Acoustic roughness measurement of railway tracks: Implementation of an optical measurement approach & possible improvements to the standard

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Abstract
The measure for assessing the acoustic quality of the rail surfaces, the acoustic roughness, is defined in the EN 15610 standard. It is shown that this standard contains gaps with regard to the applied procedures for processing the raw data to the quantity of acoustic roughness. Additions to the standard appear necessary to ensure better comparability of the results. A piece of rail tactilely measured by METAS (Swiss Federal Institute of Metrology) was used as a reference. Measurement data recorded by a laser triangulation sensor was used to quantify the adjustments to the standard. This paper provides an overview of the individual processing steps and systematically examines possible additions to the standard to improve the quality of the outcome. Special emphasis was given to a method for outlier removal, pre-filtering, spike removal, curvature correction and calculation of one-third octave bands. It becomes apparent that different implementations can have a significant impact on the final result. The filter used, the wavelength ranges, the methodology for removing outliers should be specified. The spike removal, curvature correction and the calculation of the one-third octave bands should be supplemented in detail to reduce ambiguities in the implementation.

Keywords
Railways, railway rolling noise prediction, railway technology, railway technology/engineering, wheel/rail profiles

Introduction
Traffic noise can cause various health problems as described by Héritier et al.¹ and Dratva et al.² It is therefore an endeavour to reduce the noise from rail traffic as much as possible. A large part of railway noise originates from the rolling noise of the vehicle, respectively, from the wheel-rail contact as described by Thompson.³ According to Szwarc et al.⁴ this is especially true for the speed range between 50 km h⁻¹ and 200 km h⁻¹, where rolling noise is the dominant component. As described by Grassie,⁵ various irregularities with wavelengths up to 2 m can have a significant impact on the noise level. According to Thompson,⁶ the roughness of the two contact partners is directly coupled with the noise generation of the system. One possibility to reduce the noise emission caused by the rolling noise is the acoustic rail grinding as described by Kuffa et al.⁷ The acoustic roughness has to be measured in order to assess the quality of the grinding process, which is one possible application for these measurements according to Lutzenberger et al.⁸ Measuring the roughness from the moving train would offer possibilities to monitor the state of the network and for planning grinding operations and thus increasing efficiency of the maintenance process. As Verheijen’s⁹ overview shows, direct measurements are mostly done manually and/or require a clear track. Measurements from the moving train are possible with indirect measurement methods via the measurement of axle bearing accelerations as shown by Bongini et al.¹⁰ or via measurement of the sound level close to the wheels as shown by Kuipers et al.¹¹

There are numerous standards dedicated to the topic of noise emission and measurement in the railway sector. EN ISO 3381¹² deals with the topic of noise measurement in rail vehicles. EN ISO 3095,¹³ on the other hand, deals with noise measurement on vehicles in general. EN 15610¹⁴ focuses on the noise development resulting from the wheel-rail contact and the roughness of the respective components in contact. The procedure for calculating the acoustic roughness is given by EN 15610.¹⁴ Despite this definition, ambiguities remain in the data processing which can influence the result.

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The aim of this paper is to develop an optical acoustic roughness measurement set-up, which can operate on the moving train. The direct measurement of the longitudinal profile of the rail is carried out using laser triangulation sensors. In the following, the further processing of the measured data to the acoustic roughness will be systematically examined and suggestions for supplementing its definition will be recorded. The target of this paper is to present a calculation of acoustic roughness to give a more stable definition of the evaluation process.

Method

Experimental setup

A test setup equipped with a reference rail was used. The reference rail has a ground profile, which had been tactically measured with a measuring tip size of 3 mm on two lines by METAS (Swiss Federal Institute of Metrology). The tactile measurement had a measuring resolution of 1 μm, a sampling distance of 48 μm and a measuring range of 2 mm. Segments of up to 800 mm in length were measured and joined together with an overlap of 280 mm to form the overall length. The reference rail was integrated into the experimental apparatus shown in Figure 1. Along the rail, a carriage can be automatically moved on a linear guide to record the entire longitudinal profile with a velocity of 0.031 m s⁻¹. An encoder records the position along the rail with a length of 3.3 m. The measurement was not triggered by the encoder. An optoNCDT 2300-10LL laser triangulation sensor from Micro-Epsilon Messtechnik (Ortenburg, Germany) is mounted on a sensor plate which is connected to the slider. The sensors record the analog data in a range between ~10 V and 10 V with a sampling rate fₛ of 30 kHz. A constant sample spacing of 1.03 μm was maintained. The analog signal is recorded with a NI 9222 module within a cRIO-9045 of National Instruments (Austin, Texas, USA) using LabView.

