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MONITORING VEHICLE – A BASIC ELEMENT IN MAINTENANCE PLANNING

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Abstract

Highways and bridges do not only have to be built, but must also be maintained to preserve their operational reliability. Concrete as well as asphalt pavements are exposed to many types of environmental impacts such as solar radiation, humidity, frost, de-icing salt, and of course traffic loads. Commonly used visual inspection methods are very time-consuming, costly, and only appropriate for local examinations. In this contribution, a mobile damage detection vehicle with mounted sensors is presented. It permits to assess the condition of road surfaces at average driving speed. For detecting damages such as cracks or potholes, sensors such as high speed video cameras and 3D laser profilers and sensors for monitoring the surface and air temperature are necessary. They are discussed in detail in the paper. For analyzing the measured data, special referencing systems have to be implemented. Additional to the mentioned components and their individual advantages, there is the demand for software elements that allow a fully automatic damage detection system. These tools, in combination with environmental data collected by meteorological stations, are used based on correlation considerations to evaluate the traffic and environmental impacts to the surface of bridge pavements.

INTRODUCTION

All structures naturally existing or built by men are subjected to change during time due to many different processes ranging from solar radiation, humidity, and de-icing salt to traffic loads. This especially applies to highways and bridges. For maintaining a functional and reliable traffic infrastructure, not only the safety of the structures themselves has to be considered, but especially the road safety is also of importance.

In Austria the currently existing highways comprise different building standards, asphalt pavement, as well as concrete pavement. Some date back to around WWII. So the efficient assessment of an expressway's condition is crucial to all maintenance efforts.
Historically visual inspection methods have been and are still common. This means sending a specialist out to evaluate hundreds of kilometres of pavement. Although the assessment profits from the specialist's experience this

is very time consuming, costly and actually only appropriate for local examinations. Additionally some relevant parameters like tire grip can't be determined visually or would necessitate to temporarily close down the motorway. Consequently, means have to be derived to be able firstly, to quickly assess many kilometres of pavement, secondly, to do so without obstructing traffic, and thirdly, to consume as little manpower as possible.

PROPERTIES TO BE IDENTIFIED

The most essential parameters to be determined are related to traffic safety followed by indicators which help to decide, when a road section has to be repaired or rebuilt.

Tire Grip

The tire grip a pavement allows decreases over time mainly due to abrasion. How fast this process works depends on the used building materials, traffic load and the traffic flow. Road sections for example with many curves or parts where vehicles are more likely to decelerate show increased signs of abrasion. To guarantee traffic safety tire grip must not fall below a certain threshold. This is important to ensure safe braking distances especially when the pavement is wet. Consequently, the tire grip has to be monitored. Several existing monitoring vehicles are equipped to measure tire grip. The Austrian research facility "arsenal research" for example has developed a vehicle called RoadSTAR (**Road S**urface **T**ester of **a**rsenal **r**esearch) which is among other things, capable of determining tire grip with high accuracy using a 'modified tribometer from Stuttgart'(STURM). In this case an internationally standardised PIARC tire is being pressed against the pavement with a known force, the slip is constantly measured and thus the coefficient of friction μ can be calculated. With this tire grip measuring device, different states of braking like block, ABS and slip can be simulated and evaluated. Additionally the macro texture of the pavement is measured by RoadSTAR. Texture means the geometric fine shape of the road surface and contains form, size, and distribution of the aggregates (RoadSTAR, 2007). The measurement is carried out in individual profiles using a precision laser. From the collected profiles the 'middle profile depth' MPD as well as the 'estimated texture depth' ETD then can be calculated. Together with the coefficient of friction μ the calculation of the 'International Friction Index' IFI is possible and so allows an objective assessment of the tire grip with respect to international standards.

Lateral Profile

One other very important parameter for traffic safety is the lateral profile because it allows identifying lane grooves which seriously endanger the safety of moving vehicles. Especially when filled with water distinctive lane grooves increase the probability of aquaplaning and pose a grave danger. The reason for the development of lane grooves in concrete pavement mainly is abrasion and only leads to minor problems. Of much more importance are lane grooves in asphalt pavement which form in case of high surface temperature and high traffic load because the elastic modulus of asphalt is highly dependent on the temperature.

