;
- predicting performance trends over time;
- recommending candidate projects to address system needs;
- carrying out project evaluation;
- conducting project selection;
- providing feedback to refine the analysis in subsequent decision cycles (A Guidebook..., 2012; Li et al, 2011; Multi-criteria..., 2009).

The underlying rationale for having performance indicators or measures is that the limited availability of resources for road infrastructure makes it necessary to allocate these resources as efficiently as possible among competing alternatives. Consequently, any framework for performance indicators should be comprehensive enough to incorporate functional, technical, environmental, safety, economic and institutional considerations. Cost, performance, service delivery and safety are front and centre in most transportation decision-making.

Studies that measure the impacts of planning before and after implementation can help determine whether specific forecasts are accurate and what investment decisions and planning efforts should be addressed or reevaluated. In practice, however, there is variation in the terminology. It includes performance measures, which is the term used in survey of Canadian Road Networks (Performance…, 2006), key performance indicators, which is a term originated in Australia for the performance specified road network contracts (Australian…, 2011), performance indicators, which is used in the European Harmonization on Performance Indicators in their COST-Action 354 for Road Pavements, and others. The usage herein is the term performance indicators, which accords with World Bank performance based contracting practices. In essence though, performance measures, performance indicators and key performance indicators have been used commonly and interchangeably in the roads sector.

## 3. Performance measurement in Estonian road industry

### 3.1. Estonian transport policy and road management

Given the infrastructure investment as a key prerequisite of economic development, in Estonian transportation policy is incorporated into the following legal instruments that serve as a framework for developing planning interventions: Estonian National Strategic Reference Framework 2007-2013, Operational Program for the Development of Economic Environment, Operational Program for the Development of the Living Environment and State Budget Strategy 2012-2015, Estonian Transport Development Plan for years 2007-2013.

The basic goals of the national transport policy are focused on sustainable development of the road and railway infrastructure of national and international importance, improvement of the traffic safety, encouragement of maritime navigation, integration of national transport system in the EU transport networks, achievement of balance and development of links between different transport modes. Achievement of these goals is a pre-condition for sustainable and balanced long-term economic growth (Transport…, 2007).

Estonian Transport Development Plan has been approved by the Parliament as a national development plan in the field on transportation. It is developed for introducing consistent measures at national or local level in the context of other policies:

- economic policy to be formulated to take account of certain factors which contribute to increasing demand for transport services;
- urban and land-use planning policy to avoid unnecessary increases in the need for mobility caused by unbalanced planning;
- social and education policy, with better organization of working patterns and schools' locations to avoid overcrowding roads;
- urban transport policy in major conurbations, to strike a balance between modernization of public services and more rational use of the car;
- budget and fiscal policy to achieve full internalization of external – in particular environmental – costs and completion of a transport network worthy of the name;
- research policy to make the various efforts made on national and regional level more consistent, along the lines of the European research area.

The Transport Development Plan 2007-2013 comprise two main parts – a descriptive analysis of the existing situation and the objectives set and measures and lines of action foreseen in the Development Plan. The list of the measures is not exhaustive as concrete actions are determined in annual implementation plans (Transport..., 2007). Figure 2 shows that during 2008-2010 the yearly average budget of road management was 312 mln EUR, comprising 174 mln EUR of investments in reconstructing national roads per annum. In Estonia, during the past years, 20 % of all investment made into the real sector have been investments in road management.

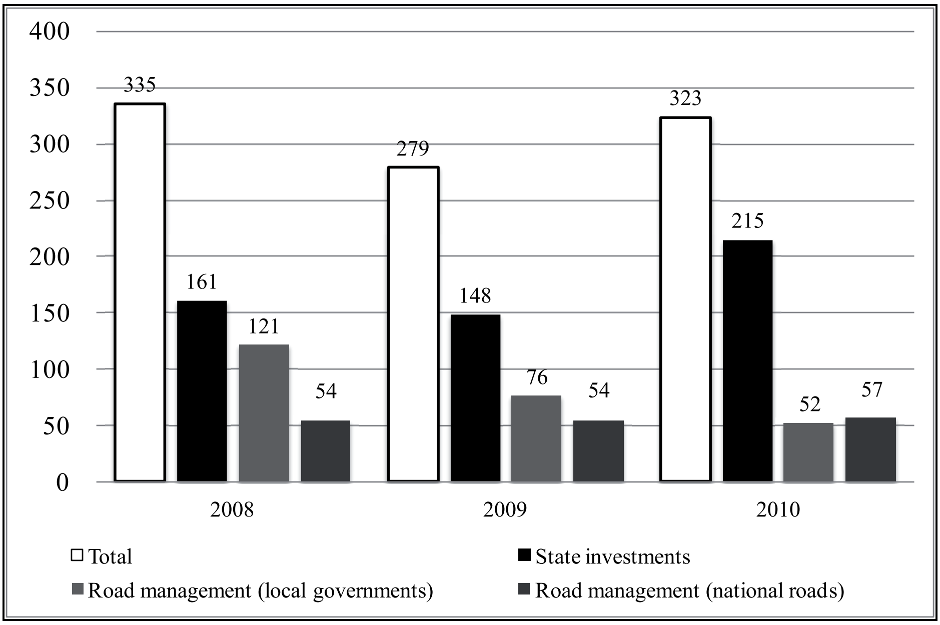

**Figure 2.** Expenditures for road management in Estonia 2008...2010 (mln euros) (Adapted from Sikk, 2008; Annual..., 2011).

According to the White paper of the European Transport Policy (2011) 30 % of road freight over 300 km should shift to other modes such as rail or waterborne transport by 2030, and more than 50 % by 2050, facilitated by efficient and green freight corridors. To meet this goal will also require appropriate infrastructure to be developed. This can be concluded that EU structural funds in the new financial perspective will be decreasing notably in road network development and increased notably in rail and maritime transport.

The significance of social benefits gained with the investment is planned to play a more determining role in investment decisions. In February 2012 the Ministry of Economic Affairs and Communication of Estonia (MoEC) started the drawing process of Transport Development Plan within the EUs new financial perspective, which has critical implications for transport infrastructure investment prioritization in avoiding the mistakes of earlier periods.

There are initially two key drivers for infrastructure investment requirements. One is GDP growth which, in turn, is a function of such factors as population increase, per capita income and productivity growth. The second is the existing stock of infrastructure, which creates a demand for periodic renewal. Therefore, as stated in previously, infrastructure investments are a key determinant of performance in the transport sector.

In Estonia the existing infrastructure network covers all areas from the accessibility goal, also due to low density of population we have very few areas where is congested and new developments do not give significant savings in travel times. New developments currently focus on upgrading the existing roads to highway standards or creating city bypasses - the greatest task is to maintain the existing road network and ensuring its sustainability.

### 3.2. Current performance measurement practice and implications for the future

The work of road administration authorities involves evaluating the technical and economic feasibility of undertaking alternative road construction techniques. The Estonian Road Administration (ERA) is a government agency operating under the auspices of the MoEC. It has a management functions, it carries out state supervision, applies the enforcement powers of the state and provides public services on the basis and to the extent prescribed by law. In performing its duties the ERA represents the state. One of the main tasks of the ERA is road management and creation of safe traffic conditions on roads. To achieve that aim, it is essential to get feedback from road users. Since 2002, the ERA has conducted surveys of the drivers` satisfaction with the driving conditions on national roads (Annual…, 2011).

Measurements of road surface roughness (according to the International Roughness Index, IRI) have been carried out and inventories of defects on paved roads have been made since 1995. The load bearing capacity (Falling Weight Deflectometer, FWD) of the roads has been measured since 1996 and rut depth since 2001. These four indicators of road surface condition together with the traffic volume are the main indicators of the Pavement Management System (PMS). Data about the condition of road surface is a part of the data in the National Road Databank and is publicly available. Two kinds of software – Estonian Pavement Management System (EPMS) and HDM-IV are used for analyzing the condition of road surface (Annual…, 2011).

The developed road construction projects are monitored and supervised very tightly during the construction process and also during the liability period. After the end of liability period regular surveillance of the road conditions as described before is carried out in a well regulated way, but without any feedback and comparison to the initial analyses, including meeting the feasibility calculations and durability of materials and comparing estimated repair span to the actual need during the lifecycle (see Figure 3).

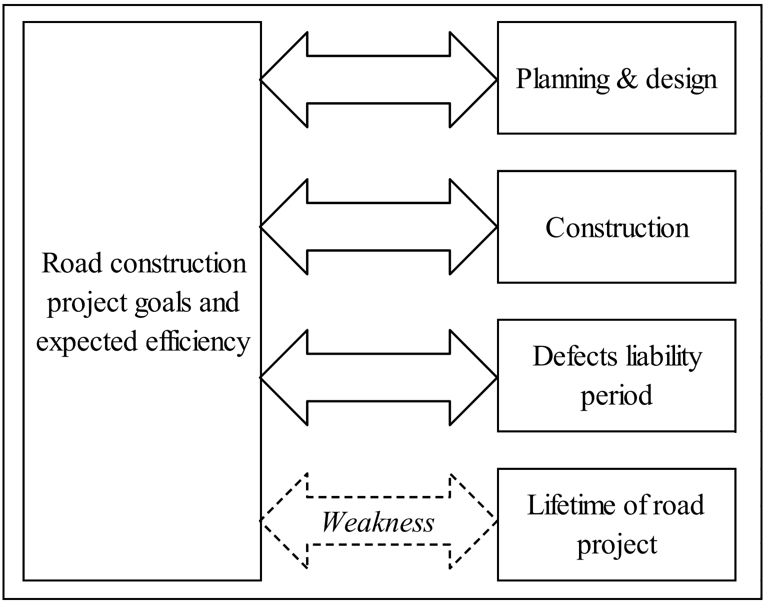

**Figure 3.** Current practice of road construction projects evaluation in Estonia (Kaare and Koppel, 2012).

Performance measures and corresponding data can be used to provide feedback to the relevant decisions (see Appendix 2). Good decision making requires a continuous reassessment of choices made in the past. Individual decision makers may learn from their own mistakes, but it is important that lessons be learned in a more formal and systematic way, and communicated to others, so that they can inform future decisions (Multi-criteria..., 2009).

Therefore, monitoring and feedback are critical components of performance-based planning that includes the ongoing monitoring of system performance and the appropriate feedback to the planning and decision making processes. This step is usually completed with observed data of actual system conditions and performance. Synthesized or forecasted data may be substituted for observed data in some cases, for example, where it is desirable to track the expected future outcome of an investment decision with a long-term payback period. At all levels of government, effective, performance-oriented project management is needed – management that focuses on project quality and on the results achieved through the use of tax revenue and other public resources (Wholey and Hatry, 1992).

Transportation agencies like ERA have usually a wealth of data available related to the services they provide and the infrastructure they maintain. The challenge facing managers is to gather and analyze data in a way that provides timely information on whether they are consistently meeting their strategic goals. Whenever the goals are not being met, management must use information to identify changes (Kaare and Koppel, 2012). Taking into account the abovementioned the following performance indicators are proposed to be gathered in Estonia throughout the life-cycle of a project (see Appendix 3).

The selection of indicators was performed by studying international practices, taken into account the special features of Estonia and the availability and accessibility of data. The presumption that the authors made was that the necessary data was already exist in databases or very easily collected, so that extra costs will be not created for the road agency. The proposed database has to take into account the rapid development of technology allowing the system to be flexible in implementation. Two issues which are of key importance and need to be addressed in future work are determining the appropriate design for the data collection activity are the anticipated use of, and planned method of storage of the collected data.

Information technology (IT) provides the means to store, manipulate, and disseminate massive amounts of data. The integration of IT at all levels of the transportation system creates the intelligence in intelligent transportation systems (ITS). But this integration is a long and difficult process of searching for and exploiting opportunities in the interconnected operations, planning, and funding of today's transportation systems (Varaiya, 2002).

For example, the proposed indicators emphasize temperature, both of pavements from the safety aspect and in bound layers as an important technical indicator. This is due to the severe climatic conditions in Estonia with sometimes several melt-thaw cycles per day call for new IT solutions in road monitoring. Many technologies are not suitable due to shifting and subsiding effect of melt thaw cycles causing unsustainable failure of these solutions. By contrast, recent tests using sensor based RFID tags have given positive feedback and have proven to be sustainable (Kaare and Koppel, 2012). Also the use of different accelerometers to measure the overall pavement condition and roughness is widely spreading and is recommended for implementation due to the solutions' low cost and wide accessibility.

Different countries, regions or road agencies have developed their PMeS that vary in chosen indicators due to on transportation policy goals, regional diverseness and inequalities, but the majority of them focus on overall performance measurement of the road network. Constructions companies measure the financial and organizational performance of individual road construction projects concluding the evaluation when the final acceptance certificate is issued or when the liability period ends. For the road agencies who take over the responsibility to maintain the constructed road during its lifetime it is important to monitor the performance to get feedback about the roads' sustainability.

## Conclusions

Transport policies arise because of the extreme importance of transport in virtually every aspect of national life. Several countries have recently stated that their transport policy needs to be performance-driven, directly linked to a set of clearly articulated goals and accountable for results. Road agencies face funding constraints and limitations, therefore performance measures are needed to evaluate the state of assets, which leads to developing priorities and allocating resources amongst competing projects.

Investment appraisal is extremely significant in transport planning and policy. The effectiveness of a road investment is determined by the costs of construction, annual maintenance and the reduction in user costs; components that, in general, constitute the total transport cost or life cycle cost of the road. Feedback in reporting about successes, opportunities, environmental impacts of the constructed or renewed road an essential in planning and evaluating new developments. Indicators proposed by authors are a tool to assess the road construction projects performance from technical, environmental, safety, and also socioeconomic viewpoint.

On the basis of performance predictions and projected structural performance that are conducted using feedback from the life-cycle analysis of previous projects, resource allocation can be optimized more reliably across limited resources and alternative road strengthening systems, providing technically sound solutions that are more economically attractive. The ability to perform accurate whole-life economic assessments associated with long-term infrastructure assets is important to sustainability.