The sensor plate carrying the sensors is connected to the slider with pneumatic actuators for an additional test series involving the simulation of the train suspension. The setup is fixed such that the pneumatic actuators are not actuated during the measurement. Thus, the degree of freedom perpendicular to the rail is suppressed. Tests were performed with a clean rail as well as with a rail contaminated with dust or water. The purpose of the latter was to create a disturbed data with real interferences that exist on the rail network set in order to challenge the optical measurement and the data processing. The raw data was stored and further processed to the acoustic roughness in a separate step. Only the data of sensor one was used for the investigations. The combination of all sensor values and the possible improvement of a measurement result are part of a follow-up study.

Data processing

The following processing steps were followed:

1. Import of the TDMS (Technical Data Management Streaming) data: The analog data was recorded with a cRIO 9045 from National Instruments. The TDMS file format of National Instruments was used due to its integrability into the LabView software and the resulting small file size. The data must also be converted from analog voltage signals to distance values.

2. Outlier removal: As the measurement was carried out optically, unfavourable reflections (e.g. speckle) can become noticeable in the form of outliers in the data set. The same applies to dust or water being present on the rail. Both were artificially applied to the rail in experiments. Outliers influence the measurement result and require further steps of the data post-processing. Therefore, the IQR (interquartile range) method for outlier removal was investigated and implemented. The objective is to remove the outliers without distorting the significance of the original data set. Usually outliers differ significantly from the rest of the data set. Thus, the outlier removal must not be set too sensitively; otherwise it will also remove spikes in the same way as the spike removal procedure.

3. Resampling: Since the measurements were not carried out at a uniform speed, the data point distances in the longitudinal direction are not constant in the unprocessed form. Therefore, linear interpolation was used to generate a constant data point spacing at the points of the reference data set. For the provided reference data in this setup, this leads to a sample spacing of 48 μm.

4. Pre-Filter of Raw Data: The wavelength range results from the range of interest given in the standards, which focusses on the corresponding train speeds where rail corrugation is deemed relevant for noise emission. EN 15610 specifies a range between 3 mm and 100 mm (optionally also 250 mm). EN ISO 3095 states a range between 3 mm and 100 mm or even up to 250 mm, depending on the speed range. EN ISO 3381 also specifies a wavelength range between 3 mm and 250 mm. EN ISO 3381 also defines limit values in decibels for the spectrum of acoustic roughness. These are given between 3 mm and 400 mm. It is not
reasonable to apply a bandpass filter between 3 mm and 250 mm. Instead, filtering was done between 3 mm and 500 mm to avoid damaging the wavelength range between 3 mm and 400 mm. Two approaches were tested. The application of a Butterworth filter and the manual transformation into the spectral range with subsequent manual removal of the undesired signal components below $\lambda_{\text{low}} = 3$ mm and above $\lambda_{\text{high}} = 500$ mm. For the manual transformation, a Hanning Window was used. The libraries signal.butter and signal.sosfilt available in Python were used for the application of the Butterworth filter.

(5) Profile comparison: Before further processing the measurement data for the acoustic roughness, a profile comparison to the METAS measurement can be performed. The longitudinal profile measured by METAS was compared with the profile estimates from the optical measurement in the time domain. The longitudinal offset of the measurements from each other were corrected. The following values were calculated and compared:

- Root-mean-square deviation
- Correlation coefficient
- Mean value of the absolute error
- Integrated absolute error
- Mean value of the relative error

(6) Spike removal: According to EN 15610\textsuperscript{14} spikes in the measurement data that are too large must be removed (e.g. small impurities) for the determination of the acoustic roughness. They could have a negative influence on the result in the short-wave range. The spike removal process is defined for a tactile measuring method with a probe tip radius of 7 mm. A graphical illustration of the spike removal process is given in Figure 2.

