Technological and market-oriented development of measuring systems

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Summary

For the evaluation of traffic noise as well as surface properties of road surfaces, a range of normative procedures are available which have been applied for years. The measurement systems used continuously develop further. Starting points for the enhancement of measurement systems are new technological possibilities as well as changing market demands. The measurement systems become more objective, precise and efficient – outdated procedures are being replaced during this development.

As an example serves the determination of texture depth which has developed from simple and imprecise sand patch procedure over laser texture systems (stationary as well as mobile systems on vehicles) to self-propelled and highly automated systems which allow measurement and analysis of surface texture in real time.

The paper gives an overview of the existing common measuring systems including texture and statistical pass-by systems and their development in the past, present and future.

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1. Introduction

For the determination of tire-road-noise and road traffic noise in general, a number of measurement procedures are available and some of them are described in detail in standards. Additionally, there are measurement systems to determine certain acoustically relevant parameters of road surfaces such as surface texture.

All of these systems are in a continuous development process to optimize their practicability and to make the results as objective and reproducible as possible. Enhancements in measurement systems are typically driven by so called accelerators in the innovation process.

External accelerators mostly drive this continuous development, such as:

- Technological possibilities: e.g. the availability of new types of sensors, analyzers, or other soft- and hardware components as well as new algorithms.
- Standards requirements: E.g. new versions of given standards including changes in measurement processes, calibration procedures and data evaluation to increase data quality.
- Customers' needs: e. g. increasing demand for measurements, increasing demand to quality, increasing competition in the market or new safety regulations.

Such accelerators allow for enhancements of measurement systems. The here proposed continuous development has proven to be a relevant methodological concept in modern management. The original concept was developed in Japan under the named Kaizen [1], in Europe it is mainly known as "continuous improvement process" (CIP) [2]. Figure 1 gives an overview for such an innovation framework.

Enhancements in measurement systems can either be to improve the efficiency, the data quality or the safety:

- Efficiency:
  - Setup time: to reduce the time to set up the measurement system in the

    field or to prepare the system in the planning phase.
    - Measurement time: to reduce the overall measurement time or the personnel needed to conduct measurements.
    - Evaluation time: to reduce the effort in evaluating the raw data.
- Data quality:
    - Representativity: to define the measurement process in a way that the measurement result is a sufficiently good representative of the present situation (i. e. the data allows to draw a conclusion for the whole situation).
    - Repeatability: to measure all relevant environmental conditions and to consider them within the evaluation. This point is contradictory to the above-mentioned point Efficiency/Evaluation time and must be handled with a lot of experience and care. A measurement procedure that needs many “correction factors” is often either not very straight forward or the correction factors cover a deeper problem in the measurement process itself.
    - Sensor quality: to use cutting-edge sensors to optimize data quality.
    - Calibration: to optimize calibration procedures to increase overall precision.
- Safety:
    - System Stability: to ensure a high stand-by time and as little downtime as possible.
    - Operator safety: to decrease the threats on the operator. This can mean to reduce the personnel needed for a specific measurement, to reduce the attention required by the measurement system, to optimize the measurement process and to ensure that the operator does not need to enter critical zones (e. g. on/next to high speed roads).
    - 3rd Person safety: to decrease the effect of the measurement on 3rd persons and regular traffic, respectively.

