Estonian Journal of Engineering, 2012, **18**, 4, 324–335 doi: 10.3176/eng.2012.4.04

Tire and pavement wear interaction monitoring for road performance indicators

Kati Kõrbe Kaare[a], Kristjan Kuhi[b] and Ott Koppel[a]

[a] Department of Logistics and Transport, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; {kati.korbe, ott.koppel}@ttu.ee
[b] Ericsson Eesti, Ltd., Järvevana tee 9, 11314 Tallinn, Estonia; kristjan.kuhi@ericsson.com

Received 23 August 2012

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_{ref} are axle loads and N_x and N_{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

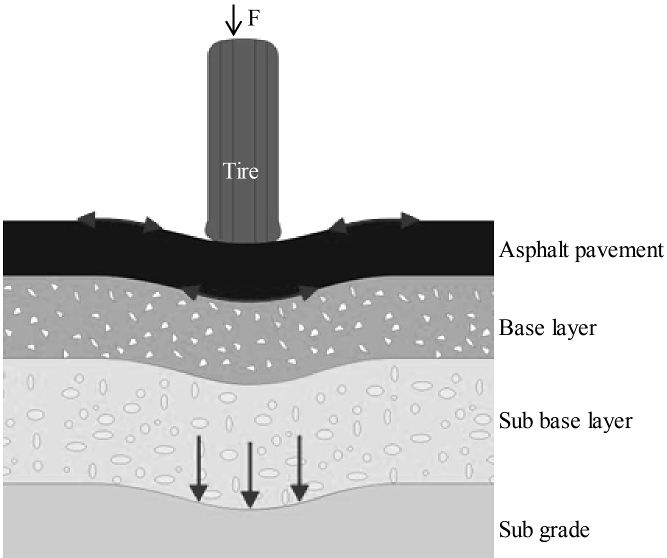

Fig. 1. Vehicle–pavement interaction [2].

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

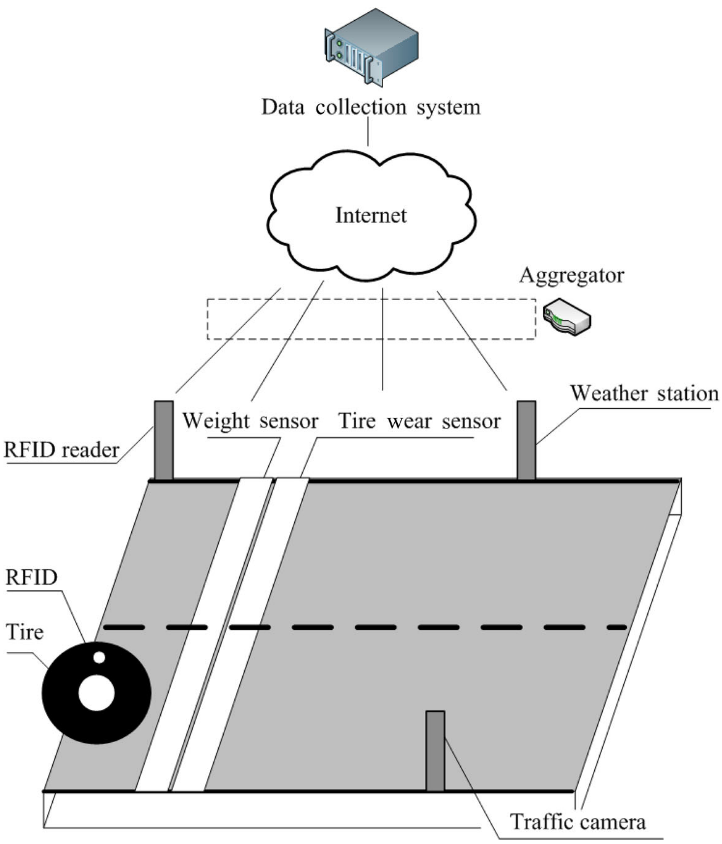

Fig. 2. System architecture.