The procedure involves the following steps with $r(x)$ as length profile:

(a) Calculation of the first derivative $\frac{dr}{dx}$ and the second derivative $\frac{d^2r}{dx^2}$ of the measured profile.
(b) Search for local maxima or minima by searching for a change in sign of the first derivative $\frac{dr}{dx}$.
(c) Check whether the criterion for the second derivative $\frac{d^2r}{dx^2} < -10^7 \text{m}^{-1}$ is fulfilled at this point.
(d) Search for the footpoints $x_1$ and $x_2$ of the spike candidates where the first derivative satisfies the following criterion: $\frac{dr}{dx} < 5 \cdot 10^3 \text{mm}^{-1}$.
(e) Calculation of the width $w = x_2 - x_1$ of the spike candidates.
(f) Check whether the ratio of peak height and width is fulfilled. The following criterion serves for this: $h > \frac{w}{x}$ with $a = 3$ m. If this is fulfilled, the peak is removed from the data set by linear interpolation between $r(x_1)$ and $r(x_2)$.
(g) Repeat the procedure until no new spikes are detected.

(7) Curvature correction (Figure 3): Subsequently, the curvature of the wheel must be taken into account. When traversing the longitudinal profile, only those parts of the profile are relevant which the wheel (Radius $R = 375$ mm) can follow. This is not the case, for example, for deep valleys in the profile.

(8) Calculation of the power spectrum: Based on the longitudinal profile, the power spectral density was calculated as a function of the spectral wavelength.

(9) Conversion to one-third octave band spectrum: The power spectral density is converted into a one-third octave band spectrum. This is done according to the specifications of EN 15610.\textsuperscript{14} A comparison to the METAS reference is afterwards performed in the wavelength domain.

**Adjustments to the standard**

**Outlier removal**

After importing the data, outliers were removed. This is not part of EN 15610,\textsuperscript{14} which only requires discontinuities to be removed. Outlier should be removed before the application of a filter in order not to falsify the result of the filter process. The raw data set was used for this study. A method based on the interquartile range was used as the approach for the numerical implementation. A description of this method can be found in the work of Moska et al.\textsuperscript{15}

Since the mean value of the data set corresponds to the waviness of the longitudinal profile, outliers that play a role on a roughness value level cannot be detected. It is necessary to divide the data set into segments of data points which are processed individually. The length of a segment is not trivial to define as it is used to determine the mean value
and the interquartile range. That determines how many data points are detected and removed as outliers. In order to remove only real outliers, the data set of an undisturbed measurement was used for these investigations. In this case, the deviation from the reference gives an indication of the quality of the outlier removal. The integrated absolute error over the spectrum of acoustic roughness provides a way to assess the deviation.

The integrated error varies between 0.82 dB/mm and 0.829 dB/mm for the different segment lengths. For 2000 data points, the minimum of the integrated error is 0.82 dB/mm. The number of data points in the longitudinal direction is directly coupled with the selected sampling frequency (constant speed). Care was taken during implementation to keep the determined ratio (with a sampling frequency of 30 kHz) between segment length and sampling frequency constant. Outliers caused by unfavourable reflection were reliably removed for each data set.

**Bandpass filter**

For the acoustic roughness, long-wave signal components as well as measurement noise are not relevant. Therefore, these components are removed by a pre-filter. The process of pre-filtering can influence the result through two main parameters:

- Choice of filter technique (e.g. Butterworth, Chebyshev)
- Choice of filter frequencies or wavelengths

First, a profile comparison was performed in the time domain. When filtering in the range between 3 mm and 250 mm, a RMSD (root-mean-square deviation) value of 5.70 μm and a cross-correlation factor of 0.85 were determined when compared with the reference of METAS. When filtering in the range between 3 mm and 500 mm, a RMSD value of 11.45 μm and a cross correlation factor of 0.92 were calculated. The selected wavelength range has a visible influence on the measurement quality. For the Butterworth filter, the 2nd, 3rd and 4th order were investigated. In a second step, a comparison between different filters was performed in the wavelength domain. The resulting spectrum of the acoustic roughness is shown in Figure 4.

One main difference appears between the Butterworth filters and the manual bandpass filter. Across the spectrum, it can be observed that the absolute values tend to be shifted to higher values with the Butterworth filter. The maximum shift for each filter order is about 5.5 dB. The largest shifts can be seen between 50 mm and 125 mm, as well as between 20 mm and 32 mm and between 5 mm and 13 mm. On average, a shift of 1.95 dB for the second order, 2.13 dB for the third order and 2.21 dB for the fourth order can be observed. Depending on the filter order, different flattening can be observed in the boundary area. It is possible to reduce the shift compared to the manual bandpass in the wavelength range between 3 mm and 63 mm with a correction factor. The PSD (power spectral density) is known to be affected by the Hanning window and can thus be multiplied by a correction factor of 9/3 (labelled as ‘FFT Adjusted’ in Figure 4) to remove these attenuating effects.