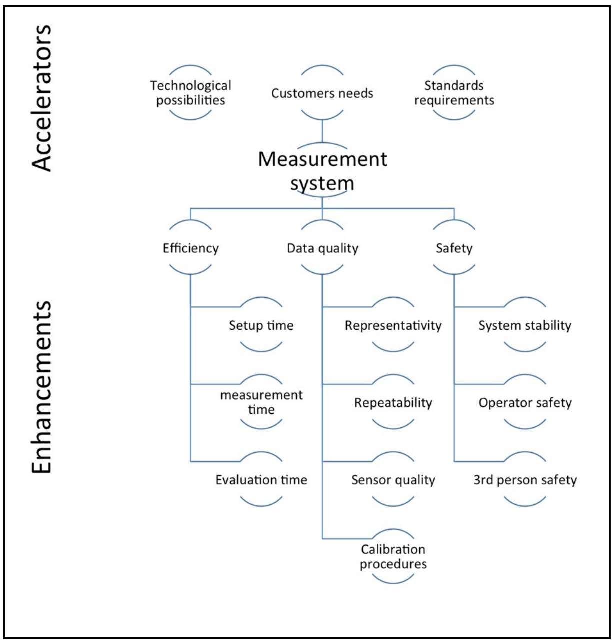

Figure 1. Innovation framework for the development of measurement systems.

Such enhancements range from small changes in the hardware increasing the practicability to a total redesign in soft- and/or hardware.
Typically, a number of smaller optimizations following the CIP concept follows a larger redesign. After several years in operation, smaller optimizations cannot be as effective as another fundamental redesign (compare to figure 2). This is comparable to consumers’ electric market: A new OS is launched and continuously optimized up to a certain point where a new main version is launched.

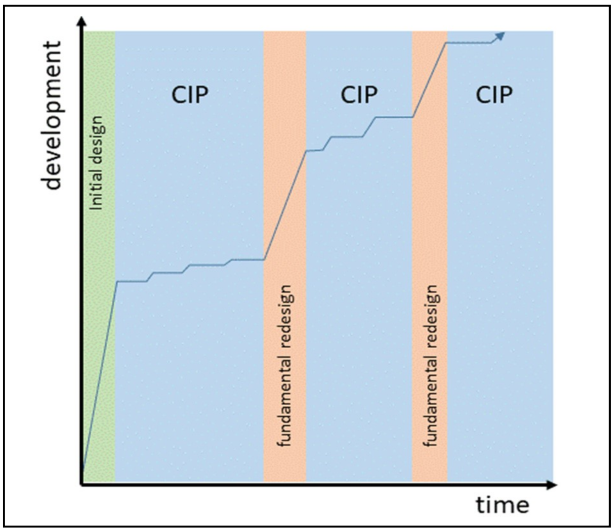

Figure 2. Typical development. Green: initial design. Blue: CIP (continuous improvement process) within the product lifecycle. Red: fundamental redesign at the end of a product lifecycle.

Sometimes also, the concept of the measurement can be changed completely within the phase of fundamental redesign (spot measurement vs. continuous measurement; accompanied measurement vs. autonomous measurement). Depending on the present situation, such changes can be in-line with the respective standards requirements or it can be shown that the results quality is higher compared to the recent standard.

2. Example 1 – SPB-measurements

2.1. General information

Statistical pass-by (SPB) measurements according to ISO 11819-1 [3] are typically combined with CPX-measurements. In contrast to CPX-measurements SPB-measurements enable to give an absolute value of tire-road-noise emission including the absorption characteristics of porous road surfaces and the damping characteristics on the early propagation path over the road surface.

SPB-measurements are the main method to derive noise reduction factors for different types of pavements. Thus SPB-measurements are an important tool in tire-road-noise investigations and in the development of low noise road surfaces in general.

2.2. Continuous improvement process

Early measurements were, more than 15 years ago, done with a sound level meter with max-hold function, a radar-gun and a simple weather station. These three systems were operated in parallel and the datasets were combined later on a spreadsheet. Basically, this method works according to the standard, but is very time consuming and error-prone. The operator does not have any feedback in the field, if the necessary 6 dB level-rise for each vehicle pass-by is reached and thus if enough valid datasets are collected in a certain time span. This means that some experience is necessary to operate such a "system" being not more than a combination of different sensors and analyzers.