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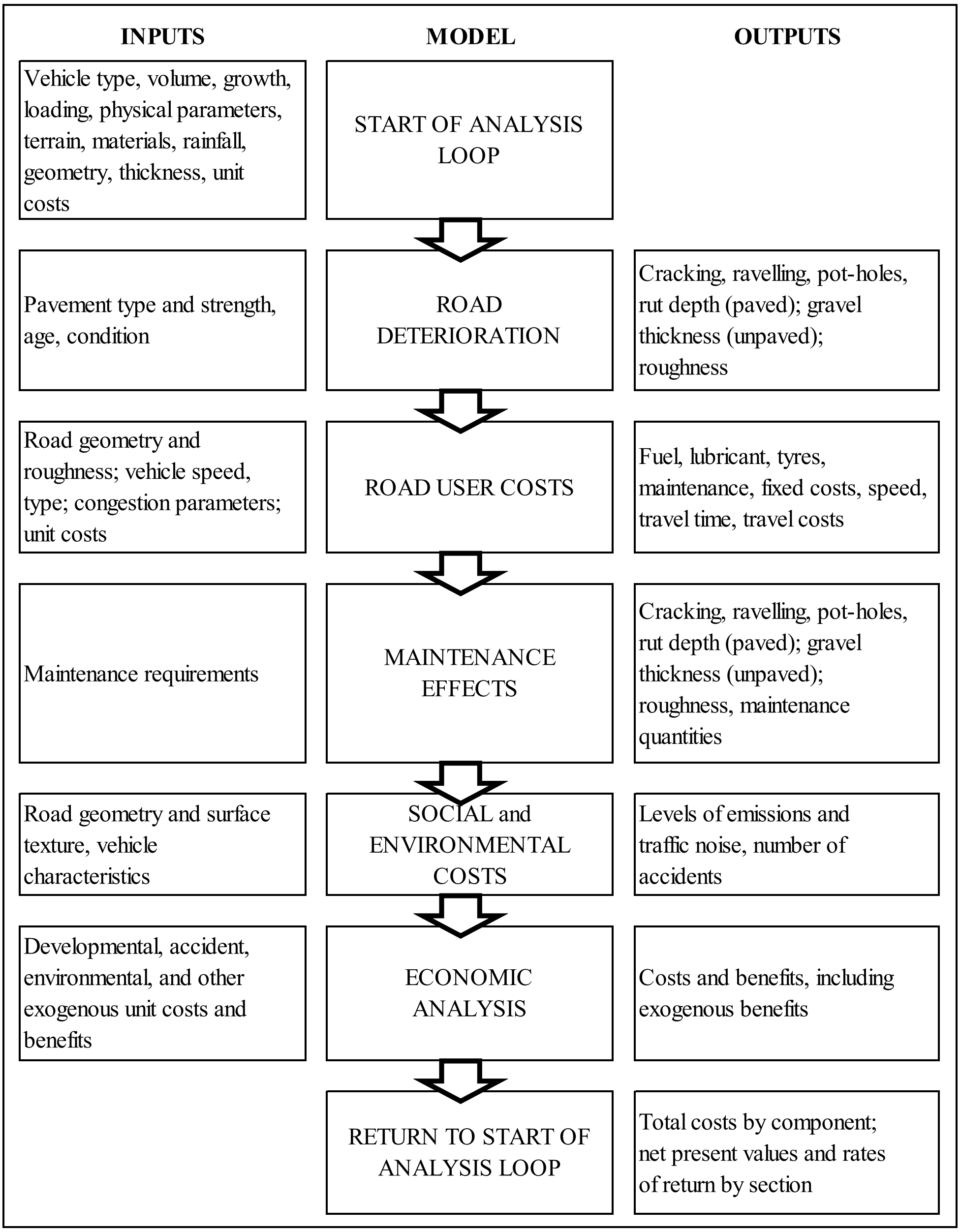
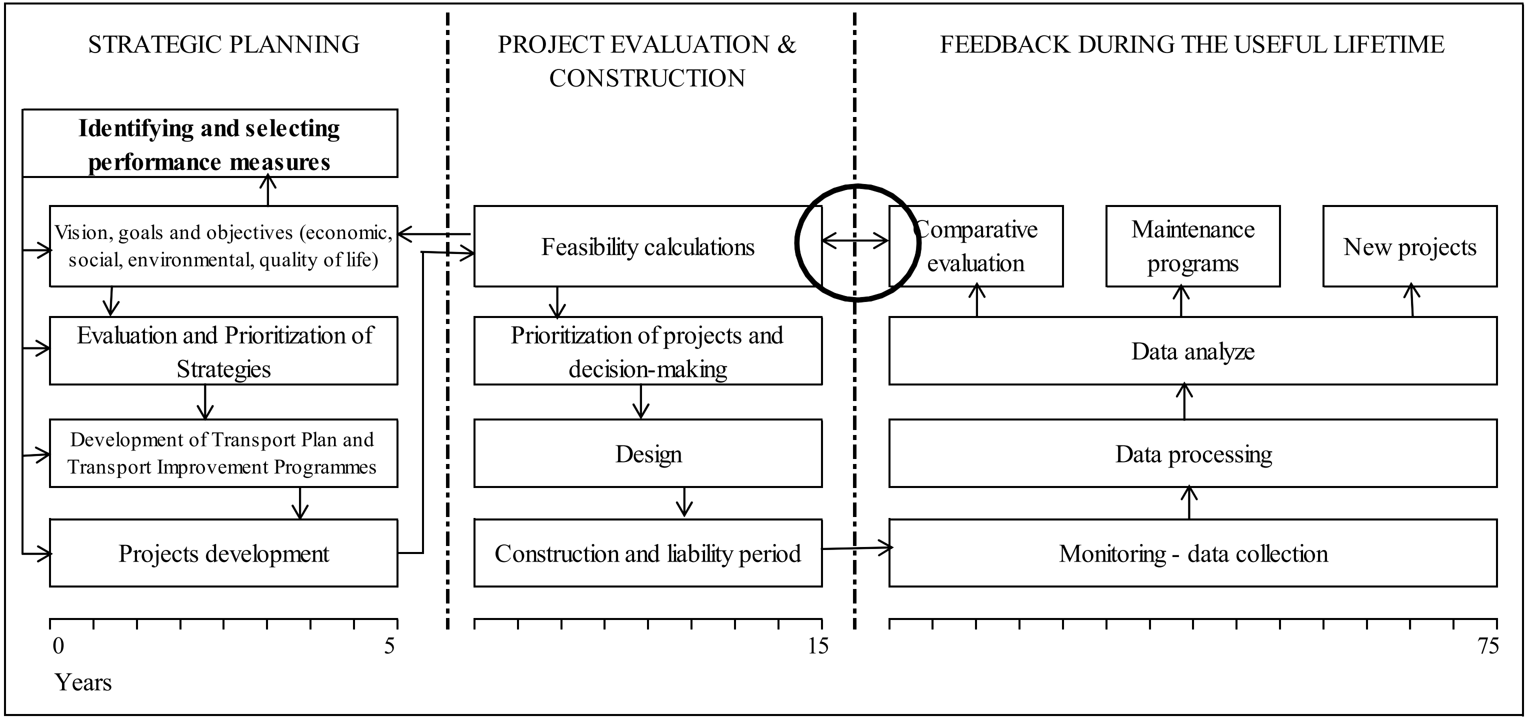
**Appendix 1.** Life-cycle analysis using HDM-IV



Source: Adapted from Kerali *et al*, 1998; Tsunokawa, 2010.

**Appendix 2.** Transportation planning framework using performance measurement system



Source: Adapted from Siggerud, 2002; A primer..., 2009; Kaare and Koppel, 2012.

**Appendix 3.** Possible performance indicators for road construction projects in Estonia (extract)

| **ACCESSIBILITY** | **MOBILITY** |
|---|---|
| • Load restrictions, incl. bridge weight limits<br>• Average trip length | • Traffic density and heavy traffic density<br>• Delays, congestion, average travel speed, closures and detours |
| **SOCIOECONOMIC ISSUES** | **QUALITY OF LIFE** |
| • Economic costs of accidents<br>• Economic costs of lost time | • Lost time due to congestion<br>• Tonnes of pollution (or vehicle emissions) generated |
| **ENVIRONMENTAL AND RESOURCE CONSERVATION** | **ROAD TECHNICAL CONDITION** |
| • Overall mode split<br>• Number of accidents involving hazardous waste | • Pavement condition indicators (distresses (longitudinal cracking, transversal cracking, alligator cracking, edge break, raveling, potholes), rut depth, skid resistance in summer and winter, strength indicators)<br>• Bearing capacity (pavement, base, embankment)<br>• Dustiness<br>• Condition of drainage/water table<br>• Temperature changes in bound layers<br>• Unpaved roads indicators<br>• State of bridges |
| **OPERATIONAL EFFICIENCY** | **SAFETY** |
| • Origin-destination travel times<br>• Total travel times<br>• Transport costs per tonne-kilometer<br>• Maintenance cost per track-kilometer | • Traffic accidents and accident classes (fatal, injured, only vehicle)<br>• Percentage of road mainline pavement (or bridges) rated good or better<br>• Pavement surface temperature |

Source: Compiled by authors using Australian..., 2011; Indicators..., 2011; Haas *et al*, 2009; Performance..., 2001; Performance..., 2006; Truu, 2012.

## PUBLICATION II

Kõrbe Kaare, K., Koppel, O. Improving the Road Construction Supply Chain by Developing a National Level Performance Measurement System : the Case of Estonia. – *International Journal of Social and Human Sciences*, 2012, 6, 225-231.

# Improving the Road Construction Supply Chain by Developing a National Level Performance Measurement System: the Case of Estonia

Kati Kõrbe Kaare, Ott Koppel

***Abstract*****—**Transport and logistics are the lifeblood of societies. There is a strong correlation between overall growth in economic activity and growth of transport. The movement of people and goods has the potential for creating wealth and prosperity, therefore the state of transportation infrastructure and especially the condition of road networks is often a governmental priority. The design, building and maintenance of national roads constitute a substantial share of government budgets. Taking into account the magnitude and importance of these investments, the expedience, efficiency and sustainability of these projects are of great public interest. This paper provides an overview of supply chain management principles applied to road construction. In addition, road construction performance measurement systems and ICT solutions are discussed. Road construction in Estonia is analyzed. The authors propose the development of a national performance measurement system for road construction.

***Keywords*****—**ICT in road construction, key performance indicators, quality performance measurement, road construction supply chain.

## I. INTRODUCTION

THE continuous development and maintenance of essential public infrastructure is an important ingredient for sustained economic growth. At a national level, transportation investment boosts productivity and economic potential. It contributes by making freight flows more efficient and reliable whilst doing the same for personal and business travel increasing also mobility and quality of life. Modern infrastructure networks create more productivity amongst businesses and individuals across the geographic landscape. "Any congestion, or lack of capacity, must be viewed as a bottle-neck not just to traffic, but to productivity and economic growth itself." [1].

Estonia is situated on the eastern boarder of the European Union having only 633 km of land border (Russia, Latvia) and a 3,794 km long coastline. Estonia's geographic position has long been used to the advantage, during the 11th century Estonia's capital Tallinn was part of the vibrant economic alliance of trading cities known as the Hanseatic League. As a major thoroughfare, Estonia's location has fostered the creation of efficient transportation links and distribution chains for goods and services to serve Estonian, European and international companies.

The Estonian transportation and logistics sector is comprised of a combination of transportation services, transit trade, distribution centers and value-added logistics.

Transport contributes considerably to Estonian export revenues and its balance of trade. Prior to the recent economic crisis, the Estonian transport and transit sector accounted for approximately 14.4% of the Estonian Gross Domestic Product (GDP) [2]. In 2008-2009, the Estonian export and transport sector was the first to recover strongly and was the locomotive driving GDP growth, with export volumes doubling in the IV quarter of 2010. In 2010, the transport sector accounted for more than 12% of Estonian GDP, and in 2011, the transport sector employed *circa* 50,000 people (over 8% of the work-force) [3].

The rapid economic growth in the beginning of this century led to transportation shortages and congestion problems and increased the demand for road quality improvement. With the help of European Union (EU) funds the Estonian government has given high priority to road development, investing particularly in the construction of high-quality roads. The amount assigned for road infrastructure development for the period 2008-2013 was 737 mil. EUR. The annual budget of the Estonian Road Administration (ERA) is approximately 300 mil. EUR which constitutes approximately 30% of state investments into the real sector.

Taking into account the magnitude and importance of these investments, the expedience, efficiency and sustainability of these projects are of great public interest. In this paper the authors give an overview of road construction supply chains, performance measurement systems, the development of related Information and Communications Technology (ICT) and current practices in Estonian road construction management. The aim of the paper is to determine if there is a need to develop and implement a national level performance measurement system that gives feedback of road construction investments throughout the lifecycle of the road.

## II. ROAD CONSTRUCTION SUPPLY CHAIN

The supply chain has been defined as ''the network of organizations that are involved, through upstream and downstream linkages, in various processes and activities that produce value in the form of products and services" [4]. Road Construction Supply Chain (RCSC) is deemed an integrated approach for road construction projects to resolve common problems and to address common deficiencies in construction management. Road construction management embodies many challenges and restrictions due to the temporary and complex nature of road construction projects. The construction of one

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road generally involves the management of numerous separate projects with responsibilities divided among several independent contractors whose involvement often includes separate phases of the lifecycle of the entire project. Efficient collaboration among all contractors throughout the road construction lifecycle is crucial to enhancing construction management performance [4].

The primary objective of supply chain management is to meet customer (in this case the national transportation authority or state) demands through the most efficient use of resources. This would include the optimal management of distribution capacity, inventory and labor. In theory, a supply chain seeks to match demand with supply and do so with the minimal inventory [5].

In road construction first the decision making process to invest in a highway is complex and time consuming. The same applies to the duration of the planning and constructing and especially the operation and useful time. Project development generally comprises several phases requiring a diverse array of specialized services and the involvement of numerous participants (see Fig. 1). There are so many independent parties including state or local authorities, developers, engineers, general contractors, subcontractors, consultants, supervisors, suppliers, and maintenance agencies in a road construction project that the construction project should be systematically broken down and all parties should cooperate with each other to implement the project [4].

Most of the projects are road maintenance and rehabilitation works that should be performed to maintain the service levels of the national and local roads. These types of road construction works will be conducted by central and local governments periodically and, therefore, will potentially require similar specifications and skills from similar suppliers and sub-contractors. Also if new road construction is undertaken, the type of works is considered linear that would require similar tasks performed by similar resources for each defined section. For this kind of characteristic of project, i.e., consisting repetitive operations, the implementation of supply chain management is reasonable and beneficial.

It has been identified that there are three models of RCSC based on the owner’s involvement, i.e. RCSC nominated by owner; RCSC created by owner, and RCSC managed by owner. The three models have different levels of owner involvement in the construction project supply chains, whereas concurrently managing their value chains [5].

Therefore to run a successful project in RCSC the following aspects must be taken into account [6]:

1) Integrated and incentivised supply chain - integrating the supply chain with its specialist knowledge, incentives for innovative ideas to give best value solutions.
2) Maintaining a competitive and sustainable supply chain - maintaining a good quality supplier base motivated and incentivised to work with the road administration.
3) Early creation of delivery team - early contractor involvement for more scope in innovation, better risk management, and forward planning of work programs and resources.
4) Clear points of responsibility, no unnecessary layers of supervision - clarifying roles and responsibilities to reduce contractual interface problems, eliminating resource wastage from unnecessary layers of supervision.
5) E-procurement - to make tender processes, communications and performance measurement more efficient.
6) Selection of suppliers on the basis of best value - identifying the aspects of quality which add real, affordable value, using reality checks to confirm quality submissions and promises.
7) Partnership approach based on long-term relationships - moving from short-term project partnering arrangements to long-term relationships for retention of skills and better resource and work programming.
8) Fair allocation of risks - risks will be allocated to the party best able to manage them and the road administration will accept risks where suppliers are prepared to work in partnership to manage them and control the consequences.
9) High quality design - design solutions will be based on whole life value.
10) *Performance measurement with continual improvement targets* - establishing benefits in the form of cost and

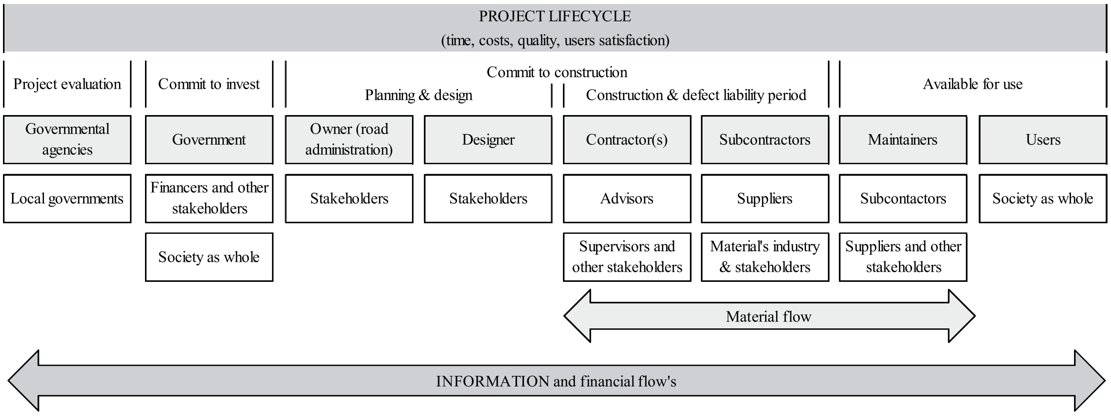

Fig. 1 Supply chain and project stages in road construction industry (based on [7]-[10])

time-savings, reduced defects and accidents, and improved whole life value and satisfaction with the project.

The principles of supply chain management and performance management require that all significant activity throughout the supply chain be measured.

## III. PERFORMANCE MEASUREMENT IN ROAD CONSTRUCTION

Performance measurement is the selection and use of quantitative measures of capacities, processes, and outcomes to develop information about critical aspects of activities, including their effect on the society. Performance measurement estimates the parameters under which programs, investments, and acquisitions are reaching the targeted results.

The main reason to adopt Key Performance Indicators (KPI-s) as performance metrics is to put strategy into operation. It has the ability to turn a sector's strategic plan into numbers that can be used to guide performance throughout the supply chain. Like in many management measures and approaches effectiveness will be dependent on the emphases placed on the approach by the government (see Fig. 2).

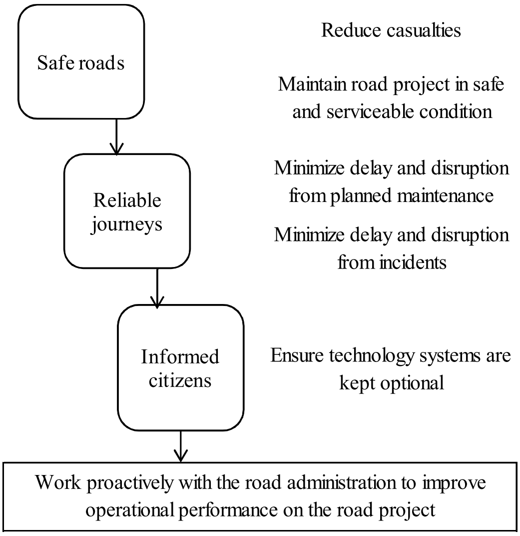

Fig. 2 Linkage between road administration goals, performance measures, and KPI-s (based on [6])

Both road construction business and national road authorities need a performance measurement system with KPIs to avoid being accused to focus on "the bottom line" and "on the short term". The use of KPIs gives a more balanced view of a sectors performance and a more holistic view of progress [11]. In the road construction sector KPIs can be applied to road programs evaluation, planning and organization management in the following ways [12]:

1) In process management, to measure the success of individual processes or groups of processes.
2) In benchmarking, to establish "best practice" or "superior performance" processes in order to improve performance of the road administration.
3) To aid the development or improvement of the functions or specific engineering tasks of the road administration.
4) In management-by-results, to set targets and evaluate the achievement of goals and objectives.