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

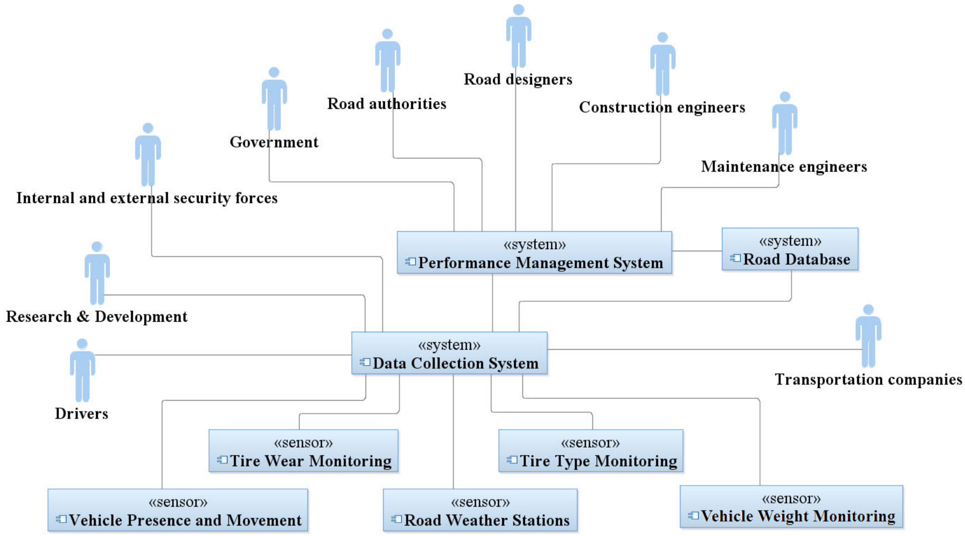

Fig. 3. Data consumers and the sensor-based performance management system.

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.

REFERENCES

1. *The Damaging Effects of Overloaded Heavy Vehicles on Roads*, 4th ed. Department of Transport, Pretoria, 1997.
2. Hjort, M., Haraldsson, M. and Jansen, J. M. *Road Wear from Heavy Vehicles – an Overview.* NVF committee Vehicles and Transports, Borlänge, 2008.
3. Thiriez, K. and Subramanian, R. Tire pressure special study: tread depth analysis. *National Highway Traffic Safety Administration Research Note*, 2001, October, 1–10.
4. Collop, A. and Cebon, D. Modelling whole-life pavement performance. *Road Transport Technol.*, 1995, **4**, 201–212.
5. Arnold, G., Steven, B., Alabaster, D. and Fussell, A. Effect on pavement wear of increased mass limits for heavy vehicles – Stage 3. *Land Transport New Zealand Research Report*, 2005, **279**, 1–118.
6. Haider, S., Harichandran, R. and Dwaikat, M. Impact of systematic axle load measurement error on pavement design using mechanistic-empirical pavement design guide. *J. Transp. Eng.*, 2012, **138**, 381–386.
7. Swedberg, C. Michelin uses RFID to track tire pressure and tread for London bus company. *RFID J. Online*, 2012, July. http://www.rfidjournal.com/article/print/9697, accessed 01.08.2012.
8. Holmes, J. British police may introduce tire tread cameras. *Automobile Mag. Online*, 2011, October. http://rumors.automobilemag.com/british-police-may-introduce-tire-tread-cameras-79083.html#ixzz22grtodf2, accessed 30.06.2012.
9. Einsiedler, I. *ThinkIO in Transportation*. Kontron, Munich, 2012.
10. Brey, T. A. *Tire tread wear sensor system*. U.S. Patent No. 7180409. Filed: March 11, 2005.
11. Manas, D., Manas, M., Stanek, M. and Pata, V. Wear of tyre treads. *J. Achievements Mater. Manufact. Eng.*, 2009, **3**, 538–543.
12. Zhang, W., Suo, C. and Wang, Q. A Novel sensor system for measuring wheel loads of vehicles on highways. *Sensors*, 2008, **8**, 7671–7689.
13. Tewolde, G. S. Sensor and network technology for intelligent transportation systems. In *IEEE International Conference on Electro/Information Technology (EIT) 2012*. Indianapolis, 2012, 1–7.
14. Wu, E., Diao, Y. and Rizvi, S. High-performance complex event processing over streams. In *Proc. 2006 ACM SIGMOD International Conference on Management of Data SIGMOD 2006*. Chicago, 2006, 407–418.

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.