A first larger innovation step was, more than 10 years ago, to combine the data acquisition of all sensors in one analyzer steered by one measurement program. This program was also able to e. g. detect the relevant 6 dB rise resulting from a vehicle pass-by, to delete invalid datasets (e. g. with too much ambient wind) and to do the complete data-analysis acc. to ISO 11819-1. Thus, it was possible for the operator to get a real time information about the measurements progress and to ensure that the dataset is sufficiently large compared to the requirements of ISO 11819-1 already in the field. It was not necessary to combine single sets of raw-data in the evaluation process – a closed process chain was built from measurement to final evaluation increasing data quality. It is clear that this development step touched almost all of the above-mentioned enhancements (compare figure 1).

After this first big step, a number of smaller improvements were implemented in the following years such as:

- Extension with computer-controlled camera to detect number plates of the measured cars for special evaluations.
- Consideration of different national standards like [4]
- Hardware-integration, to shorten installation process ("plug-and-measure")
- Add a functionality to measure bidirectional, i. e. both directions of a road in parallel or two neighboring lanes of a highway.
- Remote control of the system via "remote desktop", so that the operator can freely move in the area around the measurement spot.
- Rebuilding the code, so that it runs on an embedded system to minimize the whole system.
- Complementing the system with an internal battery to allow measurements without external energy supply.

Such smaller improvements allowed for an even higher efficiency and data quality. It was however recognized in the last years, that it is almost impossible to perform SPB-measurements in densely populated areas with a high and even further increasing traffic volume. The 6 dB rise of a single pass-by event cannot be achieved when the traffic is too dense. Even if single pass-by events can be measured, these are not statistically representative: The single pass-by events that show a 6 dB rise in a dense traffic situation are mostly those vehicles with a comparably high pass-by level (so that they are prominent within the surrounding traffic noise). Therefore, the basic premise for a Statistical pass-by measurement (i. e. statistical uniform distribution) is violated [5].

Complex measurement principles like beamforming, as described in [6], are in our opinion not a straightforward solution [7] to cover the problem of dense traffic. It is hard to control the complexity of such a system while it has to be kept in mind, that statistical pass-by measurements are very frequently requested by the market.

The only alternative is then to perform measurements in time-slots with a lower traffic volume [5], i. e. in the nighttime. This is in contrast to safety requirements for measurement personnel and regular traffic as equipment and staff is not clearly visible in the night. Additionally, the quality of measurements can be lower in nighttime measurements since the driver operation characteristics, the vehicle category and the environmental conditions cannot be monitored as well as in daytime.

This led to another major change of the measurement system. The whole process of statistical pass-by measurements was investigated and finally a concept for an autonomous statistical pass-by measurement system was developed.

This system, elaborately discussed in [8], uses a 3-microphone-array to determine the longitudinal and transversal position of cars passing by (microphone 1 and 2 are horizontally arranged, microphone 1 and 3 vertically). The longitudinal vehicle position is used to detect the position of the passing by vehicles along the road and to detect single vehicle pass-by events. This is done by evaluating the cross correlation of the horizontal microphone positions (compare to figure 3).

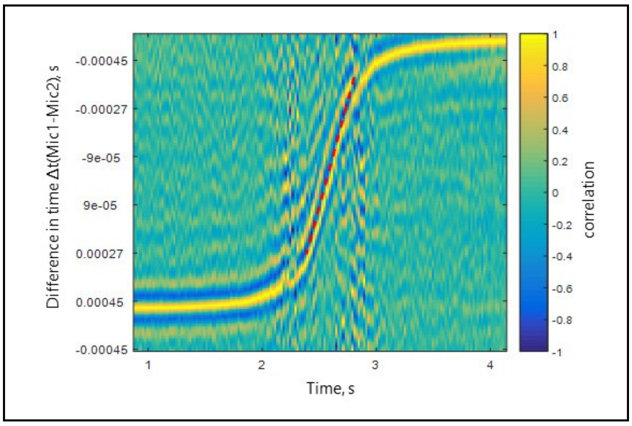

Figure 3. Typical cross correlation of the horizontally aligned microphones for a single vehicle pass by in the autonomous SPB-measurement system.