Most monitoring vehicles currently existing such as RoadSTAR, ARAN (Automatic Road Analyzer) or Rosan_{v} and Rosan_{vm} respectively (ARAN 2007 and Rosan 2007) are equipped to measure the lateral profile using several precision laser sensors or ultrasonic sensors alternatively mounted on a bar. Dependent on the length of the bar, the number of sensors and their alignment, the entire width of one lane can be covered in detail and the so recorded lateral profile can be used to determine the depth of the lane grooves and in combination with high precision gyros, also the cross fall of a road.

It is paramount that the bar does not exceed 2.5 meters so that the vehicle can be used on motorways without obstructing traffic. Additionally, the sampling frequency of the high resolution sensors has to be high enough to allow for average driving speed. Every solution requiring a stop for measurement is not suitable for use on highways.
One possibility to reduce the number of necessary sensors is a linear drive, as discussed later. By using fewer sensors mounted on an oscillating bar the entire width of one lane still could be covered depending on the velocity and acceleration of the used linear drive. In contrast to fixed sensor positions, every point of the lateral profile is being covered regularly. Figure 1 shows the principle layout of an oscillating sensor array.

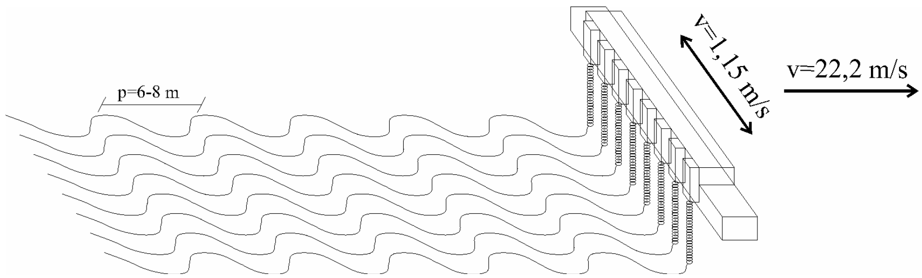

Figure 1. Oscillating sensor bar

Longitudinal Profile

The third essential parameter for traffic safety and driving comfort is the longitudinal profile. It too is recorded using precision laser sensors and allows determining two characteristic values – the ‘ride number’ RN and the ‘international roughness index’ IRI. In case of RoadSTAR and ARAN the longitudinal profile is recorded in the right and both wheel tracks respectively. Based on the longitudinal profile damages in expansion joints and displacements in construction joints due to frost can be detected. In combination with precision gyros, also the longitudinal gradient – a main property of the line routing – can be calculated. Naturally the recorded data from the lateral profile can also be used to determine the longitudinal profile but doing so requires assembling the measured data to a surface model of the road. For this, the exact position and inclination of each sensor in space has to be known with high precision at every time. This is rather difficult and the necessary calculations for generating a surface model are also rather computationally demanding. Thus, in most cases simply one reference sensor in one wheel track is used for the determination of the longitudinal profile.

Cracks and Damage to the Paving

Finally a monitoring vehicle must be able to detect damage to the pavement such as longitudinal cracks, lateral cracks, cracks corresponding to joints, and fine dispersed cracking. Figure 2 shows relevant damage types according to a paper by the Federal Ministry of Economics and Labour of the Republic of Austria (Straßenforschung, 1998).

The detection of cracks is much more demanding than determining a longitudinal or lateral profile. Most existing mobile monitoring systems use optical sensors in combination with special software developed for pattern recognition- so do both RoadSTAR and ARAN. In the case of RoadSTAR, a high resolution line scanner is used to record the surface and save the data as video stream. ARAN by contrast uses two high resolutions – high contrast photo sensors and stores the information as JPEG files. To eliminate all influence of shadows and to compensate for different luminance, a stroboscope which is synchronized with the shutter is often utilized. In both cases a lot of data is generated, which has to be stored and processed. The deployment of two photo sensors covering the same area on the road from different angles, offers the additional possibility to measure, for instance crack length, using the principle of stereo vision. Analyzing the data by hand is only possible for very short sections. In practice, automatic crack detection software is utilized to efficiently analyze the recorded data. Based on the so prepared data, a human operator can validate the results applying expert judgement and ensure the quality of the generated report.