The Organisation for Economic Co-operation and Development (OECD) carried out an extensive study in 2001 [12], which aimed to assess the applicability of the KPIs in improving the management of road administration. The 15 indicators that were field-tested included: average road user costs; level of satisfaction regarding travel time and its reliability and quality of road user information; protected road-user risk; unprotected road-user risk; environmental policies/programs; processes in place for market research and customer feedback; long-term programs; allocation of resources to road infrastructure; quality management/audit programs; forecast values of road costs vs. actual costs; overhead percentage; value of assets; roughness; state of road bridges; satisfaction with road condition.

It is suggested in the OECD report that ideally agencies need to link their higher level goals with performance measures and individual KPIs. For example, American Association of State Highway and Transportation Officials (AASHTO) strongly promote reform for the entire U.S. highway system centered on supporting the achievement of six key national interests. AASHTO is in the process of developing and establishing these broad agency goals on construction safety, mobility, and stewardship of the entire U.S. highway system. These six key national interests appear to reflect the interests of American society and address the public's major concerns about and views of the transportation system. If the reform is accepted and implemented, AASHTO believes that every highway agency in the United States will be capable of and held accountable of producing results that reflect and work toward realizing these goals. For the system to be effective, has been established as the driving force behind performance management [13].

Also in Great Britain, to deliver on its aims and objectives, the Highways Agency has established seven key program-level performance measures:

1) Reliability – Implement a program of delivery actions that tackle unreliable journeys on the strategic road network.
2) Major projects – Deliver on time and budget the program of major schemes on the strategic road network.
3) Safety – Deliver the Highways Agency's agreed proportion of the national road casualty reduction target.
4) Maintenance – Maintain the strategic road network in a safe and reliable condition, and deliver value for money.
5) Carbon emissions – Contribute to national and international goals for reducing carbon dioxide emissions by lowering the Highways Agency's emissions.
6) Customer satisfaction – Deliver a high level of road user satisfaction.
7) Efficiency – Deliver the Highways Agency's contribution to the Department for Transport's efficiency target [6].

A major concern of transportation agencies throughout the world is to develop a method to effectively and efficiently maintain roadway infrastructure. Over the last two decades, an outcome-based initiative known as Performance-Based Road Maintenance (PBRM) has produced results that are signifycant. In contrast to traditional techniques that specify materials or methods to perform maintenance work, the PBRM system specifies the desired outcome.

In order to successfully run, monitor and evaluate supply chain and performance of a project it is important to have accurate, comparable and reliable information. The Highway Development and Management Tool (HDM-IV) has been used to combine technical and economic appraisals of road projects, to prepare road investments programs and to analyze road network strategies [14]. The performance management system should ideally compare the results presented by HDM-IV with the performance of the road during its lifecycle.

Recent development in technologies enables the organization to avail information easily and also the rapid developments have decreased the cost of information. These technologies are essential to gather information to manage and evaluate the supply chain [15].

## IV. ICT SOLUTIONS

Today due to very rapid developments in new technologies as RF location-based solutions (LBS) using Global Positioning Systems (GPS), cellular triangulation, accelerometers and radio frequency identification (RFID) technologies over public and private data networks and with the use of ICT solutions it is now possible to measure the performance of road networks simply, quickly and cost effectively.

The impact of ICT on many different aspects of economy and RCSC management has been discussed also with the help of the conceptual models [16]-[19]. However, only recently empirically grounded models have been presented that have found a positive and significant impact of ICT on labor productivity and economic growth. One of the major transformations in the rapidly evolving digital economy occurs in the supply chains. ICT in general, and ICT in Supply Chain Management, is argued to enable great opportunities, ranging from direct operational benefits to the creation of strategic advantage.

Although the road construction industry has been slow to implement automation, new technologies and ICT, especially when compared to other industries such as manufacturing and service, the nature of the construction industry is changing and adoption of new technologies is required to survive and prosper in an increasing global economic system with fewer resources, complex projects, and fierce competition. As such, many construction companies have already begun implementing ICT and reported significant benefits in its use [18].

The integration of ICT technologies with the GPS technology, through the collection of real-time data to improve management and decision-making functions, contractor companies can revolutionize the way contractors do business. In the Total Jobsite Management Tool (TJMT) cycle, the real-time data produced in the field is collected and transferred to the office. In the office, ICT tools are utilized to convert the raw data into useful information to be used by management for project performance applications such as detecting cost/schedule deviations. The result of this analysis is then used to update the project database, allowing the project manager to take corrective action in the field if necessary.

This real-time GPS data can prove valuable for project management applications by reducing the time required for performance analysis, improving the accuracy and quality of the data, reducing labor costs, reducing duplication, and improving productivity. It is considered a problem that it does not take into account the whole lifecycle of the project and the data that can be gathered could also be valuable in the maintenance process and in controlling the sustainability and durability [18].

Experiments have been performed testing the use of capable smartphones for various purposes for instance traffic management, route planning, safety and conditions of vehicles and roadways, emergency services. The use of other solutions besides localization have been studied, forms of sensing have also been employed in Intelligent Transport Systems (ITS). Accelerometers are used for automotive safety applications such as detecting crashes to deploy airbags and also notify emergency services automatically. Accelerometers and strain gauges coupled with cameras have been used for structural monitoring of the transportation infrastructure [17].

Due to recent rapid developments in RFID use and expansion of mobile device applications the area of road construction and maintenance has tested and started implementing new technologies. All these new ICT solutions can give necessary information to effectively run the construction process, the maintenance and also give necessary data to draw important conclusions regarding whether the goals set in the tender were achieved and sustained throughout the lifecycle. Recent new approaches to use sensor equipped RFIDs in road construction monitoring and measuring concrete and asphalt conditions are very likely to be adopted in the near future also providing information and enabling to get accurate feedback. As a process tracking technology passive RFID technology has significant potential to enhance supply chain control and management in road construction projects.

Brynjolfsson and Hitt [19] state that productivity improvements cannot simply be achieved by working harder but must be achieved by working smarter. The greatest gains in productivity are realized when the new ICT is coupled with other complementary approaches such as new business strategies, new business processes, and new organizational structures – in case of RCSC performance measurement system.

## V. IMPLICATIONS FOR ROAD MANAGEMENT IN ESTONIA

### A. *Estonian Road Network and ERA*

In terms of infrastructure trade relies on both good rail connections and the road network. The Estonian national transit infrastructure is generally well established. The biggest economical challenge is a good road network, which in Estonia is the area that constantly needs development and improvement. The total length of national roads in Estonia as of January 1, 2011 was 16,000 km, i.e. 28.2% of the total length of the Estonian road network, which was 58,412 km. The length of E-roads (European roads accepted and systematized into international road network by UNECE) in Estonia is only 995 km [20].

The Estonian Road Administration (ERA) is a government agency operating under the auspices of the Ministry of Economic Affairs and Communications (MoEC). It has a management function, it carries out state supervision, applies the enforcement powers of the state and provides public services on the basis and to the extent prescribed by law. In performing its duties the ERA represents the state.

In Estonia road construction and maintenance are influenced and constricted by legal frameworks, political decisions and extreme climate conditions. Political and legal constraints come from being a member of the European Union and having limitations to national level decisions. Procurement regulations are strict and emphasize price as the main criteria. In addition, opportunities regarding collaboration and cooperation between organizations are limited by Competition Regulations.

The ERA has to follow legal acts of the Republic of Estonia and the EU, international treaties which bind the Republic of Estonia, the regulations and orders of the government of the Republic, the regulations and directives of the MoEC and the statutes of the ERA, as well as the relevant regulations of other ministers. The main functions of the ERA are:

1) road management and creation of conditions for safe traffic on national roads;
2) improvement of traffic safety and reduction of harmful environmental impact of vehicles;
3) organization of traffic and public transport;
4) state supervision over compliance with the provisions of legal acts within its area of activity and implementation of the enforcement powers of the state;
5) management of the National Road Databank, the Vehicle Register and the Public Transport Information System;
6) participation in the development of the legislation regulating its area of activity and making recommendations for amendments in the legislation;
7) participation in the elaboration of policies, strategies, and plans in its area of activity and participation in the preparation and implementation of international projects;
8) implementation of state policy and the development of plans in the field of traffic safety and environmental safety of vehicles, and required management of the register of vehicles and other documents prescribed by law [20].

One of the main tasks of the ERA is road management and creation of safe traffic conditions on roads. To achieve that aim, it is essential to get feedback from road users. Since 2002, the ERA has conducted surveys of the drivers` satisfaction with the driving conditions on national roads.

Measurements of road surface roughness (according to the International Roughness Index, IRI) have been carried out and inventories of defects on paved roads have been made since 1995. The load bearing capacity (Falling Weight Deflectometer, FWD) of the roads has been measured since 1996 and rut depth since 2001. These four indicators of road surface condition together with the traffic volume are the main indicators of the Pavement Management System (PMS). Data about the condition of road surface is a part of the data in the National Road Databank and is publicly available. Two kinds of software – Estonian Pavement Management System (EPMS) and HDM-4 are used for analyzing the condition of road surface (priority, need for repairs, cost-benefit analysis etc.). EPMS is specially developed software in Estonia for analyzing the condition of road surfaces and HDM-IV is a internationally known software for cost-benefit analysis.

The diagrams of changes in the amount of defects during the years 2006–2010 show a constant decrease until 2010. On main roads, which have been best financed, the defects have decreased as a result of the construction of new pavements. On basic and secondary roads, where less new pavement has been constructed, defects have decreased mostly due to increased surface dressing. IRI graphs show improvement for all road types, although at a lower speed. The average IRI value for the whole network of paved national roads improved in the years 2006–2010, as financing of construction, repairs and maintenance of pavements remained on the same level and repair sites were rationally chosen. The IRI of main roads is considered satisfactory, but the same cannot be said about basic and secondary roads, and improvement is slower than expected. For the road user that means less driving comfort on basic and secondary roads and greater indirect costs [20]-[22].

The severe climatic conditions in Estonia with sometimes several melting-icing cycles per day call for new ICT solutions in road monitoring. The use of wired loop detectors is not suitable due to shifting and subsiding effect of melting-icing cycles causing unsustainable failure of these solutions. By contrast, recent tests using RFID detectors have given positive feedback and have proven to be sustainable [23].

### *B. Improving Road Construction Performance Monitoring in Estonia*

The developed road construction projects are monitored and supervised very tightly during the construction process and also during the liability period. After the end of liability period regular surveillance of the road conditions as described before is carried out in a well regulated way, but without any feedback and comparison to the initial analyses, including meeting the profitability calculations and durability of materials and comparing estimated repair span to the actual need during the lifecycle (see Fig. 3).

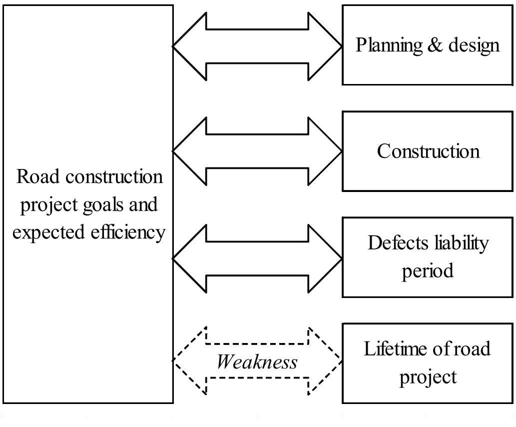

Fig. 3 Current practice of road construction projects evaluation in Estonia

The literature recognizes that in the road construction project performance measurement is more complex than merely measuring cost, time and quality [24]. Internationally, road authorities are becoming more of asset managers. As a result, road project delivery is enabling more integrated services, requiring broader know-how from service providers [25].

An emerging challenge for road administrations is to define goals and objectives pertinent to current community views, and to devise creative ways to respond to contemporary problems. Key issues facing road transport system and road administrations today include [12]:

1) Decreasing road budgets.
2) Demand for greater transparency in road administration performance.
3) Separation of the production and administration roles of road administrations.
4) Adoption of customer focus rather than an “expert knows best” attitude.
5) Demand for greater efficiency in all operations, leading to better results and quality.
6) Demand for more co-ordination and co-operation across the transport sector.
7) Demand for performance improvements to be implemented more rapidly than in the past.
8) New management aspects and the demand for an open and broad understanding of the mobility problems facing society.
9) Demand for more data and more efficient data management.

Currently in Estonia (as well in many other countries) the ERA is operating in two different areas regards road networks: a) road development and construction; b) daily road maintenance. Through a performance measurement system it would be possible to link these two areas more closely together and form a effective supply chain.

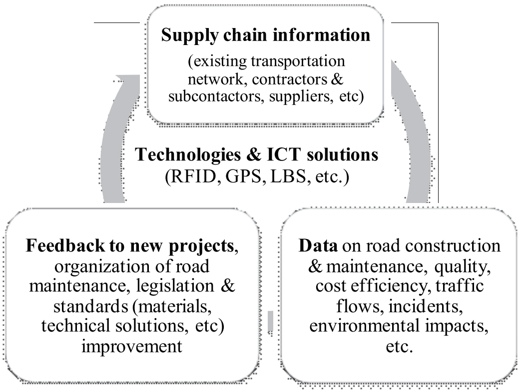

Fig. 4 Effective information flow cycle in Estonian road construction supply chain

Estonia with its innovative ICT solutions, small area and population, has implemented many successful e-developments. Therefore Estonia is an ideal place to implement a new ICT based lifecycle performance measurement system in road construction projects. Every project can get the necessary attention to draw conclusions because the size of the road construction projects is small enough to be manageable (see Fig. 4).

## VI. CONCLUSIONS

Road network development projects in Estonia are tendered on a case-to-case bases and the legal framework supports to use price as the most important criteria in decision making. ERA focuses on the project outcome and compares roads in compliance with the requirements stipulated in construction projects during the liability period. It also gathers sufficient data on the current conditions of roads from maintenance and repairmen point of view but does not evaluate and give systematical feedback on the road development project lifecycle from the supply chain point of view.

Currently there is no national level system for assessing the performance and sustainability of road investments throughout their lifecycle and through the supply chain. It should be considered in the new Estonian Transport Development Plan to add a set of KPI-s and a system of measuring them due to the lack of performance measurement methods and pre-defined KPI-s in public procurement for roads.

KPIs suggested by the OECD should be analyzed and that a set be developed and implemented on a national level. This has the potential of supporting the development of a performance measurement system that through feedback loops can contribute to the improvement of the RCSC. It can also generate information that can be used to avoid inaccuracies and lack of performance in new projects.

Taking into account new developments in ICT, the amount of data currently available and gathered in databases and the cost of managing and acquiring that data, the authors of this article conclude that establishing a performance measurement system will not produce extra cost. Also new developments in RFID, GPS, mobile technologies and ICT should be studied and in case proven to be reasonable implemented to increase efficiency and reliable feedback on the performance of both RCSC and sustainability and quality of materials.

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# PUBLICATION III

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# Wireless sensing in road structures using passive RFID tags

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**Abstract.** In northern countries several freeze-thaw cycles may occur per day making it especially significant to monitor temperature and water content in road structures. This information is a valuable feedback in performance measurement systems to avoid unsustainable road technologies and as an input by choosing the suitable road design. The way to acquire this data in different layers of the road structure is costly, difficult and time consuming. In this article an idea is presented and preliminary laboratory tests are carried out to use radio frequency identification (RFID) tags with sensors in road structures to measure real-time data about significant parameters throughout the designed lifespan. RFID technology is a relatively new technology in road construction field that has widely spread in intelligent transportation systems (ITS). Because of its benefits, construction and transportation industries are researching and implementing RFID technology to improve data acquiring and storage applications. The results of these tests have proved that RFID tags can be read through different layers and depths of road construction materials. The use of gathered data in road performance measurement systems is proposed.

**Key words:** road structures, data acquisition, sensor networks, radio frequency identification.

## 1. INTRODUCTION

In all Northern countries similar special problems with road deterioration due to cold climate occur with variations in temperature, geology and other conditions as traffic configuration, road design practices etc. The deterioration of roads can have serious consequences for the safety and comfort for road users and reconstructions cause extra need for financial assets.

The focus of this research is to verify feasibility of RFID technology in road structures to gather continuously and with relatively low cost significant information about processes in road structures. RFID technology is becoming increasingly viable as a commercial and technological solution to wireless identification [1].

In developed countries, investments in transportation infrastructure form a significant part of all investments. Adequate data from performance measurement systems is required for making investment decisions and in monitoring executed projects. RFID technology is a relatively new technology in road construction field but has widely spread in intelligent transportation systems. Because of its benefits, construction and transportation industries are researching and implementing RFID technology to improve data storage applications and also to develop "smart RFID tags" that are able to sense, monitor, and adapt to their changing environment. RFID has been identified as one of the cornerstones of the upcoming Internet of Things and the focus is moving from conventional RFID towards next generation networked and inter-connected systems [2].