The transversal position allows determining the distance of the car to the microphones (i. e. the driving lane). The evaluation is based on the cross correlation of the vertically aligned microphones. Figure 4 shows the geometrical scheme for the measurements and the finally evaluated transversal position of several vehicles passing by.

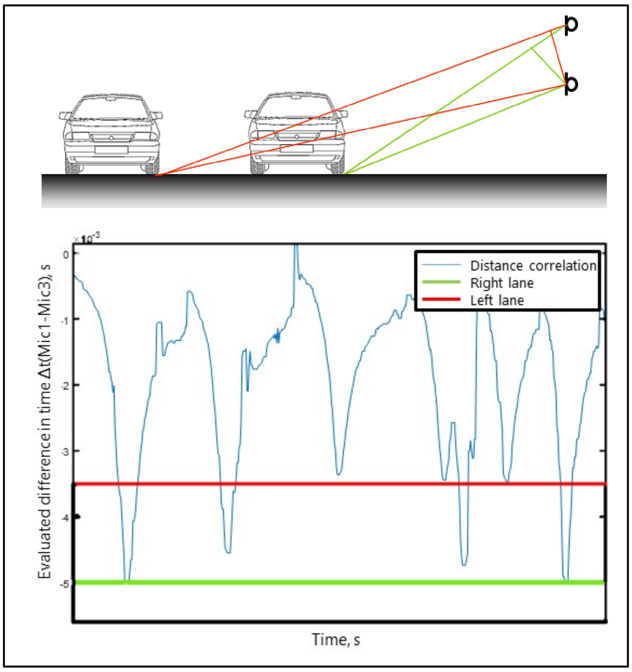

Figure 4. Geometrical scheme for the measurements to determinde transversal position, i. e. driving lane (upper picture) and evaluated transversal position of 7 vehicles passing by (lower diagram).

In the fully automated evaluation, a pattern recognition algorithm is used to distinguish between vehicle categories and to separate vehicles with atypical noise generation. It is – as a classical SPB-system – combined with a radar-system to measure speed and collects meteorological data. The pattern recognition algorithm works truly objective and ensures that all measurements are evaluated with the same precision.

Such a system can be installed in the evening, collects data over night and can be dismounted in the next morning. Within one whole night, typically 300 to 700 vehicle pass-by events are detected. This means that the population of datasets is much larger compared to a conventional guided SPB measurement.

2.3. Conclusions for SPB-systems and outlook

Within a timespan of more than 10 years, a first measurement system being not more than a combination of different sensors and analyzers was further developed to an integrated system that combines all relevant data-streams in the measurement and analyzes the data automatically. This system was improved over the years; it got lighter, quicker in installation and easier to be used. Finally, it turned out that the conventional SPB-process, as a guided measurement is not applicable with increasing traffic volumes. Therefore, the whole system was redesigned and fully automated. In the end an autonomous SPB-measurement system was developed. This system is now in its final validation phase and will replace the conventional system latest by the end of 2018. With the new autonomous system a larger datasets can be measured, the decisions that are normally done be the operator are done autonomously and thus much more objective.

The effective time consumption for one SPB-measurement dropped within this time dramatically.

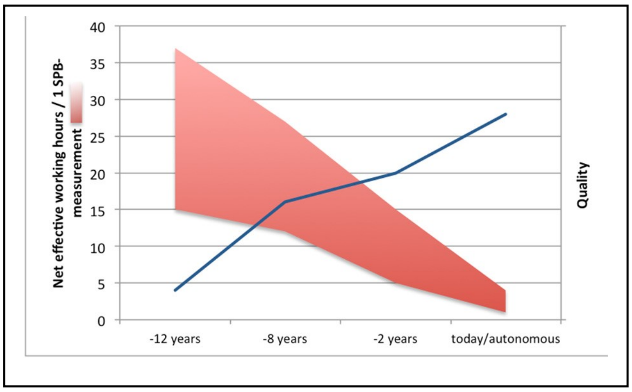

Figure 5. Time consumption and quality as a function of time in continuous improvement for one SPB-measurement within 10 years.