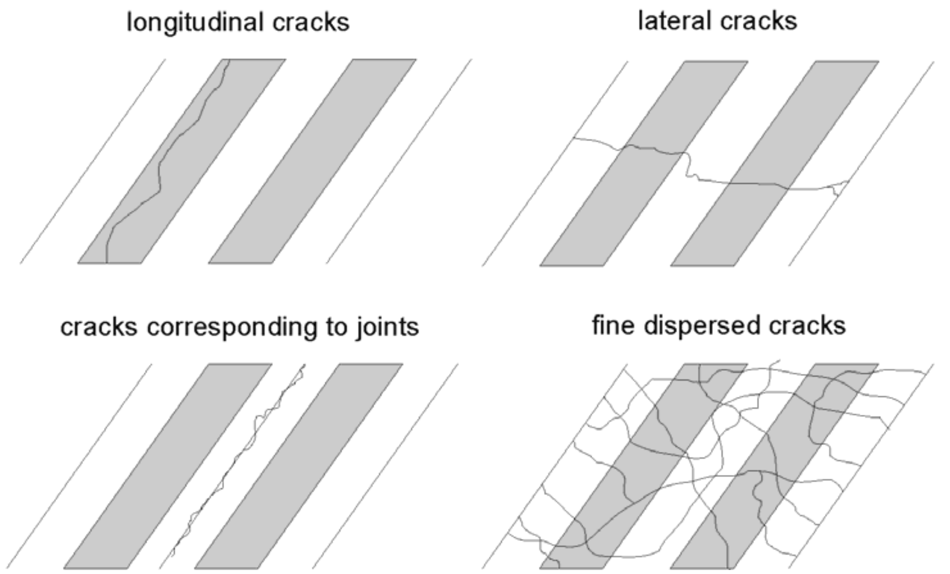

Figure 2. Damage types (Straßenforschung, 1998)

Detecting damage that already exists is important for efficient maintenance planning, but anticipating damage in critical areas allows for even better planning. In some cases, damage might be repaired before it poses a serious and expensive problem.

In Austria, there has been much research on typical damage processes. Some critical factors and processes could be identified to be surface-temperature, succession of frost and thaw and the amount of water present on the road according to a paper by the Austrian Federal Ministry of Transport, Innovation and Technology (Straßenforschung, 2001). Particularly, the influence of frost and deicing agents are highly significant in Austria due to its geographical and climatic characteristics.

Based on these facts, monitoring systems should not only focus on determining the state of the paving but should also try to cover some of the main influence parameters for damage such as surface temperature or amount of water on the road.

DEMANDS ON MONITORING SYSTEMS

Every sensor discussed up to now produces data of its own, which is of little use until referenced to each other and absolutely to the current position of the vehicle. This is especially important for the individual recorded image frames and the measured distances using laser and ultrasonic sensors respectively. Only then, a useful interpretation of the stored data is possible.

Basically there are two possibilities for determining the current position of the monitoring vehicle. Firstly, the revolution speed of the tires can be recorded and used to calculate the position. The main advantages are the low costs and complete autonomy. The cons are a reduced accuracy due to tire slip and the dependency on the tires' diameter. Consequently, the position measurement system has to be calibrated regularly. A more common solution is the use of a differential global positioning system dGPS combined with an inertial navigational system INS- used by both ARAN and RoadSTAR. Simply put, the GPS device determines the position which can be improved using realtime dGPS correction data and information from the inertial sensors. This allows for a rather precise determination of the position of the moving vehicle and additionally provides the inclinations in space necessary for reverencing the data recorded by other sensors. However this system can not be used in long tunnels because it needs a line of sight to at least four GPS satellites and the realtime dGPS correction data is chargeable.

Processing data recorded by several different sensors is very difficult. One way to simplify this task is the use of a precise trigger mechanism which ensures that the data recorded each time step is measured exactly at the right time. Photo sensors and stroboscopes for example have to be synchronized and are ideally triggered, dependent on the velocity to save redundant data.

As already discussed, a mobile monitoring system should not obstruct traffic. In Austria, the limit for trucks on highways is 80 km/h corresponding to 22.2 m/s or 49.7 mph which should be the design speed for a monitoring vehicle. Dependent on the desired resolution, high sampling frequencies for all sensors are required. Unfortunately high resolution, accuracy, and sampling frequency constrict each other. So a compromise has to be made when choosing an appropriate sensor to meet all requirements.

If you imagine surveying several kilometers of road and using several different sensors and even photo sensors, you will realize that the produced amount of data at average driving speed is huge. The demand on the hardware for simply acquiring and storing all the data is excessive, not to mention the real time evaluation of some of the data. Hence, most of the evaluation has to be done in post-processing and at least some degree of automation is required to be able to deal with all the recorded data. For this purpose special software has been developed by different companies mainly aimed at referencing the recorded data and pre-evaluating it with respect to some defined thresholds and parameters. A human specialist still is necessary to set them and control and interpret the prepared data. Based on a final report by the human specialist and the acquired data, a useful and efficient maintenance strategy can be derived.