In soil, RFID applications are currently used in farming to regulate irrigation. Vuran developed the world's first underground radio frequency (RF) sensor network [3]. Embedded wireless sensors monitor soil condition underground, transmit the data from one sensor node to another, and finally either to a hand-held computer, a fixed base station or an irrigation system. The use in agriculture and positive test results gave confidence to the authors that RFID technology can be used in moist soil conditions.

Off-the-shelf passive RFID tags as a telemetry link in a wireless sensor for real-time monitoring of soil properties such as temperature, but also how the same RFID system could be used for various types of sensors was investigated in [1]. The concept of using radio telemetry for wireless monitoring of soil properties is not new. NASA researchers have developed a wireless mesh of radio sensors for monitoring heat, humidity, and soil moisture. In 1984 a wireless soil moisture telemetry system was developed that had multiple individually addressable moisture sensors in the field [1]. The base station would query all the sensors in turn using RF transmission, and the appropriate sensor would transmit data in reply, also over RF.

In road construction, several RFID applications have been tested, but their focus has been on the increase of the supply chain efficiency. Researchers at the University of Alaska evaluated how RF identification can be used to track the amount of time that passes between the moment a truck is first loaded with asphalt and the instant the hot mixture is dumped [4]. They have reported that RFID was effective to gather information and to issue alerts regarding the movement of those vehicles.

## 2. MOTIVATION OF THE RESEARCH

Currently pavement and road structure monitoring needs significant personnel time or the use of costly equipment. This data is an important input by the design of new roads [5]. In this article we suggest to use passive and battery assisted passive (BAP) RFIDs with sensors in road structures to measure continuous data about significant parameters throughout the lifecycle of the road. Previous research [6] has indicated readability problems with the use of RFIDs; therefore the authors conducted preliminary tests to verify the suitability of RFID.

The estimated lifetime and durability of suggested technologies are more close to the lifetime of the road than other low-power wireless technologies such as wireless sensor networks and active RFID sensor tags. Therefore they do not require intrusion to road structures for data acquisition and maintenance reasons.

The climate of Estonia, comprising several freeze-thaw cycles even per day in winter, makes it particularly important to have information about temperature changes and about the amount of water moving through pavement in different layers of the embankment. Cracking of pavements related to low-temperature frost and freeze-thaw cycles is a well-recognized problem in most northern countries. Premature deterioration of road pavements is related to high frequency of freeze-thaw cycles, primarily where subgrades are composed of fine-grained, saturated material [5,7].

Once in a pavement or embankment, water plays a primary role in shorterning the service life of the pavement and increasing the need of rehabilitation measures. In order to have a sustainable road it is necessary to consolidate well the earthworks, have good sub-base drainage, keep the water-table low, prevent increasing of the moisture content of the sub grade, avoid failures due to binder stripping and not to allow water to remain on top of the surface, weakening the surface due to hydraulic pressure. If improperly canalized, water can also cause soil erosion and a breakdown of pavement edges.

By freezing temperatures, the deteriorating effect of water is even greater. Cold temperatures in winter are a significant concern for transportation agencies because due to frost the phenomena called *frost heave* occurs, a road will actually "heave up", being the major deterioration of roads, especially in case of insufficient drainage.

Therefore it is essential to monitor the above mentioned causes of deterioration in order to avoid design failures and to give support to the road agencies to establish the best requirements for designing and constructing sustainable roads. Authors suggest to measure water content and temperature simultaneously in road structures using passive and BAP RFIDs with sensors (see Fig. 1).

## 3. RFID TECHNOLOGY

RFID technology as we know it today dates back to 1970's [8]. Cardullo's and Walton's devices were patented in 1973, succeeded by the marketing of first usable products in 1979. The RFID technology is a means for uniquely identifying an object with a wireless radio link, allowing data to be stored on an RFID tag and retrieved in remote application at a later point of time.

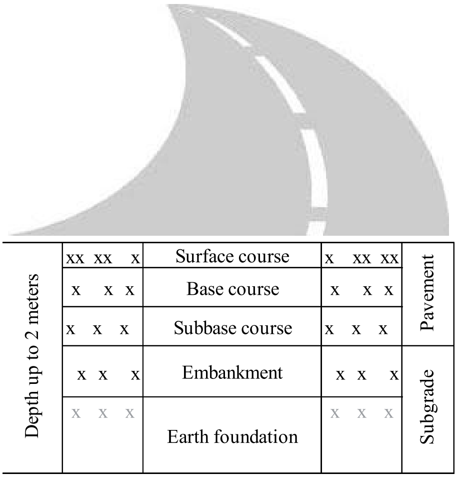

**Fig. 1.** Road cross-section (x marks the planned locations of tags).

Wireless sensors, incorporated in RFID systems, are important in several industrial, consumer and logistics applications. By extending RFID tags to sensing applications, the products become smarter and RFID sensor network applications are emerging and moving towards commercialization [9].

RFID tags can be classified into two categories: passive and active. The active RFID tags have their own internal power source that is used to power the integrated circuits and broadcast the response signal to the reader [10].

Two passive RFID technologies are available: surface acoustic wave (SAW) and integrated circuit (IC) based. Passive RFID sensor tags may be categorized as SAW, IC Passive and IC BAP (Fig. 2).

These technologies have been successfully used in various applications, amongst others also in the construction industry. Due to the progress in integrated circuit technology, it is expected that RFID will play an important role in the global circulation infrastructure. It is expected that more RFID tags will be used in the future as sensory functions come more commonplace [11].

A typical RFID system includes three components: an antenna or coil, a transceiver (with decoder), and a transponder (RFID tag), electronically programmed with unique information, as shown in Fig. 3 [12].

There is an emission of radio signals by the antenna in order to activate the tag and to read the data written to it. Antennas establish the communication between the tag and the transceiver. The transceiver is responsible for the data acquisition. The antenna can be packaged with the transceiver and decoder in order to form a reader. An RFID reader contains power supply and software to enable it to communicate with both RFID tags and an upstream computer system.

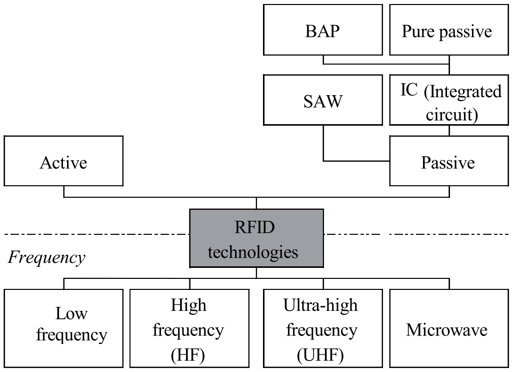

**Fig. 2.** Typology of RFID technologies.

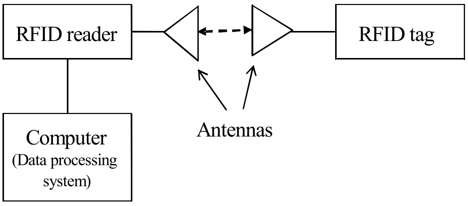

**Fig. 3.** RFID system generic structure.

In case an RFID tag is found in the electromagnetic field that is produced by the antenna, it detects the activation signal of the reader. The reader decodes the data that are encoded in the integrated circuit of the tag and the data can then be transferred to any computer system for processing.

RFID tags can be designed to transmit at one of several frequencies. Generally, the higher frequency tags transfer data more quickly but are less able to penetrate water, grease, and other obstructions.

## 4. SYSTEM DESIGN

### 4.1. System architecture

Authors have studied RFID tags with sensor functions because it is assumed that the RFID tag can detect the conditions of structures and transfer its information through the external reader [10]. With this in mind, a system was developed (Fig. 4) to monitor the condition of the road structure and establish the impact of water content and temperature change to road deterioration.

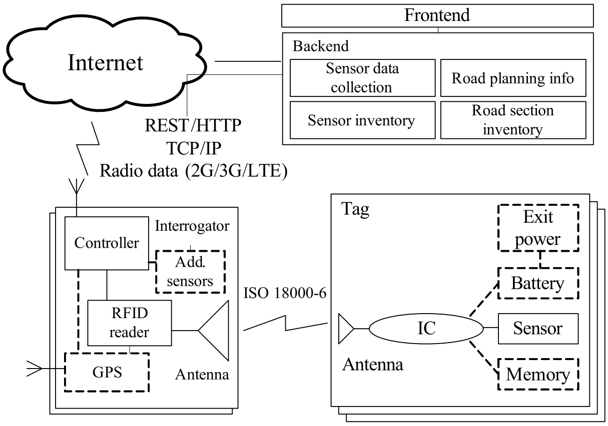

**Fig. 4.** System architecture.

The interrogator may be located in the moving vehicle or placed stationary on the road side. The RFID reading on motion adds certain requirements on the tag and reader antenna orientation, but at the same time reduces costs. Having many metering points with stationary readers costs more than a few, but often the bypassing vehicles have the interrogator on board [12,13].

Interrogator processes and enriches the raw sensor tag data. It consists of a RFID reader together with an antenna and data processing system. It may contain the GPS module to add the location coordinates to the sensor reading, to allow reporting on deviations of stored data and field information. The backend system will do the matching of the received information based on tag identifier and reporter trustworthiness. If the coordinate deviation threshold is calculated based on the speed of the vehicle, a signal to sensor inventory maintenance personnel is created to check the coordinates. Interrogator contains additionally sensors for reading the air temperature, relative humidity and speed of the interrogator when in motion.

The data from interrogator towards the backend server is transmitted over REST style HTTP(S) interface on top of the TCP/IP network to avoid possible data communication network operator restrictions. For moving units, radio network is a necessity. Stationary units may be connected to the fixed communication line, if available.

Backend server keeps the inventory of installed sensors (location, installation date, depth, layer material) and collects the sensor data (interrogator identifier, sensor identifier, reading location, temperature and water content in road structures, signal strength, temperature and relative humidity in air) sent by interrogators. Road section inventory (section name and identifier, owner, maintaining organization, condition, and history) is kept in the same database to allow reporting, based on the road sections.

Backend server keeps also road planning information (e.g price of the road section) to be able to report on the deviations between the plans and current situation and to do the cost calculations to assist modelling of upcoming road construction projects. The reports and online sensor data is displayed and rendered to the graphical format in frontend graphical user interface to be used by the stakeholders. Sensor data is made available to third parties through public application programming interface using open data principles. Correction functions for sensor readings are applied in the backend during the data collection process.

### 4.2. Sensor applications

For IC tags, normally a sensor tag comprises four major blocks – an analogue sensor, analogue-to-digital converter (ADC), digital controller circuit and RF part with antenna. The BAP tag may contain optionally non-volatile memory (e.g. FeRAM) for data storage, ultra long-life energy storage (e.g. lithium-polymer, thin film super-capacitor) and renewable power source (e.g. piezoelectric or photovoltaic generator).

It is known that low-cost capacitive soil water content sensors are sensitive to soil density, temperature, salinity, and supply voltage (RF signal strength) variations [14,15]. The calibration method to correct the readings, based on geostatistics, sensor clustering and information sharing has been proposed in [16].

The proportional-to-absolute temperature (PTAT) current generator, directly representing the temperature, delivers the PTAT current and a reference current, keeping the latter's value constant over the temperature range of interest. In the RFID tag the ADC then processes both currents into the digital data stream and passes it to the controller, which encodes the result into the response [17,18]. Also a design without ADC has been proposed in [19] to even more reduce the power requirements to the sensor.

The capacitance and time domain reflectometry methods are two widely used electromagnetic (EM) techniques for soil water content estimation. Both methods make use of the strong dependence of EM signal properties on volumetric water content that stems from the high permittivity of water compared to mineral soil solids, and air. The basic principle of the capacitance method is to incorporate a dielectric medium (e.g. soil) as part of the dielectric of the sensor capacitor [14].

Temperature and water content measurement using SAW tags has been considered in [20]. The SAW RFID tag consists of an inter-digital transducer (IDT) and a series of acoustic reflector traps, etched into a piezoelectric substrate. The tag reader emits a radio wave pulse to IDT that is converted piezoelectrically into a nanoscale acoustic wave. The wave travels past the reflectors to produce a unique pattern of reflected pulses. These travel back to IDT, where they are piezoelectrically converted into an encoded radio wave reply signal to the reader. The SAW chip operates in a purely passive mode and does not require supplementary direct current [21].

## 5. PRELIMINARY TESTS

Authors conducted a preliminary empirical test in laboratory conditions to check whether the ultra-high frequency (UHF) IC passive tag transmittance in dry soil and in road construction materials is similar to the expected.

For that we connected ThingMagic Vega UHF RFID reader to RHCP (Right Hand Circular Polarized), 7.5 dBiC antenna and to a PC with software needed for reading. In another end, the authors used Confidex Ironside metallic, ALN-9629 “Square” Inlay and Avery Dennison AD-824 RFID tags. Authors were aware of the fact that the metallic tag performance is suboptimal when placed on a non-metallic surface, but it was decided to test a tag with average performance in the air, which is approximately at a four meter distance from our reader. All the tests were executed in laboratory environment at room temperature.

Second set of tests was conducted at a road construction site to get a proof that the signal could be read through different materials used in road construction from the depths up to two metres. During the experiment we inserted the tag at various depths into the soil, going up to two metres, and took readings leaving the variable air gap between the soil and antenna so that the distance between the antenna and the tag was never bigger than three metres. The success rate of the reading was as expected and we were able to get readings using all three types of RFID tags.

The results provided a solid ground for continuing the testing with different materials to simulate actual conditions. In the preliminary field trials authors tested the Confidex Ironside metallic RFID tag in soils (sand, gravel) with various moisture. We placed the tags in depths up to two metres, leaving the gap between the antenna and the tag so that the distance between the antenna and tag was also never bigger than three metres. Authors were able to get readings through all tested materials and are confident to move to the next stage to start preparing a field test at a road construction site.

## 6. CONCLUSIONS

In all Northern countries cold climate is a cause for road deterioration. Long term monitoring of the parameters of the pavement and traffic helps to reduce maintenance costs, improves longevity, enhances safety and research in pavement design.

The use of sensor equipped RFID technology in agriculture as part of automatic irrigation systems gave the idea to use passive and BAP RFID tags with various sensors in road structures to measure temperature and water content. Authors conducted a series of tests in laboratory and field conditions and confirmed the RFID tag applicability in different depths up to two metres in soil and road construction materials. Literature review and preliminary tests prove that the technical solution presented in this article is perspective.

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## Juhtmevabade RFID-tehnoloogial põhinevate sensorite kasutamine teekonstruktsioonis

Kati Kõrbe Kaare, Ott Koppel ja Kristjan Kuhi

Infrastruktuur, eriti kvaliteetne teedevõrk, on iga riigi jaoks strateegiliselt oluline. Sellest sõltuvad nii elanikkonna rahulolu, paljude elutähtsate valdkondade toimimine kui ka majanduse areng tervikuna. Seega on möödapääsmatu, et teedeehituses kasutatakse konkreetse paikkonna klimaatilistele tingimustele ja liikluskoormusele vastavaid tehnoloogilisi lahendusi ning materjale. Normdokumentide koostamiseks, millest tulenevad ka vastava piirkonna jaoks soovitatavad tehnoloogiad, on muude parameetrite kõrval vaja ka väga täpseid andmeid temperatuuri ja niiskussisalduse kohta teekonstruktsiooni erinevates kihtides.

Käesolevas artiklis on autorid kirjeldanud võimalust kasutada teekonstruktsioonides passiivseid või poolpassiivseid RFID-kiipe, paigutades need tee erinevatesse kihtidesse. Juhtmevabad kiibid on varustatud sensoritega, mis mõõdavad temperatuuri ja niiskussisaldust pinnase erinevates kihtides. Toiteallika ja juhtmega lahenduste kasutamist ei pidanud autorid otstarbekaks katsetada, sest külmakergete ning nihkepingete tagajärjel on juhtmeühendused varasemates uuringutes ebakindlateks osutunud.

Autorid viisid laboritingimustes läbi esialgse katsetuste seeria, mille käigus testiti RFID-kiipidest lugemite saamist pinnasest ja erinevatest teedeehituses kasutatavatest materjalidest eri sügavustel. Kiipidest kasutati Confidex Ironside Metallic'u, ALN-9629 “Square” Inlay ja Avery Dennison AD-824 RFID-d. Sellise valiku tegid autorid, arvestades mitmeid varasemaid uuringuid, mis kaardistasid erinevate transponderite tagasilevi signaali tugevust lugeja konstantse väljundsignaali korral.

Antud kiibid osutusid oma klassis omadustelt Eesti kliimatingimustele kõige sobivamateks. Pinnasest oli võimalik saada andmeid kuni kahe meetri sügavuselt. Sellel sügavusel lõpetati katsed, arvestades külmumispiiri. Teise katsete seeria viisid autorid läbi tee-ehitusel, paigaldades kiibid pinnasesse, kontrollimaks, kas on võimalik lugemeid saada. Katsetatavateks materjalideks olid pinnas, liiv ja killustik, sügavuseks samuti kuni kaks meetrit.