3. Example 2 – Texture measurements

3.1. General

Texture measurements e.g. according to [9] are a relevant tool to determine the acoustic performance of road surfaces. There is a number of parameters available that can be used to characterize road surface textures like the Mean Profile Depth, the shape factor, the mean peak shape and the spectrum. It has to be mentioned that texture parameters are widely used to define road surface specifications – this makes it extremely important that the definition of the parameters stays consistent and traceable over time – also if the standard is being revised.

3.2. Continuous improvement process

When describing the development process of texture measurement systems it is indispensable to start with the “sand patch”. It is clear that the sand patch method is not really a measurement method but more a rough estimate. However, since this method was still the main method described in ISO 10844 until the revision in 2011 was published, the description of the continuous development process starts here.

For more than 20 years, a number of optical and tactile systems are available competing the sand patch. The most common systems are laser-triangulation systems. They were in the past often mounted on a stationary, movable scanning frame, which moves the laser-sensor along the driving direction for several meters (typically about 2 meters). There are also some more exotic systems available that measure the texture on a circular or spiral-shaped path but due to the orientation of a rolling tire (along a straight path along the road), it is clear that such exotic systems cannot cover the application area thoroughly.

Texture measurement systems got very important in the last 5 to 7 years. In this time two main accelerators can be identified:

1. Porous, sound absorbing road surfaces are more and more replaced by dense low noise road surfaces. The acoustic performance of dense road surfaces is mainly depending on the surface texture.
2. In ISO 10844: 2011, the *MPD* value [9] is given as a specification and replaces the “sand patch”.

These two accelerators increased the market request to texture measurements dramatically and accelerated especially the development of vehicle-mounted systems. Vehicle mounted systems are relatively small and can be shipped easily from one site to the next. Depending on the use-case the measured data may be corrected for vertical vehicle movement before analyzing the data according to given standards. They allow also for high speed measurements as long as the used laser-sensor has a sufficiently high sampling rate, but they have also some disadvantages. They need, for example, a base-vehicle that travels them along the surface, which implies that:

- A car has to be available at the measurement site.
- The system has to be installed on a car – or the whole car including the system has to drive to the measurement spot.
- It is necessary to enter the measurement surface with a car – this can be a problem when measurements should be done directly after (or even within) the laying process of a road surface.
- It is hard to design them as a fully integrated system.

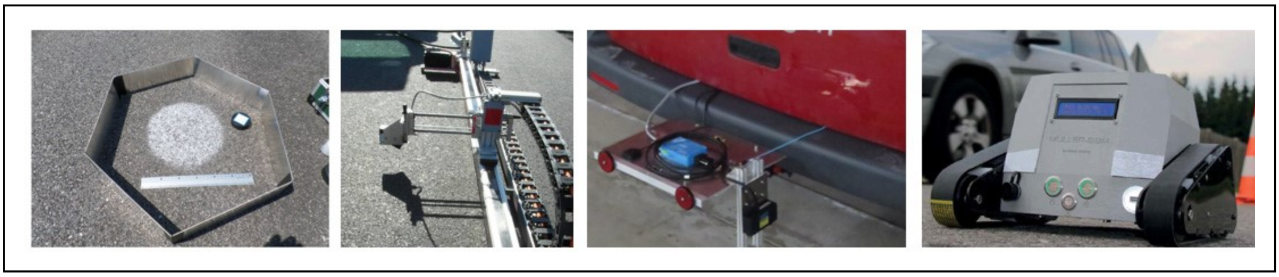

Figure 6. Development of measurement systems for texture measurements. From left to right: sand patch, stationary movable laser-scanner, vehicle mouinted laser-scanner, self-propelled multi-sensor-system surface drone.