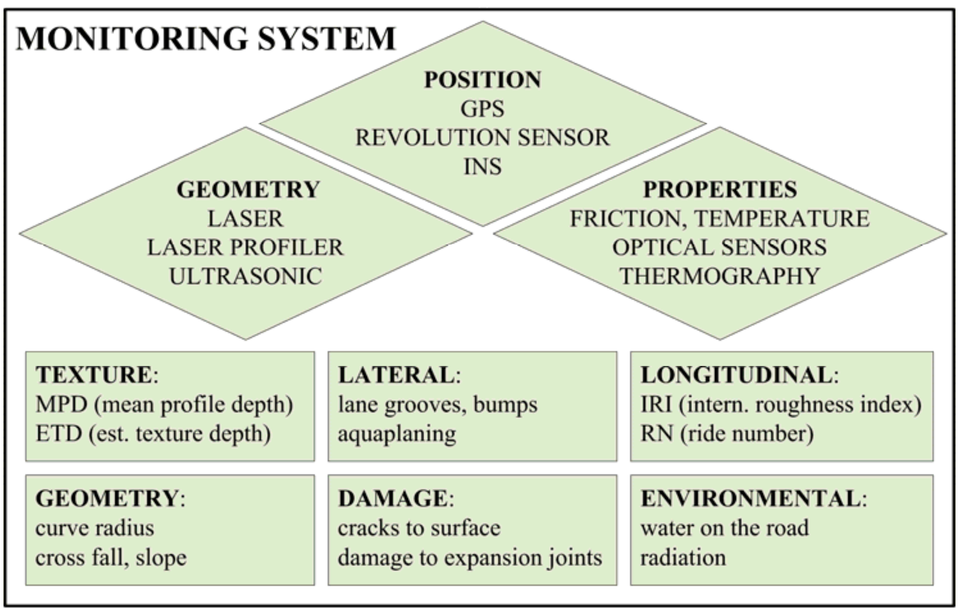

Figure 3. Components of a monitoring vehicle

POSSIBLE IMPROVEMENTS

Many different sensors are necessary to get the important parameters to describe a road's state and deduce a useful maintenance plan, most of which are already covered by existing monitoring systems. Of course improvements are still possible.

Using a laser profiler instead of a sensor bar equipped with laser sensors for instance, could increase the achievable resolution of the generated surface model. A laser profiler consists of a high resolution laser sensor rotating at high speed which enables the system to cover not only the entire width of one lane but also the marginal strip and the entire area around the vehicle. In the case of tunnels, additionally the state of the tunnel itself could be determined. Apart from that, no bulky bar would have to be used.

All currently existing monitoring vehicles are very complex, expensive, and not really suitable for the sole use of one road operating company. Alternatively, a mobile frame carrying a reduced number of sensors which could be mounted on several multi-purpose vehicles is an alternative. This way, the operating company would be able to shorten the interval between single inspection runs for certain more sensitive parameters while saving the costs for a full inspection and thus gain more information for maintenance planning.

As discussed earlier, it also would be very interesting to get information about influence factors that could lead to certain kinds of damage. Thus, damage could be anticipated and repaired at an early stage. Relevant parameters are air and surface temperature which can easily be measured by the monitoring vehicle along the road. Based on air und surface temperature, the solar radiation can be calculated, which provides in combination with stationary meteorological stations, all necessary environmental data for analysing correlations between environmental impacts and damage to the paving.

An additional inspection tool that will be considered during the set up of the mobile monitoring vehicle is infrared thermography. This technology uses special imaging chips that are sensitive to infrared radiation, which ranges from about 750nm to 15µm wavelength and follows the visible light which signifies electromagnetic radiation between 400 and 700nm. Part of this IR spectrum – the range between 8 and 12µm – we perceive as heat. Based on Planck's law of black body radiation, every object emits electromagnetic radiation at all wavelengths dependent on its temperature. Between the peak of the emission spectrum and a body's temperature, there is an inverse relationship according to Wien's displacement law. Thus, using more than visible light yields additional information for damage detection. Damage within the paving for example affects thermal radiation and so can be identified.

Due to the fact that this kind of device works contactlessly it can also be used on moving vehicles. It is of special interest whether detected damages to the surface correlate with damages in the pavement.