Peamise järeldusena leidsid autorid, et on põhjendatud detailsema uuringu läbiviimine RFID-tehnoloogia kasutamise võimaluste kohta erinevatest materjalidest koosneva teekonstruktsiooni sees temperatuuri ja niiskussisalduse mõõtmiseks.

# PUBLICATION IV

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# Tire and pavement wear interaction monitoring for road performance indicators

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**Abstract.** The design, building and maintenance of national roads constitute a substantial part of the government budget. Taking into account the magnitude and importance of these investments, the expedience, efficiency and sustainability of roads are of great public interest and their performance should be measured. For performance assessment of roads or road sections it is important to gather data about different key performance indicators. Flexible pavements deteriorate under traffic loads and climate effects. This effect depends on the technology and materials of the road, but the greatest effects depend on traffic loads and volumes. Systems can be developed to give information about tire wearing and its impact on the pavement wearing. To ensure traffic safety, especially in countries with cold climate, it is very important to gather continuously data about tire tread wear. New technologies have made it possible to integrate the measuring of tire tread wear and tire type on roads continuously and present new opportunities to monitor and analyse conditions of tires. This paper is part of a road performance measurement system presenting a concept for input data collecting.

**Key words:** pavement wear, tire wear, sensors, road performance measurement.

## 1. INTRODUCTION

Roads and streets are the most important elements in transport communication and are used by almost everyone on a daily basis. Besides the fact that roads are provided for the benefit of the road user, they also play a significant role in promoting economic growth and the living standard of the population. During the last decades the volume of traffic has significantly increased putting more stress on the road pavements [1].

Performance measures and a well-developed performance measurement system are the basic input to a variety of decision processes and activities in road infrastructure management. Officials and managers need accurate, timely and relevant information about the infrastructure for decision making, along with the skills and knowledge to analyse results and design improvements when needed.

This paper is part of a research project that is conducted to develop a novel nationwide road monitoring system that gives input and data to the central road performance measurement system. Every vehicle, which passes over a road, causes a momentary, very small, but significant deformation of the road pavement structure. The passage of many vehicles has a cumulative effect, which gradually leads to permanent deformation and road surface deterioration. The proposed system is able to provide information to interested parties authorized to view the information. The system consists of different kinds of sensors that are considered valuable by the road authorities or are required by legislation. While planning a new road, this kind of measuring point should be designed at the beginning of every road section as a part of the road construction project. During the life cycle of the road, the collected data gives possibilities to analyse the results from various sides – environmental impact, technical sustainability, wearing of the road, etc.

Emphasis of this paper is put on finding the effects of the traffic volume, axle load and tire type on the pavement wearing, but also on proposing solutions for measuring tire wearing. The results can be used for pavement design, but also for determining the pavement wear from different tires and axle loads. With time, the pavement will deteriorate until it reaches an unacceptable condition and will be rehabilitated by resurfacing and possibly strengthening. Therefore road wear is a very important parameter to focus at for the design and maintenance of road pavements.

## 2. WEARING

### 2.1. Pavement wear

Pavement wear is a process in which several different deterioration processes act and interact, influenced by a variety of factors. These factors include environmental issues such as temperature and moisture, but also various traffic-related factors. The focus of this paper is on the influence of various vehicle parameters, such as the tire type (single/dual/wide single), tire size, axle load and traffic volume. To describe the effect a vehicle has on road deterioration, distinction has to be made in its different modes.

Pavement wear or pavement distress is the degradation of the pavement quality due to traffic and climate. For flexible pavements, the most relevant are cracking and rutting. We can distinguish fatigue cracking, thermal cracking, surface cracking and reflective cracking. Rutting can be divided into primary or permanent rutting of bituminous layers, secondary rutting in the subgrade, rutting due to abrasion of the surface by studded tires. Other distress modes that are taken into account are ravelling, roughness and potholes [2].

The road wear from actual commercial vehicles depends on the degree of loading and type of goods carried by the vehicle. The actual road wear caused by the traffic on pavements can only be determined by weighing actual trucks, buses, semi-trailers etc in the traffic flow. Maximum permissible gross weight and axle loads are not always reached by regular commercial vehicles, because a great proportion of the freight is volume based.

The road freight transport industry understandably wishes to increase its efficiency. Some organizations, for example Forest and Wood Industries Association in Estonia, have been lobbying for the increase in the allowable mass limits for heavy vehicles on the basis of increased efficiency and benefits to the economy. Some of the proposals for increased mass limits involve increased axle load limits, which would clearly lead to additional pavement wear. The vehicular traffic on the road is the major cause of road deterioration, especially on heavily trafficked roads. It has been proved that the impact of passenger cars is not significantly damaging to the pavement and road structures. On the other hand, the impact of trucks with heavy axle loads is severely deteriorating the road [2,3]. The vehicle operating costs are to be compared with the impact of the vehicles of greater mass [4].

For pavement design, but also to determine the pavement wear from different tires, wear effects of different axle loads have to be determined. Generally, this is described by the load equivalency factor (LEF, also equivalent axle load factor), where an axle load is said to be equivalent (producing equal pavement wear) to a number of applications of a reference (standard) axle load. The most well-known LEF is the so-called "fourth power law", which is expressed mathematically as follows:

$$\frac{N_{\mathrm{ref}}}{N_x} = \left( \frac{W_x}{W_{\mathrm{ref}}} \right)^4 , \tag{1}$$

where $W_x$ and $W_{\mathrm{ref}}$ are axle loads and $N_x$ and $N_{\mathrm{ref}}$ are the corresponding numbers of load applications.

The use of the fourth power relationship predicts that, e.g., the 7.3% increase in allowable load for a single axle results in the 33% increase in pavement wear, and consequently road authority can expect a 33% increase in the length of pavement rehabilitation required per year [5].

Different distress modes react differently to changes in the influencing factors. Take, e.g., the influence of the tire type, where the stress and strain conditions near the surface of the pavement are strongly influenced by the contact stresses and their distribution in the tire-pavement interface, whereas the stresses and strains deeper in the structure are mainly influenced by the total load. Therefore, a change in contact stress distribution due to a change in the tire type can generally have most influence on the upper layers (Fig. 1).

The current trend in Europe is smaller tire diameters and higher tire pressures. A smaller tire diameter enables lower vehicle floors, which increases the volume

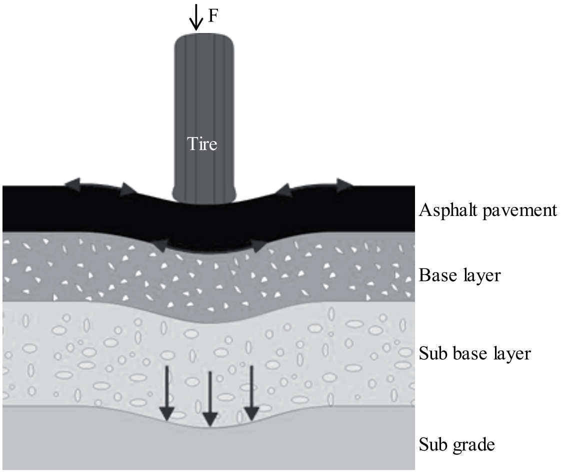

**Fig. 1.** Vehicle–pavement interaction [2].

that is possible to transport. A higher tire pressure might have a positive effect on fuel consumption. Also, wide single tires are beginning to replace the traditional dual tyres which can be explained by a lower weight, reductions in fuel consumption and a lower cost of tire wear. Although beneficial for transporters, the effect of these trends might be an increase of the road wear since they imply a smaller contact area between the tire and the road. This area, henceforth called "footprint", is an important road wear factor. The larger the footprint, the less is the load distributed on every road area unit. The difference in road wear between single and dual tires is thus not caused by the differences in tire types as such.

The deviation of axle loads from different axle load levels are examined to establish a representative value for axle loads, based on weight in motion (WIM), for the registration of regular traffic load's exposure on pavements. The log-normal distribution is used for the description of the normal axle load distribution. Especially, inference of axle loads from WIM registration must be investigated in relation to the calculation of road wear from the regular traffic flow [6].

It is clear that these different distress modes react differently to changes in the influencing factors. For example, the influence of the tire type, where the stress and strain conditions near the surface of the pavement are strongly influenced by the contact stresses and their distribution in the tire-pavement interface, whereas the stresses and strains deeper in the structure are mainly influenced by the total load. Therefore, a change in the contact stress distribution due to a change in the tire type can generally have most influence on the upper layers.

## 2.2. Measuring tire wear

Worldwide, poor tire treads are one of the most common technical reasons for traffic accidents: in wet and slippery road conditions, tires with low tread depth lose their grip on the road surface that results in extended braking distance. The danger of aquaplaning can also increase, the vehicle skims over the surface and goes out of control. However, spot-checking of the depth of tire tread is carried out only by the police at irregular intervals. Drivers with bald tires are a potential threat to the safety of other passengers. A study by the United States National Highway Traffic Safety Administration (NHTSA) showed that 9% of all passenger cars in the United States had at least one threadbare tire [3].

In many countries the established method to measure the wearing of tire tread depth is with a mechanical gauge that reads in millimetres or inches. In some countries, portable digital tire gauges or laser-based tread analyses condition (TAC) scanners are used. Some methods need a drive over the measurement unit, but most of them cause slowing of vehicles and form a bump on the road which is not the best suitable solution in highway circumstances. To avoid these negative effects, the authors have searched for alternative methods amongst new technologies. The most advantageous solutions are described below.

From safety reasons, good tires are very important, therefore tire producers have implemented new radio frequency identification (RFID) solutions to measure besides tire pressure also the tire tread wear. Michelin has tested 50,000 tires with RFID-s that record tire pressure, the tread wear is still being tested with a handheld device. Monitoring tires can be a slow process as each tire has to be identified by its sidewall markings, which are often not easy to see due to dirt or scuffing. RFID means that an operator can quickly identify each tire by passing a RFID hand-held scanner around the sidewall and then have that information accurately electronically recorded. Another benefit is that the tires can be monitored throughout their service lives, including retreating. While RFID chips, used by Goodyear, currently only carry identifying data, it may be possible in the future to make them dynamic for real-time monitoring of pressure and temperature [7].

In 2011, the United Kingdom police started randomly deploying an automated system, which can measure the tread depth on the tires of cars passing over an in-road sensor, with automated ticketing of people driving with badly worn tires. The system uses lasers and cameras embedded in the roadway to automatically measure the tread depth of every tire that passes it. If a tire has less than 1.6 mm of tread remaining, the system sounds an alarm. That could signal to a nearby police checkpoint to pull over the offending car and to examine its tires [8].

ProContur System, developed in Germany, can measure tire tread patterns contact-free in moving traffic – reproducible even at speeds of up to 120 km/h [8,9]. The computing required for this high-speed image capturing is carried out by the Kontron’s ThinkIO-Duo. The traffic safety system ProContour H3-D measures tire tread depth without any influence on the flowing traffic. In order to achieve this, four measuring heads are embedded in shafts or ducts in the road. Every measuring module covers a breadth of approximately 380 to 670 mm. Depending on the size, the modules have one or two laser diodes, a laser beam controller and complementary metal-oxide-semiconductor (CMOS) sensor-controlled digital cameras with GigE vision interface. The measuring method of the ProContour H3-D is based on the principle of laser triangulation.

Brey invented a system and method for monitoring belt wear or tread wear of a tire [10]. That includes at least a RFID tag with unique identification, embedded in the belt or tread of the tire at one or more wear points. A Radio Frequency (RF) tag reader can periodically monitor signals from at least one RFID tag. If the RF tag reader fails to obtain any signals from the at least one RFID tag, indicating a destroyed RFID tag, the user can be warned about a wear problem of that belt or tire. RFID tags can be distributed at different depths of the tires, or across the tread at the same depth, to determine different wear problems. The same RFID tag can also be used for inventory tracking purposes [10].

## 3. WEAR MEASUREMENT SYSTEM

### 3.1. Sensors

Accurate measurement of vehicle static axle or wheel loads has long been a major objective of highway engineers. The static weight of a vehicle is used to provide a basis for pavement analysis and design. Traditionally, these weights have been collected by pulling the vehicles off the roadway and weighing them at weigh stations while the vehicles are at rest. The static weighing of vehicles in highways has several disadvantages, being time consuming, expensive, and dangerous on heavily travelled roads [11,12], as shown in the previous chapter.

In this study the authors propose a concept and technical architecture for the measurement of the pavement wearing by axle weight, type of vehicles and type of tires using sensor networks. Modern embedded computer systems enable *in situ* data acquisition and processing with relatively low cost and high precision. Embedded data acquisition systems can be used for measuring various properties of the road. The system contains many different types of sensors. Some possible sensor types are listed below.

**Stationary sensors:**

- for measuring vehicle presence and movement by traffic volume, types of vehicles, speed;
- road weather stations for measuring condition on the road: temperature, humidity, iciness, de-icing salts;
- for pavement condition monitoring inside the road;
- for vehicle weight monitoring on the road.

**Mobile sensors:**

- for monitoring movement of critical loads (location, vibration, pressure, temperature, etc);

- for monitoring heavy loads;
- for monitoring tire pressure and tread depth [13].

Mobile sensors are communicating either directly with the backend data collection system or with the roadside sensor system (e.g., RFID-based sensors in tires).

Manufacturers are installing different stationary sensor types in road monitoring systems or road weather stations. From the integration and maintenance cost perspective it is important to choose the sensors and systems that use standardized and/or open communication protocols. Depending on the set-up and for best performance, near real-time communication between the sensor system(s) and the data collection system is needed to assure the sequential processing of the sensor events collection. If this is not possible, different methods to assure the correct message sequence must be applied. The data communication must also be secure to avoid manipulating with sensor values.

Precise and reliable WIM matrix sensor with mini shear beam sensors, embedded electronics and communication interface with sufficiently high data acquisition rates can be placed in the pavement (Fig. 2) to estimate measuring

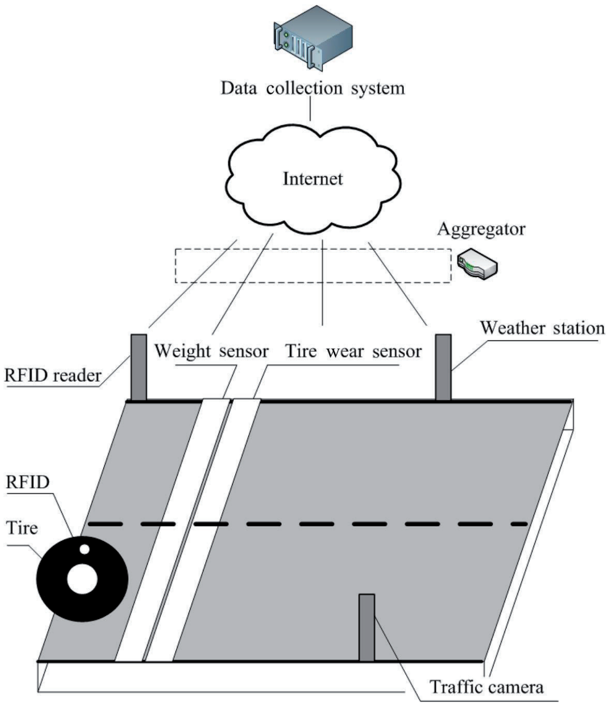

**Fig. 2.** System architecture.

gross- and axle weight, tire footprints, tire pressure and pressure distribution and vehicle speed. Sensors detecting presence and movement of vehicles and RFID readers can be placed on the side of the road to identify the vehicle and tire type and size.

If pre-processing and aggregation of the sensor values is not needed then also direct communication path may be allowed from the consumer to sensor using alternative communication protocols.

The impact on the wearing of pavement from studded winter tires has been discussed in countries where those tires are allowed. The information gathered with this system gives adequate data for conducting thorough calculations and studies.

As an innovative further application, an image processing camera can be added to the system, identifying and photographing the numbers of the cars with worn tire treads. For safety precaution purposes a notice to check tires can be sent via different communication channels.

### 3.2. Data collection system

Sensors feed the collection system with a constant flow of values depending on the traffic load distribution in the time domain on the measured road sections. During peak hours, the data flow amount grows proportionally with the traffic volume. The backend data collection system hardware and communication channels must be dimensioned accordingly to accept the sensor data.

The physical server architecture depends on pre-processed data feeding requirements towards other systems and on the amount of deployed sensors. Prearranged level of operational performance requirements put high availability requirements for the architecture. Load balancing techniques must be used to distribute workload across multiple servers to achieve optimal resource utilization and avoid overload of the computational nodes.

Additional local or regional aggregation layer may be reasonable to introduce. Aggregators do certain amount of data pre-processing in the location where the combined sensor event series are created before sending the values to the data collection system. It will reduce the event load to central system. If standards on data formats are not agreed, typically all vendors choose the format unique to them. Therefore data transformation from the sensor system format into the common data model format must be performed. To save computing power and the data transmission channel, it is reasonable to do it in the aggregation node. For the same reason, pattern matching techniques for data filtering and aggregation of different sensor values into one message are recommended to add into the aggregator.