For the following investigations, the manual bandpass filter was consistently applied without a correction factor.

**Spike removal**

The process is shown in Figure 2. Since the method is designed for tactile measurement, the numerical parameters mentioned in EN 1561014 are not necessarily useful for an optical measurement of the acoustic roughness. In the following, the limit values for the first and the second derivative given by EN 1561014 were used. The procedure itself is sufficiently defined in the standard. An exception is the definition of the spike height h.

There are five possibilities to calculate h numerically:

1. Based on left footpoint: \( h = r(x_{Spike}) - r(x_1) \)
2. Based on right footpoint: \( h = r(x_{Spike}) - r(x_2) \)
3. Maximal h: \( h = \min(r(x)); x \in [x_1,x_2] \)
4. Minimal h: \( h = \max(r(x)); x \in [x_1,x_2] \)
5. Based on \( x_{midpoint} \):

\[
    h = r(x_{Spike}) - \left( \frac{r(x_2) - r(x_1)}{x_2 - x_1} \right)(x_{Spike} - x_1) + r(x_1)
\]

Where \( x_1 \) represents the position of the footpoint on the left side of the spike, \( x_{Spike} \) represents the position of the spike itself, and \( x_2 \) represents the position of the footpoint on the right side of the spike. The implementation that calculates the spike height via the position of the spike, as shown in Figure 2, was examined. Furthermore, a definition via the left footpoint of the spike as well as the right footpoint of the spike were examined. Since the option of the maximum and minimum tip height is not different from the implementation based on the left or right footpoint, these are not explicitly mentioned in addition. For the undisturbed data set with a clean rail, no differences
between the implementations could be found. A different situation arises as soon as water is on the rail. Figure 5 shows the spectrum of acoustic roughness for the different approaches for a rail wetted with water.

In the case of the definition via the left footpoint, a maximum deviation of 4.24 dB was observed. For the definition via the right footpoint, a maximum of 2.80 dB was determined. The largest deviations are evident in the wavelength range between 10 mm and 125 mm.

**Curvature correction**

For each data point \( r(x_i) \), it is checked for \( N \) data points whether a wheel with the curvature function \( C(x) \) intersects the profile \( r(x) \). The process is shown in Figure 3.

The standard EN 15610\(^{14} \) does not explicitly specify how many data points \( N \) are to be considered for one step of the correction. In the example code which was still attached in the 2009 version of EN 15610,\(^{16} \) \( N = 40 \) is set for the number of data points taken into account, arguing with the computational cost of the evaluation. A fixed number of data points can result in very different distances between them, depending on the sampling frequency and the moving speed. Thus, 40 data points can cover or exceed the Hertzian contact area of the wheel contact point. EN 15610\(^{16} \) states that the data point distance must be \( \leq 1 \text{ mm} \). Since the standard is based on tactile measuring methods, it can be assumed that \( N = 40 \) can also be interpreted as a contact length of 40 mm to be taken into account. Nevertheless, it should be noted that a fixed definition of the contact length does not exist. It appears more robust to set a physically sound definition of the number of data points to be considered. In this context, a definition via the aforementioned Hertzian contact surface between wheel and rail seems appropriate because only the part of the wheel is considered which can be in contact with the profile. The situation is shown in Figure 6.

According to Fendrich et al.,\(^{17} \) the length \( L \) of a rectangular approximation of this surface is defined as

\[
L = 3.04 + \sqrt{\frac{Q_0 R}{B + E}}
\]

The length \( L \) depends on the wheel contact force \( Q_0 \), the radius of the wheel \( R \), the width of the driving facet \( B \) and the Young’s Modulus of the contact partners \( E \). The following parameter values taken from Fendrich et al.\(^{17} \) were used, with the value for the radius taken from EN 15610\(^{14} \) standard

- \( Q_0 = 100 \text{ kN} \)
- \( R = 375 \text{ mm} \)
- \( B = 12 \text{ mm} \)
- \( E = 210000 \text{ MPa} \)