OUTLOOK

A monitoring vehicle is an essential part of maintenance planning. It not only provides the necessary information to identify relevant damages to the paving and sections which might pose a danger to traffic safety, but it also provides data about the state of the paving, possible damages to an engineering structure supporting a subsection and environmental data. Based on this data, correlations between different properties will be identified and used to detect damage in an early stage or identify areas which can be used as indicator for the overall condition of road sections. This could extremely simplify efficient maintenance planning and cut costs.

As already mentioned above, there is the demand to investigate the dependency between the ageing effects of the structural surface (pavement, surface of the structural components) and the internal physical properties of a structure. Based on data form the proposed monitoring vehicle, thermography devices and together with environmental conditions and the results of dynamical and traditional inspection methods detailed correlation considerations can be performed.

Basically there are three approaches considered, kendall tau or Spearman correlation coefficient respectively, sensitivity factor based correlation approaches, and neuronal nets. Kendall Tau is a non-parametric, rank-order correlation and provides a distribution-free and robust measure of the statistical correlation between two variables (Kendall and Gibbons, 1990) and (Samra and Randles, 1988). Sensitivity factor based approaches are based on sensitivity considerations between inputs and outputs of a model, a process etc. and in consequence allow the systematic fitting of an assumed model to real data, one kind of these approaches is developed at BOKU University (Strauss et al, 2006). Artificial neuronal nets (ANN) are the attempt to numerically model processes of the human brain. Basic information about ANN, can for example, be found in Cichocki and Unbehauen (1993). The main advantage of neuronal nets lies in their ability to describe rather complex relations between different variables that can not be described using analytical expressions. Working with neuronal nets essentially comprises two phases. Firstly – in the adaptive phase – the net has to be trained using ordered pairs of known input and output variables, for example water on the road and damage to the paving. During this process the weights of connections between the different neurons are optimized to best reproduce the used data. In the second – the active phase the ANN applies the learned relations to new data, for example water on the road, and identifies areas of potential damage.

Since data obtained from measurement programs are scattering and large in their amount, a special data acquisition and preparation routine will be necessary to make these correlation tasks practicable.

Apart from trying to correlate environmental data and damage to the paving, both approaches discussed will also be used to investigate the influence damage to the paving has on the dynamic behavior of an engineering structure like a bridge. It will be very interesting whether correlations between condition and structural safety (surface condition vs. internal condition) can be found or not. If any significant correlations can be determined, many improvements to monitoring strategies and maintenance planning of structures will be feasible.

In the near future, RoadSTAR will be used to assess a short section of the Brenner highway, the Colle Isarco Viaduct. Based on these results, environmental data, and together with the also performed dynamic measurements, the methods presented will be applied and results available soon.

Additionally the Autostrada del Brennero s.p.a is working on a small modular monitoring system of its own with a reduced number of relevant sensors, which will be tested shortly.

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REFERENCES

1. RoadStar (2007). http://www.arsenal.ac.at/roadstar/, link visited February 24, 2007.
2. ARAN – Automatic Road Analyzer (2007). http://www.transview.org/aran/, link visited February 24, 2007
3. Rosan v (2007). http://www.tfhrc.gov/hnr20/rosan/rosandoc.htm, link visited February 24, 2007
4. ‘Langzeitverhalten von Straßenbefestigungen (Schlussbericht des Managementkomitees der COST- Aktion 324) ‘, Straßenforschung Heft 472, (Bundesministerium für wirtschaftliche Angelegenheiten, 1998) 79-86.
5. ‘Klimakenngrößen für den Straßenoberbau in Österreich‘, Straßenforschung Heft 507, (Bundesministerium für Verkehr, Innovation und Technologie, 2001) 26-32.
6. Kendall, M. and Gibbons, J. D. ‘Rank Correlation Methods.’ Edward Arnold, fifth edition (1990).
7. Samra, B. and Randles, R.H. ‘A test for correlation based on Kendall's tau.’ in ‘Communications in Statistics - Theory and Methods’, 17, (1988) 3191-3205.
8. Strauss, A., Bergmeister, K., Lehky, D., Novak, D. ‘Inverse statistical nonlinear FEM analysis of concrete structures’. In ‘Meschke, G.; de Borst, R.; Mang, H.; Bicanic, N.: Euro-c 2006. Computational Modelling of Concrete Structures., 27 - 30 March 2006, Mayrhofen, Tirol, Austria’, (Taylor Francis, London, Leiden, New York; 2006) 897.
9. Cichocki, A., Unbehauen, R. (1993). ‘Neural networks for optimization and signal processing’. (John Wiley & Sons Ltd. & B.G. Teubner, Stuttgart, Germany, 1993).