Aggregator core functionality includes also the communication and data security functionality of the sensors in the same location in a single node. The solution reduces the overhead in data communication and computing power required in sensor nodes for encryption.

Functionality of the data collection system includes the ability to transform, process, aggregate, query, store and dispatch sensor data streams. The system consists of two modules: the complex event processing (CEP) platform and data storage [14]. CEP module is for querying and analysing the sensor data stream, for digging and sending the conclusions to third systems. Data storage will be used to log the raw data and the conclusions.

The internal architecture of the data collection system must be constructed in a way that supports effortless integration with any number of third party systems. The integration with asset, provisioning, fault and performance management systems of road authorities will be required.

Access control to the data collection system is controlled via security levels – an information consumer is only able to consume the data on the level to which it has been provided access; e.g., some users may only have access to aggregate and pre-processed data, while other users have access to data at the sensor level. The data access mechanisms stay the same, no matter what level access or to what data is requested and granted.

### 3.3. Data consumers

System architecture and the data collection system will be such that information will be provided to consumers dynamically as they request it. A sample usage scenario in Estonia may be a driver starting to drive from Tallinn to Tartu, requesting road condition information from the system – the car will subscribe to the road condition information on the route, receiving it directly and incrementally in real time from the server as the car proceeds on the route. Similarly the police may request information on traffic loads on different roads or locations receiving it from the sensors in the location. Other potential beneficiaries are:

- internal and external security forces (police, criminal police, customs, border guard authorities, defence forces),
- road maintenance and construction authorities,
- transportation companies (Fig. 3).

Because of the limited funds available for the construction of new roads and for road maintenance, it is essential that effective enforcement of the axle load regulations be carried out throughout countries, limiting access of heavy vehicles on roads not suitably designed and constructed. The underlying rationale for having performance indicators or measures is that the limited availability of resources for road infrastructure makes it necessary to allocate these resources as efficiently as possible among competing alternatives.

Comparing the data from distinct sensors and locations enables identification of correlations between as-constructed properties of asphalt concrete in construction databases and field performance of pavements in pavement management systems to quantify the link between material quality, traffic flow and performance. By comparing traffic data and wearing of several lanes gives for data

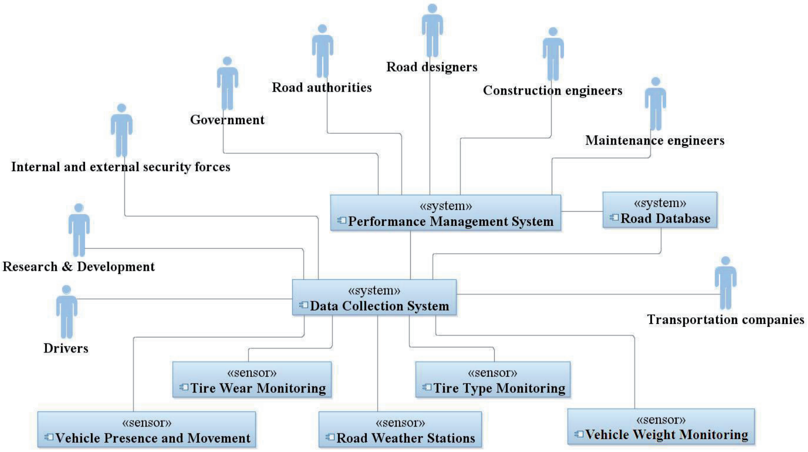

**Fig. 3.** Data consumers and the sensor-based performance management system.

users feedback about the impact of traffic load and tire type on that particular asphalt mix. Further on, with more test fields the performance of different asphalt mixtures can be evaluated. A conceptual model was developed that enables to analyse and predict more precisely future pavement deterioration in highways, based on road utilization. By adding climate data to the traffic model, prediction of the approximate timeline for probable maintenance needs of a flexible pavement will become possible.

## 4. CONCLUSIONS

For decisions, regarding investments and technical solutions in road construction, road authorities need feedback from previous projects about the performance of constructed roads and their sustainability. To calculate and analyse the performance, various performance indicators should be measured and analysed. This paper presents one possible solution to gather data about key performance indicators and to give feedback about constructed road sections. The results of this work have been planned to be implemented in cooperation with the Estonian Road Administration.

Depending on the needs of miscellaneous interest groups, this throughout the lifecycle gathered information can be analysed and used in decision making processes in various fields, not only regarding technical solutions for road sustainability. Part of the further research is the development of a program that is able to model all the gathered data into easily readable and accessible database. If there will be accurate data regarding traffic volume, axels load, tire type and tire tread wear, comparative analysis can give evidence of impact on pavement wear. Dynamic measurement of tire tread depth could bring about a radical change in flowing traffic, 100% of all vehicles, trucks, buses and cars could be controlled.

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## Rehvide ja teekatte kulumise jälgimine teehoiu tulemusnäitajate süsteemis

Kati Kõrbe Kaare, Kristjan Kuhi ja Ott Koppel

Investeeringud teehoidu on väga mahukad ja neid rahastatakse enamasti riigieelarvest. Selleks et kontrollida vahendite kasutamise otstarbekust ja olla veendunud valitud konstruktsiooniliste lahenduste õigsuses, peab olema välja töötatud vastav tulemusnäitajate süsteem. Süsteemi sisenditeks saavad olla ainult täpsed ja

pidevalt mõõdetavad andmed, mida tee elutsükli jooksul kogutakse, analüüsitakse ning süstematiseeritakse. Käesolevas artiklis on autorid esitanud tehnilise lahenduse kontseptsiooni, kus tees asuva anduri abil jälgitakse erinevaid teekatte kulumist põhjustavaid tegureid: liiklussagedust, sõidukite teljekoormusi ja temperatuuri. Uuenduslik on, et sama seadme abil jälgitakse ka rehvide kulumist. See on saanud võimalikuks tänu tehnoloogia arengule, mille tulemusena on rehvimustri sügavuse mõõtmine teostatav liikuvate sõidukite puhul. Edaspidi peaks rehvimustri kulumise mõõtmine toimuma rehvides asuvate RFID-kiipide abil, mis teavitavad aegsasti autojuhte rehvide kulumisest. See on oluline, kuna paljud riigid peavad üheks liiklusõnnetuste peamiseks põhjustajaks kulunud rehve, eriti kriitiline on rehvide nõuetele vastavus talviste teeolude korral. Vastav info edastatakse ka liiklusohutuse eest vastutavatele institutsioonidele, kel avaneb võimalus ennetavaid meetmeid kasutusele võtta.

# PUBLICATION V

Kaare, K. K., Koppel, O., Kuhi, K. Use of smartphone accelerometers for winter road maintenance improvement in urban areas. – *Urban Transport XIX. Urban Transport and the Environment in the 21st Century. Southampton : WIT Press, 2013.* [Accepted for publication].

# Use of smartphone accelerometers for winter road maintenance improvement in urban areas

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## Abstract

The objective of the winter maintenance is to maintain transport links and enable everyday life to continue during adverse weather conditions. In urban areas in northern regions, especially with large population and numerous streets the topic to increase efficiency is an important agenda for local authorities. The issues of safety, environmental and health impacts, street availability and minimum delays to the travelling public on the treated network need to be addressed and improvement measures to be taken. This paper investigates an application of participatory mobile sensing with smartphone tri-axial accelerometers: detecting and reporting the surface conditions of roads. The proposed solution is an elaboration of mobile pothole detection using sensor networks for road surface condition monitoring when snow and ice occurs.

*Keywords: traffic safety, road maintenance, accelerometers, mobile sensing, participatory sensing*

## 1 Introduction

Controlling snow and ice buildup on streets during winter weather events presents several challenges for local road authorities in northern countries. Transportation problems carry severe costs to society – streets covered with ice and snow are slippery and inherently less safe for driving. Furthermore, the number of accidents always increases during and just after winter storms (see Figure 1). Increased competitiveness requires predictable and regular transit times without delays. Effective and comprehensive winter maintenance is costly and as it is financed by local governments frequently pressured subject for budget cuts.

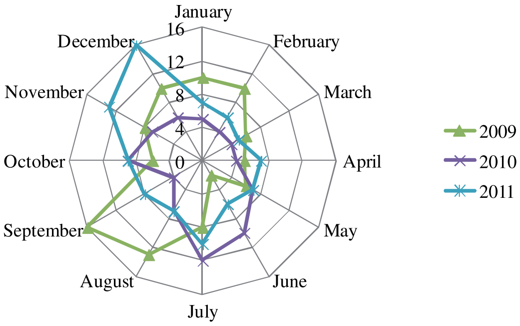

Figure 1: Life-cycle of accidents with fatal consequences in Estonia [1]

Besides snowploughing the most common way of dealing with ice and snow is to apply salt or abrasives. However salt can cause significant damage to pavements, cars and environment therefore it is important to have information about areas in need of maintenance. Safety concerns provide a major stimulus to improvements in winter street maintenance. Considered together these forces make it highly appropriate to study new methods to improve winter road maintenance planning.

Good analysis and decision making in the transportation industry is often restricted by a lack of adequate information. Costly data collection procedures mean infrequent sampling and delays in maintenance works. Cost considerations and easy access contribute to the wide use of free weather information sources. However, these sources may have problems with timeliness and a lack of detail, which may result in the use of inaccurate weather information.

The most widely used weather information sources for winter maintenance personnel are the free National Weather Service (NWS), private-sector weather providers, and the Road Weather Information System (RWIS). Survey results showed that maintenance personnel relied less on forecast weather parameters than information on current conditions [2].

The optimal distribution of resources for winter street maintenance is possible providing the availability of comprehensive and objective real time data about the state of the streets. Using mobile smartphones makes a substantial set of precise sensors readily available. This provides without significant extra cost reliable and exact information, with extensive coverage. This kind of a solution where citizens contribute to collecting data about the environment has been called participatory sensing [3]. Participatory sensing using smartphone accelerometers as an approach for data collection is proposed in this paper due to its low cost, the large number of road users and large real time coverage.

## 2 Related research

Due to the increasing demand of the transportation authorities for rapid, accurate data acquisition about the road pavement, a mobile mapping system has been developed primarily for road surface detection. As mentioned by Paterson & Watanatada already in 1985 [4] here is very clear correlation between vehicle speed, ride quality and road roughness. Road roughness is measured in different ways, using The International Road Roughness Index (IRI) as an indicator to describe it.

IRI is essentially a computer based virtual response type system that summarizes the roughness qualities, that impact vehicle response and is most appropriate when a roughness measure is desired that relates to overall vehicle operating cost, overall ride quality, dynamic wheel loads and overall surface condition. The IRI measurement has m/km (sometimes mm/m) or in/mi units. The determination of IRI can be easily done from the intersected surface points; only the longitudinal profile has to be used [5].

Within the transportation technology industry, there has been an increasing interest in road surface monitoring and in finding easier ways to map and monitor potholes. The current state-of-the-art in industry is to measure road surface quality using a Falling Weight Deflectometer (FWD). These devices apply a fixed load to the road surface and measure the distortion of the road to that load, giving an estimate of how imminent road surface failures are [6].

Road conditions are naturally sensed from a moving entity that can measure vibrations and impulses during a drive. There are several vehicular sensing systems for pothole and roughness detection, particularly [5] - [11]:

- BusNet system developed at University of Colombo;
- Tri-axis accelerometers in an embedded Pothole Patrol system together with GPS receivers developed at Massachusetts Institute of Technology;
- Mobile devices as a surrogate traffic sensing and communication systems like Nericell and TrafficSense developed at Microsoft Research India;
- A system developed at National Taiwan University what is using motorcycle-based mobile phones;
- A pothole detection approach in the context of offline data mining, proposed at University of Jyväskylä (Finland);
- A mobile sensing system for road irregularity detection using Android OS based smart-phones developed at University of Latvia;
- Photogrammetry Based Road Roughness Measurement System developed at Budapest University of Technology and Economics (Hungary);
- Different laser scanners.

All the abovementioned solutions focus on finding a cost effective way to detect road surface irregularities but are not designe to take into account winter weather peculiarities in the north and ways to improve safety and effeciency with the same devices and software platforms. An increasing demand for a safe drive during all seasons on various road hazards becomes an important element in ITS (Intelligent Transportation System) platform [12].

Accelerometers have been used for a variety of uses throughout the world today, from medical to research, from car performance to robotics. However, with the advent of the iPhone and Android, accelerometers are much more commonplace in the world of today.

## 3 Weather information and winter maintenance decisions

The local governments are responsibility to guarantee good quality transportation infrastructure in urban areas. The task is carried out by urban road authorities who are obliged to make effective maintenance decisions. Controlling snow and ice buildup on streets during winter weather events presents several challenges for them in northern countries (see Figure 2). Treatment types, timing, rates, and locations are decisions that have a considerable impact on roads safety and efficiency. Additionally, poor decisions can have adverse economic and environmental consequences.

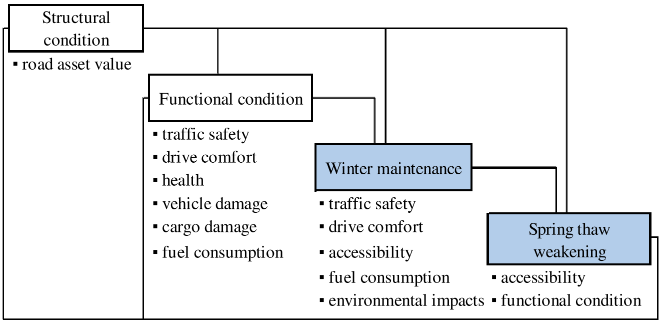

Figure 2: Northern region road condition management areas and their internal relationships for local road authorities [13]

Estonia, for example, is situated on the coasts of the Baltic Sea, being geographically situated in a region where during mild winters there can be several freeze thaw cycles per day. The long coastline supports temperature and humidity changes in very short distances complicate and diverse to manage road maintenance. Road maintenance agencies need real time information about weather conditions and conditions on the roads [14].

To ensure efficient and safe use of roads in winter, snowploughing is carried out and primarily road salt (sodium-chloride) is used to melt snow and ice, and in some places sand to provide traction for vehicular traffic. The environmental impact of salt and sand use has been widely discussed, but their application is effective, convenient, and inexpensive. To create a balance between safety and environmental protection, it is necessary to use a variety of strategies to enhance winter road maintenance, including improving operational practices, implementing new technologies, and using state-of-the-art equipment.

The most noticeable benefit of using weather information for winter maintenance is reducing maintenance cost. Weather information is important in supporting a variety of winter maintenance operations; however, respondents reported needing more weather information to support anti-icing and ploughing/de-icing than to support sanding/grit operations.

Together, these findings suggest that the demand for weather information among winter maintenance personnel will increase in the future. Air temperature, wind, and the type and amount of precipitation are primary parameters of current and forecast weather conditions. Road weather elements such as pavement temperature, bridge temperature, and pavement conditions are also widely used in winter maintenance.

But weather forecasts alone do not give enough precise data and more online information is needed. That can be acquired from weather stations that are costly to erect and maintain: costs 30,000-40,000 EUR per item, density should be one station per 100 km$^2$ [15]. Different built in sensors for road network monitoring are also a costly solution. Smartphone accelerometers can fulfill the gap of giving sufficiently precise information without significant extra costs.

## 4 System design and implementation

In this section, authors introduce the design and implementation of proposed road winter condition detection system. First is presented the system over-view followed by the design of detection algorithms and elaboration on implementtation details. Design is general, not constrained to any particular brand or type of mobile phone; and also power-aware, as hardware such as the screen is only activated when necessary.

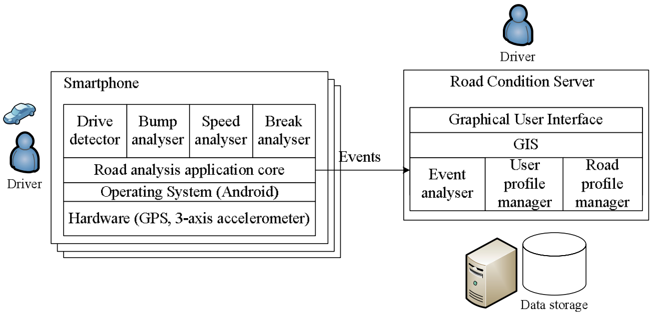

Figure 3: System high-level architecture

The conceptual system contains two main components: Road Condition Server and the smartphone (see Figure 3). The smartphone application will take care of analysing different sensors and will produce the events towards Road Condition Server. The events are sent over mobile packet data communication channels.

The driver has smartphone. The smartphone hosts special application for road condition monitoring. Applications can be written to record, analyze and upload accelerometer data to a remote server so information about the transportation network can effectively be measured continuously [3].

The application proposed by authors has the following sub-components:

- drive detector,
- road bump analyser,
- speed analyser,
- break analyser.