With the calculated length \( L = 11.73 \text{ mm} \) and the known measuring point distance \( dx = 48 \mu\text{m} \), the number \( N \) is given as

\[
N = \frac{L}{dx} = 244375
\]

The relevant number of data points for the contact is taken into account regardless of the sampling frequency. Comparing both possible implementations, deviations become apparent depending on the wavelength of the respective band. Figure 7 shows the deviations of the constant point definition of \( N = 40 \) compared to the definition based on the wheel-rail contact zone. The measurement data for this comparison was recorded undisturbed (dashed curve). After resampling, the data set used has a data point spacing along the rail of 48 \( \mu\text{m} \) which corresponds to a contact zone with a length of 1.92 mm with \( N = 40 \).

For long wavelengths between 80 mm and 400 mm, there are only slight deviations in the value range below 0.10 dB. At a wavelength of 63 mm, the deviation rises above 0.10 dB to 0.17 dB. The deviation increases further below a wavelength of 32 mm. The largest deviation is found for the smallest wavelength of 3 mm with 2.10 dB. The deviation increases for a disturbed data set which was recorded with water on the rail. The measured longitudinal profile is influenced by the water due to the approach of an

![Figure 5. Spectrum of acoustic roughness for different spike height calculations, measurement with water on the rail.](image)

![Figure 6. Data points within the Hertzian contact zone.](image)
optical measurement and shows more peaks. The progression of the deviation can be seen in Figure 7 as well (dotted curve). The 0.1 dB deviation is already reached at a wavelength of 125 mm. For a wavelength of 50 mm, the deviation is already 2.24 dB. This corresponds to the maximum deviation for an undisturbed measurement. The maximum deviation increases to a value of 9.77 dB. This is the case for the wavelength of 5 mm. If it is assumed that the contact zone has a length of 40 mm (data point distance 1 mm), there is no relevant difference to the contact zone definition. A small deviation of 0.28 dB is detectable only at a wavelength of 3 mm when using a disturbed data set with water on the rail. The progression of the deviation can be seen in Figure 7 (straight curve).

**One-third octave band calculation**

After calculating the power spectrum, the individual discrete level values are transformed into one-third octave bands. Each individual discrete value is considered as a narrow band of width $\gamma$. This process is specified in EN 15610. The calculation is given as

$$L_{\text{Band}} = \frac{\gamma_1}{\gamma} * L_{i-2} + \sum_{j=1}^{i-1} L_{i-j} + \frac{\gamma_3}{\gamma} * L_{i+1}$$

With

- $L_{\text{Band}}$: Level in one-third octave band
- $L_{i-2}$: Level of the left boundary narrow band
- $L_{i+1}$: Level of the right boundary narrow band

Also specified is the approach how to include narrow bands at the edge of a one-third octave band. These are added to the respective one-third octave band proportionally to their width. The calculation is shown graphically in Figure 8. Shown in red is the range of a single one-third octave band while the narrow bands are shown as bars. In Figure 8, the discrete level values serve as the centre of the narrow bands. This is not explicitly specified in EN 15610.

Alternatively, it would be possible to define a narrow band starting from the left edge, which would shift the narrow bands across the width of the spectrum. This alternative is shown in Figure 9. The blue bars correspond to the non-central value implementation of the narrow bands.

The crucial question is to what extent both definitions affect the spectrum of acoustic roughness. The data was previously processed according to the described processing procedure. Figure 10 shows the spectrum of acoustic roughness for a central value implementation.

Two peaks are contained at 8 mm and 16 mm. Figure 10 shows the spectrum of acoustic roughness for the non-central value implementation as well. The spectrum is shifted compared to the central value implementation and deviates significantly. For example, the peak at 16 mm is now present at 13 mm and at 16 mm. This peak is clearly located at 16 mm in Figure 10.

The absolute value also differs at this point. For the central value implementation, this was 5.11 dB at 16 mm. For the non-central value implementation, this results in a value of 3.93 dB for the same band. This corresponds to a relative deviation of 23% for this one-third octave band only. The 13 mm band has a larger deviation. A value of

![Figure 7](image-url)

**Figure 7.** Absolute deviation for $N = 40$ and $L = 40$ mm compared to the contact zone definition, undisturbed measurement (dashed curve), water on the rail (dotted curve).