These disadvantages of vehicle mounted devices and the ongoing globalization of the market for road surface measurements led to another fundamental development step.

The aim was to develop a system based on the following performance specification:

- Fully integrated: all sensors, cabling, data acquisition, data evaluation, user frontend (including some kind of display) and the mechanics to move the system should be integrated in one case.
- Easy to use: there is no need for intense user interaction. In the optimal solution no keyboard or similar should be necessary to operate the system.
- Portable: the system should be small enough to be taken as hand luggage on planes.

The given performance specification was very different to available systems, so that a complete redesign was necessary. It was necessary to redesign all components, soft- and hardware.

Prior to first feasibility studies, an indeep project scheme using the Theory of Inventive Problem Solving (TIPS) [10] was created.

Finally, a concept for a self-propelled, remote controlled measurement robot was chosen. The drivetrain is built as a belt drive. The chassis for the robot was customized to the performance specification and the special requirements for extensive use on road surfaces. Selective laser sintering was chosen as an adequate production method to allow for complex geometries. The cassis is designed as a multifunctional integral semi-monocoque construction.

This chassis allows integrating all relevant hardware elements like:

- Laser sensor
- Tilt sensor
- Surface temperature sensor
- GPS sensor
- Power supply (i. e. Li-Ion battery)
- Motor controller
- Electric motors
- Active system cooling
- Data acquisition and analysis unit
- Remote control receiver
- Velocity measurement system

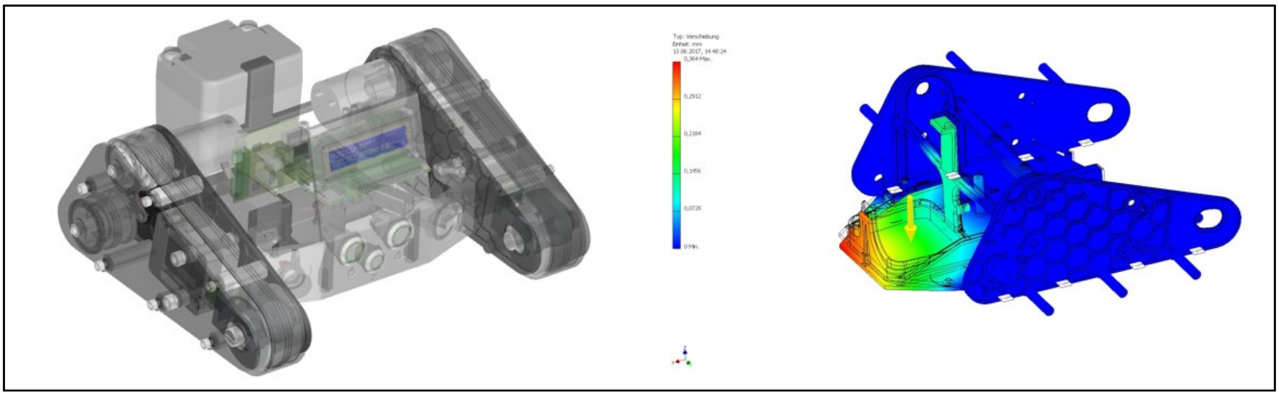

Figure 7. Self propelled texture robot. Left: CAD model of the system (shown without cover). Right: FEM result to determine the stress distribution in the semi-monocoque resulting from the power supply load.

The semi-monocoque was virtually designed and optimized in terms of stress and vibration using FEM.

It has turned out, that the realized belt drive allows for extremely smooth movement also on rough rigid ground. Calibration measurements on a trapezoidal calibration beam show maximum vibrational amplitudes in the range of 0.001 mm to 0.0026 mm.