Drive detector is using accelerometer and GPS speed data to detect if the movement of the smartphone could be caused by moving vehicle. The vehicle movement fact is published to other modules to use it as input.

Road Bump analyser is using the mechanisms familiar with Pothole Patrol concept to detect irregularities in the pavement.

Speed analyser is comparing the speed of the vehicle against thresholds. Passing the threshold generates an event towards backend server.

The events may be classified as:

- irregularity event – produced when the road surface irregularity is detected by the detection algorithm,
- speed event – produced when the speed of the vehicle passes the pre-configured thresholds,
- break event – produced when the accelerometer detects negative acceleration.

The event information is collected by the backend Road Condition Server and analysed further.

## 5 Information collection process

### 5.1 Sensor data acquisition

The road quality data acquisition process is divided into the following main steps: 1) sensor data acquisition, 2) feature extraction, 3) classification, 4) anomaly detection, 5) profile calculation and blacklisting, and 6) information distribution. Steps 1-3 are executed in the smartphone application, steps 4-6 in server side (see Figure 4).

Android Operating System based smartphone hardware platform contains several types of sensors that can be categorized as motion, environmental and position sensors, including triple-axis accelerometer, and GPS to capture geographical coordinates and vehicle speed. Other smartphone hardware platforms have similar functionality available.

The accelerometer measures the acceleration in $m/s^2$ that is applied to a device on all three physical axes (x, y, and z), including the force of gravity. Applying high-pass filter to the accelerator values linearizes the values and gives the acceleration value excluding force of gravity.

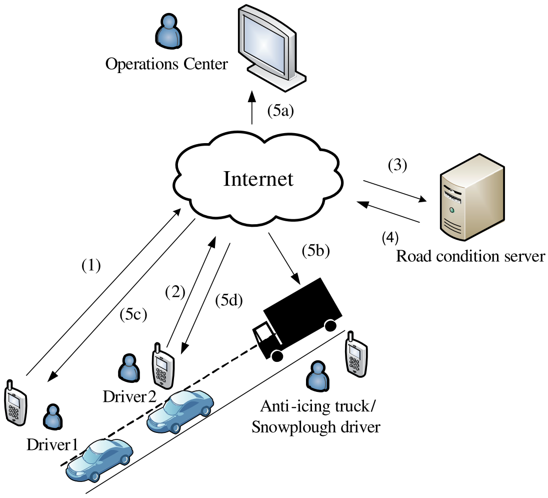

Figure 4: Example scenario

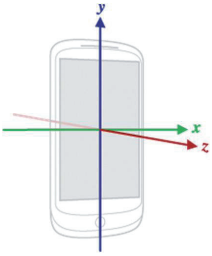

Figure 5: Smartphone accelerometer coordinate system [17]

The accelerometer coordinate-system (see Figure 5) is defined relative to the screen of the phone in its default orientation. The axes are not swapped when the device's screen orientation changes. The x axis is horizontal and points to the right, the y axis is vertical and points up and the z axis points towards the outside of the front face of the screen. In this system, coordinates behind the screen have negative z values [16].

The accelerator three-dimensional input signal is merged into one acceleration magnitude by taking the Euclidean magnitude of the three individual values. It can be done since the bump detection algorithm does not require distinction of directional accelerations [18].

The vehicle location and speed is obtained using GPS sensor. Geographic location is sensed at a particular time. A location consists of latitude and longitude, a Coordinated Universal Time (UTC) timestamp, and optionally information on altitude, speed, and bearing.

GPS accuracy is important in pothole detection they need to be properly located and multiple detections combined to report a single pothole. In case of maintenance planning solutions the accuracy is not so important, it is important to know where are the areas in need of maintenance and which are in good condition.

The acceleration magnitude and GPS signal obtained by the phone is noisy. The noise comes from two primary sources: irregular sampling rates and discrete physical sampling of a continuous function. In parallel with the acceleration magnitude and location data the vehicle speed is captured and analysed.

### 5.2 Feature extraction and classification

Dynamically sized sliding window is applied to the acquired data and different features are extracted:

- vehicle speed – minimum, maximum and arithmetic average values in the time window;
- acceleration magnitude – fundamental frequencies, arithmetic average, minimum, maximum value, standard deviation, mean, variance;
- acceleration values for each axis – fundamental frequencies, arithmetic average, minimum, maximum value; standard deviation, mean, variance.

The features are classified and published as events from the smartphone to the server when enough evidence is found using Naïve Bayes classifier. On server side another more resource intensive classification algorithm will continue evaluation of the events.

The real time event collection feed (steps 1…3 in Figure 4) is evaluated on server side based on the event class, location, driver profile, weather forecast and road weather station readings, collection time, and closest data in time when the road section was clean. Another sliding time window of an event is dynamic and based on the amount of events in time interval on that particular road. Data processing anomalies are detected during the process and logged for learning purposes.

For example: first driver smartphone application classifies an event. The event data together with metadata is passed on through Internet (using mobile data communication technology) to the backend Road Condition Server (step 1). The second driver detects an event approximately in the same location (step 2) and passes the data to server. The real time event collection feed (step 3) is evaluated on server side based on the event class, location, driver profile, weather forecast and road weather station readings, and collection time.

The event is sent out from the server (step 4) and distributed to interested parties (step 5). The time window of an event is dynamic and based on the amount of events in hour on that particular road. After successful evaluation of the series of events, the road profile (and the map) is updated with the combined event information. Also the user profile will be updated with higher trustworthiness rank.

A key to the system success is making it possible to have communication between any information provider and information consumer without the need for complex integration work. Access to the system is controlled *via* security levels – an information consumer is only able to consume the data on the level to which it has been provided access, e.g. some users may only have access to aggregated and pre-processed data, while other users have access to data at the sensor level. The data access mechanisms stay the same, no matter what level access or to what data is requested and granted.

## 6 Conclusions and further research

Over the past decades attention has been turned towards improvements in winter highway maintenance operations to accomplish three critical goals: reducing costs, increasing safety and minimizing environmental impacts. In this article the authors have proposed a new approach to winter road maintenance improvement for transportation agencies. It is especially useful tool in urban areas with extensive street networks and high population.

The proposed solution that gives information about road roughness and maintenance needs in winter time is a further development of existing systems that use smartphone accelerometers in characterizing pavement condition. Participatory sensing using smartphone accelerometers for data collection is proposed due to its low cost, large number of road users and real time coverage.

The use of participatory sensing is an easy and operative tool of real time monitoring the condition of roads in urban areas. The simultaneous and online information gives maintenance companies a database to be efficient. An advantage is given to use limited maintenance funds where only and exactly where servicing is needed increasing safety, environmental responsiveness and helps to avoid excess wasting of resources.

The proposed solution measures road quality during the year, forming a database of the state of the road network. With the yearly advent of winter weather the same description of road network is the base dataset starting to gather new information about weather caused abnormalities. Both ports of the applications can be implemented as parts of Performance Measurement Systems (PMS) for roads and authors have planned addressing this issue during further research.

To determine the potential of smartphones in transport monitoring and additional applications authors are considering a number of successive trials and further research. The work described in this paper is part of a larger effort to mine, collect and systemize online sensor data from wireless devices. Authors believe that information acquired by mobile sensing provides tremendous opportunities for data mining and we intend to leverage our smartphone-based data collection platform to the fullest extent possible.

Wider objective of further research is: develop a country-wide road monitoring system that collects data about parameters of interest and is able to provide information to any interested party that is authorized to view the information. Potential beneficiaries of this system are:

- society as whole;
- government and local road administration authorities;
- road maintenance and construction companies;
- design and research institutions;
- transportation and forwarding companies;
- internal and external security forces (police, customs, border guard authorities, defence forces), *etc.*

Present research shows that sensors in the smartphone platform could support and substitute in some areas costly weather stations leaving their density optimal. The solution gives information to route maintenance equipment to the streets that require servicing and avoid unnecessary travels.

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# PUBLICATION VI

Kõrbe Kaare, K., Kuhi, K., Koppel, O. Developing Road Performance Measurement System with Evaluation Instrument. – *World Academy of Science, Engineering and Technology*, 2012, 72, 90-96.

# Developing Road Performance Measurement System with Evaluation Instrument

Kati Kõrbe Kaare, Kristjan Kuhi, and Ott Koppel

***Abstract*—**Transportation authorities need to provide the services and facilities that are critical to every country's well-being and development. Management of the road network is becoming increasingly challenging as demands increase and resources are limited. Public sector institutions are integrating performance information into budgeting, managing and reporting via implementing performance measurement systems. In the face of growing challenges, performance measurement of road networks is attracting growing interest in many countries. The large scale of public investments makes the maintenance and development of road networks an area where such systems are an important assessment tool. Transportation agencies have been using performance measurement and modeling as part of pavement and bridge management systems. Recently the focus has been on extending the process to applications in road construction and maintenance systems, operations and safety programs, and administrative structures and procedures. To eliminate failure and dysfunctional consequences the importance of obtaining objective data and implementing evaluation instrument where necessary is presented in this paper.

***Keywords*—**Key performance indicators, performance measurement system, evaluation, system architecture.

## I. INTRODUCTION

ROAD networks are important lifelines for modern societies. Social prosperity and economic development are directly related to mobility and accessibility of communities and are, therefore, highly dependent upon the existence of high quality road networks. Currently, roadways are the dominant mode of transport, particularly in developed countries [1].

Trend towards greater public accountability and transparency in decision making has been an important characteristic of transportation planning, decision making, and organizational management during recent years [2]. One way of accomplishing that has been through the use of performance indicators. When monitored they, provide decision makers with some sense of whether their decisions are improving road network performance, quality and organizational productivity of the road authority. Through the monitoring of such indicators, officials, legislators, and the general public can follow the continuing efforts of transportation agencies to improve the performance and quality of the road network.

Performance measurement is understood as an instrument for improving the efficiency, effectiveness and objectivity of developments or projects, organizations and services. Performance measurement can enhance the transportation planning, programming, and budgeting process. Good planning and effective programming are necessary, but not sufficient in themselves proper feedback about performance during the lifespan of roads is also expected by policy makers and the public. They want to know what transportation agencies have done and are doing to address mobility, reliability, quality and safety issues.

Performance measurement provides data and analysis that validate the accuracy of transportation planning forecasts and affirms that decisions are leading to promised results. As public agencies face demands for greater public accountability, performance measurement and reporting help answer those demands. In order to make performance measurement a useful tool for improvement the gathered knowledge, must be carefully tied to the agency's mission and strategic goals regarding the development of road networks.

Performance measurement in the transportation sector has been applied in many different ways depending on the goals set by the country's governing body or transportation agency. Therefore in the road sector we have examples of performance being measured from various perspectives and for different reasons. Three most common approaches are: to assess the efficiency of road network, to assess current and future technical conditions of road infrastructures or to evaluate road agency efficiency with respect to provided services [3].

Road authorities collect and retain extensive datasets related to their services and the life-cycle of their infrastructure. It is important to note, that proper data collection, analysis, refinement and presentation is a prerequisite for using it and for reporting to a broader audience. Development of appropriate performance indicators is required for linking transportation and infrastructure data for road management. After the phase of data gathering and analyses and before implementing any changes for improvements an evaluation audit may be required to avoid making false or incorrect conclusions.

P. Smith [4] has presented that many of the expected distortions arising from reliance on performance indicator schemes, and concludes that they may have significant dysfunctional consequences. But at the same time he is against abandoning the performance audit in public sector. In this paper authors present the idea of including evaluation process to avoid dysfunctional consequences and suggest that great

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attention should be given to the incentives implicit in any strategic control scheme, and that the style with which the scheme is applied will have important bearings on its effectiveness.

The use of performance management system (PeMS) in conducting operational analysis, planning, and evaluation studies is described here. The database provides managers and officials with a uniform, comprehensive assessment of road network performance and furthermore engineers can base their operational decisions on knowledge of the current status of the network.

## II. PROJECT PERFORMANCE MEASUREMENT

### *A. Literature Overview*

Performance measurement has been widely promoted by governments for more than 20 years, for the express purpose of increasing management's focus on achieving results. It was introduced in Canada in the mid-seventies. At the beginning of such reform managers were advised to identify and report "performance indicators". In the last decade, interest has grown in the art and science of performance measurement, particularly as it applies to road and transportation systems. The topic is well documented in the literature with significant treatises from many organizations around the world, including the U.S Federal Highway Administration (FHWA) and the Transportation Research Board (TRB), the Organization for Economic Cooperation and Development (OECD), Austroads (Australia) and the Transportation Association of Canada (TAC) [1], [5]-[9].

Literature does not show agreed upon definitions and connections between performance indicators, performance measures and performance information [6]. The research and practice reports provide perspectives as to why performance measurement is important and what is typically measured. Integrating performance information into budgeting, managing and reporting has become a common component of good public and not-for-profit management [4], [10]-[11].

The theoretical models of Rogers, Prochaska & DiClemente and Gladwell provides a valuable framework for understanding why the use of performance measures is stalled (the circle of unaccountability) and for generating ideas about concrete steps that could be taken to accelerate adoption. Six steps are recommended:

(1) raise public awareness,
(2) redesign measures and reports,
(3) make the delivery of information timely,
(4) require public reporting,
(5) develop and implement systems to reward quality, and
(6) actively court leaders [12].

The recommended six steps are interconnected; action on all will be required to drive significant acceleration in rates of adoption of performance measurement and reporting. Coordination is necessary to ensure these steps are taken and that they work in concert with one another [12].

Collected performance information may be used as an input in performance measurement as well as in evaluation. The main difference between performance measurement and evaluation is that the first is a frequent, almost ongoing activity intended to improve the performance, often of an activity, service or organization, whereas evaluation is carried out on an either *ad hoc* or regular basis, with the purpose of independently questioning the relevance, quality and even appropriateness of a project, solution, service, policy or program [8].

Therefore, performance measurement tracks the network and its parts throughout the lifecycle. Whereas authors propose that evaluation should be an integrated part of the road network performance measurement system.

### *B. Importance of Evaluation in Performance Measurement*

In road network performance measurement, evaluation should complement and support the system. Evaluation and performance measurement share many of the same features with regard to structuring and planning, obtaining data, analyzing and evaluative judgment (see Fig. 1).

Differences as said in previous sub-chapter lie in the scope, depth, multiplicity and frequency of the tasks to be carried out rather than in kind. One may even argue that good performance measurement systems may help to highlight the themes and questions that evaluation studies should cover. Indeed, monitoring and evaluation studies should be seen as closely interlinked and complementary; monitoring providing data for evaluation and thus constituting one of several data sources, and evaluation being the necessary add-on to monitoring in order to focus on causality and deeper explanations conducted from time to time to qualify monitoring data.

Literature states that evaluation studies and performance measurement are highly complementary forms of knowledge production [10]. Evaluation tools can remedy a number of the shortcomings of performance measurement when applied in performance management and also contribute to research-based policy development. Improved technology has enabled monitoring and reporting systems to collect outcome data on a regular basis and thus measure performance in a more balanced and focused way.

Institutions sometimes draw conclusions from performance indicators and implement changes based on raw observations and output measurements and lead to unwanted outcomes. This automatic transformation into performance information has caused many performance measurement systems to fail [5] and therefore it is important to involve data analyzes and evaluation process into performance measurement.

Failure of PeMS is often described from organizational point of view. Bourne [13] has stated that there are three main blocking factors to implementation of the measures that refer to the road network performance measurement:

- the effort required;
- the ease of data accessibility through the IT systems;
- the consequences of measurement.

The measures may therefore prove inaccurate and these cannot be used to track the pathway to strategy execution. Information from performance assessment that should necessitate adjusting activities, do not bring this effect. Even improvement activities are undertaken these are not based on the facts collected by the system. [13].

Contrary to performance measurement, evaluation can question the very relevance and appropriateness of the development, program, project or solution and as such identify unintended as well as expected and planned results. It can further explore the reasons for the documented results. In this sense, evaluation has a deeper heuristic and penetrating nature than performance measurement.

The tool to collect data mirrors the different roles of evaluation and performance measurement. Evaluation, besides being used for management and accountability purposes, is also used to determine causality. In performance measurement, the production of data is carried out through routinized processes, whereas in evaluation studies data collection is customized to the needs of the single study only, data collection is structured specifically to test hypotheses or the question of attribution.

Therefore evaluation studies need to be designed in a way that provides the best possible evidence to answer the attribution question. The key consideration for performance measurement is to generate data on indicators that drive performance through changing the behavior of those involved. The analyses made aim to improve in performance measurement and finding reasons providing the necessary changes is done by evaluations.

As has been stated, performance data feeding back into the program organization needs to be analyzed in order to identify the contextual evidence that may explain good or poor performance. It is thus important that performance data is reported on the basis of balanced assessment. Evaluation audits are a tool to help in creating such assessments.

Performance measurement has a wider scope, lesser depth and they gather data collection is continuous. Evaluation audits are supporting measures of the PeMS and good PeMS helps to highlight themes and questions that evaluation studies should cover.