![Figure 8](image-url)

**Figure 8.** Calculation of the one-third octave band based on narrow bands and central value implementation.

![Figure 9](image-url)

**Figure 9.** Calculation of the one-third octave band based on narrow bands and non-central value implementation.
It is crucial how the measured longitudinal profile data may be processed through a filter before the acoustic roughness is calculated from it. Uncertainties exist both in the use of filter technology (software used) and in the permitted wavelength range in which filtering is allowed in order not to influence the measurement result. Both issues should be addressed to ensure the comparability of different measurements. For a manual bandpass filter, it would also be necessary to determine which window is to be used for the transformation into the frequency range and whether the PSD is multiplied with a correction factor.

**Spike removal**

It could be shown that the definition of the spike height can already have an effect on the result as long as the measurement data have sufficient disturbances. This deviation cannot be detected for a completely undisturbed data set, which in turn could be attributed to the reduced amount of spikes. It is suggested to calculate the spike height \( h \) at the position of the spike. Since the method was defined for a tactile and not for an optical method, it is necessary to further investigate whether the given values of the standard for the spike removal are still suitable. If an optical system is installed on the train, interference from moisture on the rail as well as from dynamic influences is possible, which may require an adapted method for spike removal.

**Curvature correction**

It could be shown that the choice of the value for the considered number of data points \( N \) during the curvature correction step influences the result relevantly. This degree of freedom in implementation should therefore not be left open but clearly defined. A physically reasonable definition is proposed which corresponds to the basic idea of this processing step. The number of data points \( N \) considered should be calculated based on the contact zone being formed and the measurement resolution in the longitudinal direction. This ensures that the same area is considered in each case and that neither the sampling frequency nor the driving speed have any influence on the result of the curvature correction. The parameters used to calculate the contact zone approximation were taken from the literature. From this point of view, it is necessary to discuss and define which parameter values are set in the standard to calculate the contact zone. This corresponds to a procedure comparable to the definition of the wheel radius \( R \), which is already defined today. Another alternative would be to define a fixed length of the contact zone in the standard. Furthermore, instead of an approximation of the contact zone, the real contact zone could also be calculated. In addition, the length of the contact zone could be slightly increased to prevent the influence of larger rail defects on the curvature correction in practice. It has been shown that the deviation is strongly increased with occurring disturbing influences (water on the rail). Further investigations into the influence of interference on an optical measurement must therefore be carried out and quantified.

**One-third octave band calculation**

The spectrum of acoustic roughness is strongly influenced by the chosen implementation of the narrow band definition. The result can be influenced simply by the way the narrow bands are computed into one-third octave bands. The problem could be further exacerbated with lower sampling frequencies. The narrow bands would become wider and accordingly have a stronger influence on the calculation in the boundary areas. It is proposed to add a stable definition.
for this topic to EN 15610 in order to prevent deviations of measurements from each other. The approach of defining the narrow bands via the centre point seems robust and allows an implementation that is largely independent of the sampling frequency. In future studies, the calculation of the power spectrum should be considered in more detail and concretized. This aspect was not considered in this study, but could as well have a relevant influence on the result.

Conclusion

Based on the described observations, the EN 15610 should be supplemented in several parts. If all the implementation options considered are inserted differently from a calibration measurement, significant deviations in the measurement results can be the consequence. This greatly limits the comparability of the measurements. There is also the theoretical possibility of adapting the measurement result without contravening the current status of the EN 15610 standard. A supplement to the standard seems to also make sense in order to establish better comparability between the various measurement approaches. It can be seen that EN 15610 was designed for a tactile method. Other measurement approaches are not taken into account. Parameters for the spike removal method are explicitly specified for a tactile tip size of 7 mm in EN 15610. Optical measurement methods should also be considered here. It is advisable to indicate which implementations were used and how the raw data for the acoustic roughness spectrum were further processed. Many deviations could possibly be explained by this fact. The next step would be to test the influence of external interference on the measurement setup. In addition, measurement methods such as the chord method described by Grassie et al. should be evaluated experimentally.

Acknowledgements

The authors would like to thank the Swiss Federal Office for the Environment (FOEN) and the Swiss Federal Office of Transport (FOT) for the financial support.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by Swiss Federal Office for the Environment (FOEN) and the Swiss Federal Office of Transport (FOT).

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