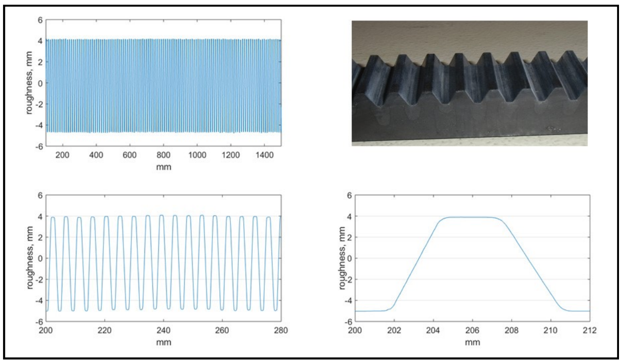

Figure 8. Rawdata from a surface drone calibration run in 3 different zoom levels and picture of the calibraton beam with trapezoidal shape.

3.2. Conclusions for texture measurement systems and outlook

Texture measurement systems have rapidly developed in the last years. While the main measurement principles (e.g. laser triangulation) have not changed dramatically, the practical application has developed quickly. The measurement robot surface drone is one result of this intense innovation cycle.

In the future, the demand for texture measurements will further increase. It was shown in the past that other relevant road surface properties like the rolling resistance are a function of the road surface texture [11]. This means that the determination of the surface texture might in future give enough information to estimate the rolling resistance.

Another example is tire-road-noise estimation: [12] shows that – within one type of road surface – it is possible to generate statistical models to derive tire-road-noise levels directly from surface textures. Comparable results were also derived for other road surfaces. Figure 9 shows the calculated noise levels using a statistical model compared to measured CPX-Indices [14] using tire P1 on dense hot rolled asphalt with a maximum chipping size of 5 mm.

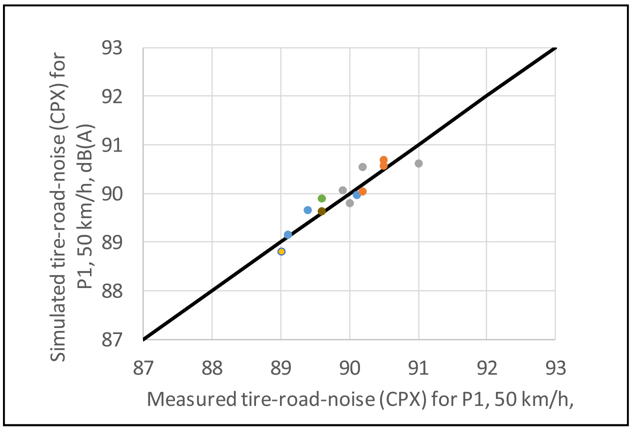

Figure 9. Calculated noise levels using a statistical model compared to measured CPX-Indices using tire P1 on dense hot rolled asphalt with a maximum chipping size of 5 mm.

4. Final conclusions

Technological possibilities have dramatically increased within the last 20 years, so that it was possible to improve measurement systems in terms of efficiency, quality and safety.

Especially the increase in computational power allowed for more elaborate and integrated measurement systems and for real-time evaluation of measurement data.

Within measurement systems development both continuous improvement and fundamental redesign takes place. In some cases also the measurement principle may change, e.g. from spot measurements to continuous measurements or from accompanied measurements to autonomous measurements.

Often, the change of a measurement principle can be done in line with the normative standards. However, it must be kept in mind that normative standards can only describe the technological history of the last years.

Modern evaluation techniques like pattern recognition are already implemented in some evaluation procedures. This allows increasing the objectivity of the measurement systems (e.g. for vehicle characterization in SPB-measurements). In the future, further modern algorithms and technological concepts like machine learning and artificial intelligence will be used to evaluate data. For such concepts, cloud computing systems can be used to update datasets continuously for machine learning. This will allow e.g. to share and update pattern recognition algorithms instantaneously.

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