### *C. Data availability in Road Authorities: the Example of Estonia*

The Road Administration Agency in Estonia currently does not have a compound broad-based system for Road Network Performance Measurement. There is a demand to receive feedback information about life-cycle performance about specific road construction projects or even in detail about specific road sections. There are currently three larger databases in use:

- Road Register;
- Pavement Measurement System (PMS), that gathers information about International Roughness Index (IRI) and other technical details;
- Smart Road database – comprising information about traffic, safety, traffic signs, traffic restrictions *etc*. [15].

Information from these databases is not available to the stakeholders without substantial effort and further processing. Therefore the aim of this research is to list current problems with feedback from road construction projects and network performance and to identify all potential stakeholders. Using a recommended list of key performance indicators a united platform of performance measurement system is presented [15].

There is no one measure, or one set of measures, that could be identified as the “best” for all cases. Furthermore, although there are many common issues to be considered, there is not just one good way to develop a set of performance measures or establish a PeMS. In each case, the performance measures used must depend on the specific conditions of an agency, its goals, its resources, and its audience. In case of Estonia the authors have suggested focusing on measuring technical data to get feedback in improving quality and sustainability.

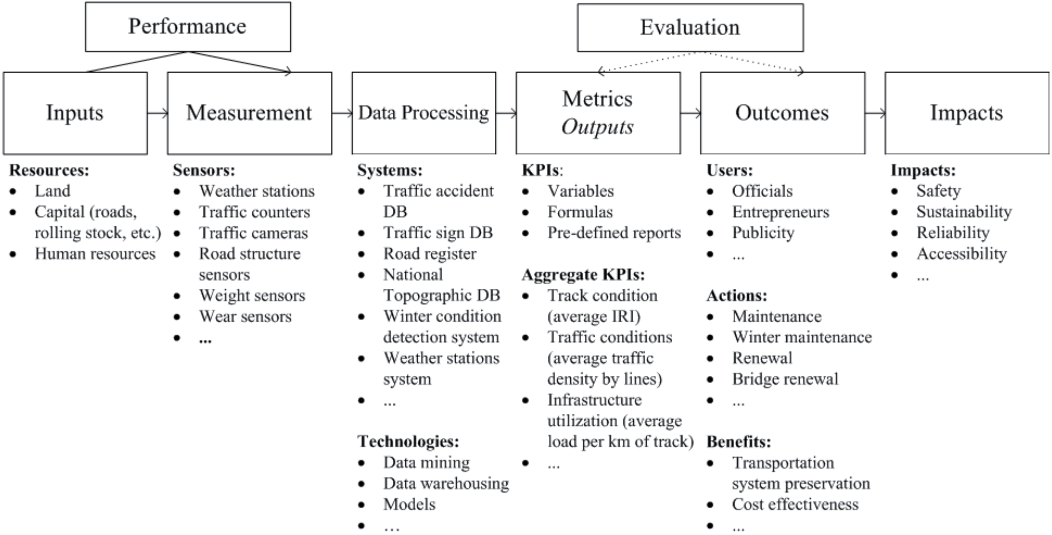

Fig. 1 General Framework of the Road Performance Measurement Process (compiled by author’s based on [8], [14])

## III. SYSTEM DESIGN

### A. *General Requirements for the System*

To improve performance for the benefit of users, it is critical to implement processes that enable the assessment of operations. Performance assessment methods must be both reliable and credible and must serve as a means of changing how things are done. It is thus advantageous to establish specific performance indicators, methods of analysis and evaluation, as well as structured and quantified quality plans. Some of the major reasons for adopting performance include:

- Accountability: performance measurement provides a means of determining whether resources are being allocated to the priority needs;
- Efficiency: performance measurement focuses actions and resources on outputs and the process of delivery;
- Effectiveness: performance measurement provides a link between ultimate outcomes of policy decisions and the more immediate actions of transportation agencies. It provides a means to evaluate how well we are achieving our goals;
- Communications: performance measurement provides better information to customers and stakeholders on progress being made toward desired goals and objectives;
- Progress: performance measurement allows periodic refinement of programs and service delivery [16].

### B. *Performance Metrics*

Performance indicators are required for eight different purposes of use: evaluation, control, budgeting, motivation, promoting, celebrating, learning and improvement. Roles of PeMS in road management are:

- The internal efficiency of the road administration.
- The quality of the administration’s products and services.
- The outcome for the road transport system.
- The consequences for society.
- Any particular process or learning exercise for a specific engineering task.

Therefore, questions that the PeMS tried to answer are [17]:

- Has the specific road been designed and built to be sustainable during its estimated life span without substantial reconstruction. If reconstruction has occurred has it been due to factors that were not predictable during the designing process?
- Do the current Road Design Guidelines ensure given 15 year durability for new constructed roads that?
- Do the current Road Designing Guidelines rely on proven test results and data?
- Are the financial allocations based on priorities, the funds used rationally and in the most needed areas? How is the evaluation of priorities carried out?
- Does the system take into account the estimated volume of traffic in choosing the suitable design? Does the road comply to the approved design?

A key component of the most successful road projects and programs is a well-defined set of goals and objectives. However, the use of performance indicators goes beyond evaluating the degree to which goals and objectives have been achieved.

The use of performance indicators by a road administration depends on the particular needs for development or improvement in performance (see Table I). The main aspects that influence decisions on the use of performance indicators are:

- The main characteristics of the road transport vision in the country.
- The position of the road administration in the process of organizational reform.
- The specific functions that require development or learning
- The management style of the organization.[5].

### C. *Data Obtaining Tools*

The Performance Management requires physical measurements of different characteristics on field to calculate key performance indicators (KPI-s). Measurement data can be feed into the system in three different ways:

- Directly via environmental sensors.
- Manual measurements on field.
- *Via* other information management systems.

The data collection architecture depends on the data flow characteristics for each type of measurement.

Sensors feed the collection system with constant flow of values depending on the traffic load distribution in time domain on the measured road sections. During peak hours the data flow amount grows equivalently with traffic volume. The backend data collection system hardware and communication channels must be dimensioned accordingly to accept the

TABLE I
DETERMINATION OF ERA’S PERFORMANCE METRICS (EXTRACT)

| Stakeholder | Aggregate KPI-s | KPI-s | Variables | Data Source |
|---|---|---|---|---|
| Road maintenance department | Road technical condition | Average IRI (International Roughness Index) per km of track | IRI<br>Road section length | PMS<br>Road register |
|  | Infrastructure utilization | Average load per km of track | Rolling stock weight<br>Road section length | Weight sensors<br>Road register |
| Traffic management department | Traffic density | Average traffic density by lines | Traffic modal split<br>Road sections length | Traffic counters<br>Road register |
| Traffic safety department | Traffic safety | Traffic accidents per km of track | Traffic accidents and accident classes<br>Road sections length | Traffic Accident Database<br>Road register |

sensor data.

Entering manually measured and collected information is typically less computing heavy and affects the system setup minimally. At the same time, there might be also measurements that require more resources for information extraction (e.g. images).

The integration with other Information Management Systems must be taken into account when designing the architecture of the data collection system. It is constructed in a way that supports effortless integration with any number of third party systems in the south-bound interface.

The physical server architecture hosting the data collection depends on the data feeding requirements towards other systems and on the amount of deployed sensors. Prearranged level of operational performance requirements state high availability requirements for the architecture. Load balancing techniques must be used to distribute workload across multiple servers to achieve optimal resource utilization and avoid overload of the computational nodes.

Additional local or regional aggregation layer may be reasonable to introduce when large amount of data in feed into the system. Aggregators do certain amount of data pre-processing in the location where the combined sensor event series are created before sending the values to PeMS. It will reduce the event load to central system. To save computing power and the data transmission channel it is reasonable to do the data format transformation in aggregation node. For the same reason pattern matching techniques for data filtering and aggregation are recommended to add into aggregator.

Information Collector functionality includes the ability to transform process, aggregate, query, store and dispatch sensor data streams. The Complex Event Processing (CEP) platform [18] may simplify the processing of the sensor information. CEP is for querying and analyzing the sensor data stream, dig and publish the conclusion to third systems.

### *D. System Architecture*

Performance data does not tell us why the outcome occurred. Performance systems need to be designed in a way that they do not only gather , store and provide data outcomes (score), but they also need to have built into them opportunities to analyze the details of performance and steps to seek explanations for the outcome data such systems produce [12].

Performance indicator database collects all the measurements and stores them until required for the KPI reporting functionality. When the data is no longer needed, it will be removed from the live data schema and archived. Also the preparation, cleansing and consolidation of the data into different Performance Indicators are done there.

KPI-s are calculated based on the data in the Performance Indicator Database and calculation formulas. KPI formulas may be deterministic or probabilistic. Different authors ([9], [13]) have shown the applicability of Probabilistic Graphical Models (Markov Networks, Bayesian Belief Networks) in road performance index calculation. KPI-s may have multiple (aggregation) levels based on user needs. KPI-s are displayed in the User Interface showing the current situation or as historical trend. Drilldown from KPI value until the specific performance indicator or sensor value is needed to understand the root causes of different situations (see Fig. 2).

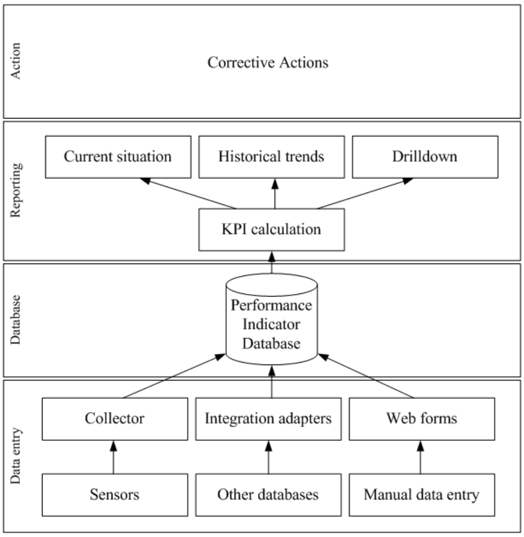

Fig. 2 PeMS architecture

Corrective actions will be taken in response the KPI shows deviation from the norm. The architecture enables systematic investigation of the root cause of the non-conformities to prevent their occurrence, recurrence or minimize the effect on the road performance.

Access control to the data collection system is controlled *via* security levels – an information consumer is only able to consume the data on the level to which it has been provided access, e.g. some users may only have access to aggregate and pre-processed data, while other users have access to data at the sensor level. The data access mechanisms stay the same, no matter what level access or to what data is requested and granted.

## IV. ROLE OF PERFORMANCE MEASUREMENT SYSTEM IN THE DECISION PROCESS

There is a significant role of performance measurement outcomes in strategic processes carried out by the transporttation agencies. They are listed as following:

- Resource allocation.
- Monitoring programs/projects/whole network.
- Strategic planning.
- Reporting to the elected officials.
- Reporting to the internal management.
- Reporting to citizens (and media).

One of the lessons that many countries and institutions (including Estonian Road Administration) have learned is the need for modesty. The difficulty of developing and using performance information, as exemplified by these challenges, should be recognized by all. Further, the role of performance information is one of informing decisions not determining them. There is a real need to educate the users of such information on how to use the information and on its possible interpretations and limitations. The need for experience and management skills will always remain at the center of public sector management [10].

The importance of sensible and informed use of performance information may be especially pertinent for budget decision-makers. There may be a temptation to use evidence of poorly performing programs but to ignore or question performance information about well-performing ones. Misuse here will send quite strong messages. Performance information will normally not be comprehensive, will contain some uncertainty; its role should always be seen as informing [19].

Performance measurement systems with accurate data are needed both when agency's face reducing of budgets or increases in funding. They can be used effectively to establish the need for increased funding with policy makers and the public. Performance measures provide valuable information to communicate with policy makers on transportation funding needs. Performance measures provide an important mechanism to communicate planning and programming results to decision makers and the public.

The PeMS should also help to addressing the overall need or rationale for why any decisions are made and to be a tool to help the agency to do the best possible job given the circumstances, resources and constraints, consistent with the overall mandate. Performance measurement is needed for the network to function as a whole. Performance management should be an ongoing activity for road network agency. The use of performance measurement information will help set agreed-upon performance goals, allocate and prioritize resources, inform road network operators to either confirm or change current policy directions to meet those goals, and finally, report on the success of meeting the goals set.

In order to make performance measurement a useful tool for improvement the gathered knowledge, must be carefully tied to the agency's mission and strategic goals regarding the development of road networks [4].

## V. CONCLUSION

Given the large amount of road transportation users globally, governments and road authorities are expected to plan and offer road networks with safe, convenient and efficient transportation services as well as adequate accessibility to communities.

This paper proposes system architecture of a road network performance measurement system that has the ability to gather knowledge from qualitative databases and if necessary uses data evaluation audits. With these additional steps the authors try to eliminate dysfunctional consequences and wrong conclusions that lead to a performance measurement system to fail.

The aim of this system is to produce results that improve the networks sustainability, durability and effective maintenance throughout the life cycle. This model of road network performance measurement provides a systematic framework where identifiable problems within specific stages in the area of road network performance are addressed, analyzed and solutions suggested. The primary focus is not the financial incentive but more on the continuous and responsive learning from feedback to gather knowledge for decision and policy process.

Author's point of view are, that the adoption and use of performance measures by transportation agencies can foster understanding, accountability, trust, support, and collaboration with decision makers and the public as well as improvement in the quality of road networks.

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# CURRICULUM VITAE

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| 2003 | Tallinn University of Technology | Tallinn School of Economics and Business Administration, MSc in Economics |
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3. Language skills

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| 2012 – | Tallinn University of Technology | Department of Logistics and Transport, researcher |
| 2011 – 2012 | Tallinn University of Technology | Faculty of Civil Engineering, project manager |
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| 2005 – 2009 | Ministry of Economy and Communications | Head of Building and Housing Department |
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5. Scientific Work

Papers in peer-reviewed journals

- Kõrbe Kaare, K., Koppel, O. Improving the Road Construction Supply Chain by Developing a National Level Performance Measurement System : the Case of Estonia. – *International Journal of Social and Human Sciences*, 2012, 6, 225-231.
- Kõrbe Kaare, K., Koppel, O. Performance Indicators to Support Evaluation of Road Investments. – *Discussions on Estonian economic policy : Current problems in the EU Member States*, 2012, 2, 88-107.
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- Kõrbe Kaare, K. Creating future urban environment. – *Think Tank on eGovernance Technologies : from applications to innovation, Shanghai, 31.10.2012.*
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- Kõrbe, K., Mäe, K. Hoonete energiakasutus kontrolli alla. – *Ehitaja käsiraamat,* 70-71. Tallinn : Presshouse, 2008.

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Kõrbe Kaare, K. Economic Comparison of fee-for-service and diagnose-related group Finance Models in Healthcare / A. Purju (Sup.) : MSc thesis. Tallinn : Tallinn University of Technology, Tallinn School of Economics and Business Administration, 2003.

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- 20th International Conference on Urban Transport and the Environment, 28-30 May, 2014, The Algarve, Portugal (member of the International Scientific Advisory Committee).
- Development of MSc-level curricula “Supply chain management” and “Logistics” in cooperation between Tallinn University of Applied Sciences and Tallinn University of Technology based on the requirements of labour market.
- Multimedia dictionary of logistics and supply chain management in www environment.
- Review of annex "Highway desiging norms" to Regulation No. 55 of the Minister of Roads and Communication from 28.09.1999 "Norms of road design".

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### Eelretsenseeritud artiklid teadusajakirjades

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3. **Kent Arvidsson**. Analysis of Interacting Systems of Shear Walls, Coupled Shear Walls and Frames in Multi-Storey Buildings. 1996.
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14. **Alvina Reihan**. Analysis of Long-Term River Runoff Trends and Climate Change Impact on Water Resources in Estonia. 2008.
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17. **Alvar Toode**. DHW Consumption, Consumption Profiles and Their Influence on Dimensioning of a District Heating Network. 2008.
18. **Annely Kuu**. Biological Diversity of Agricultural Soils in Estonia. 2008.
19. **Andres Tolli**. Hiina konteinerveod läbi Eesti Venemaale ja Hiinasse tagasisaadetavate tühjade konteinerite arvu vähendamise võimalused. 2008.
20. **Heiki Onton**. Investigation of the Causes of Deterioration of Old Reinforced Concrete Constructions and Possibilities of Their Restoration. 2008.
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28. **Karin Pachel**. Water Resources, Sustainable Use and Integrated Management in Estonia. 2010.
29. **Andrus Räämet**. Spatio-Temporal Variability of the Baltic Sea Wave Fields. 2010.
30. **Alar Just**. Structural Fire Design of Timber Frame Assemblies Insulated by Glass Wool and Covered by Gypsum Plasterboards. 2010.
31. **Toomas Liiv**. Experimental Analysis of Boundary Layer Dynamics in Plunging Breaking Wave. 2011.
32. **Martti Kiisa**. Discrete Analysis of Single-Pylon Suspension Bridges. 2011.
33. **Ivar Annus**. Development of Accelerating Pipe Flow Starting from Rest. 2011.
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