1. Introduction

A newly constructed road in the province of North Holland in the Netherlands (N201) had to meet all the requirements of the Dutch Noise Scheme [1] and the Dutch Nuisance Act [2]. In order to fulfill the accompanying strict noise limits, a noise reducing pavement has been applied. However, after reconstructing, numerous complaints occurred about annoying noises caused by passing trucks. An investigation has been executed to determine objectively the possible source of these complaints. Emission measurements have been performed as well as psychophysical analyses based on immision measurements to identify possible tonality and saliency of the noise immisions. Simultaneously, a questionnaire had to be filled in by the inhabitants of the adjacent residential areas. Since it became clear that almost 100% of the measured heavy vehicles emitted a tonal noise, additional FFT measurements of passing-by trucks have been performed to identify the sources. With all the results, some appropriate measures against the occurring tonal noise have been advised.

2. The Road under Study

2.1 N201, North Holland

The N201 is one of the busiest provincial roads in Holland, the Netherlands. The infrastructural quality of the road was far behind the economic development of the region. The result was an increasing pressure on the N201, caused by commuter, work, and transport traffic. This increasing traffic loads caused more and more problems with regard to safety, quality of life and accessibility of the adjacent municipalities. To improve these important aspects, relocation of the N201 was desirable. This relocation would also improve the accessibility of the area around Schiphol Airport and the Aalsmeer Flower Auction. A partial widening and relocation, among other measures, were necessary to steer the growth of road traffic in the right direction. The construction of the new route also solved a number of bottlenecks in the context of the Environmental Noise Directive [3].
2.2 Noise

In 2008, a noise study was carried out for the relocation of the N201. This investigation showed that the noise levels from the N201 had exceeded the preferred limit value of 50 dB(A). Various measures could be taken to limit this noise pollution. Given the landscape value of the area near the road, applying noise barriers along the entire route was not desirable. That is why a noise-reducing road surface (thin wearing course) on the entire section of the road has been chosen. The average noise reduction of this road type for mixed traffic is approximately 4 dB(A) at 80 km/h relative to the Dutch Reference [4]. Without measures, there are a number of houses that have experienced relevant noise pollution, a number of which exceeded the maximum exemption value.

An inquiry among the contractors of the work concerning the N201 showed that a thin wearing course called Microflex has been applied. This road surface corresponds to the starting point in the earlier mentioned acoustic study. The paving had to meet the (noise) requirements as expressed in the accompanying contract. A specification in the contract states how the achieved noise reduction should be tested immediately after constructing. Inquiries with the Province, contractor and consultancy firms showed that these measurements had never been carried out.

3. Complaints

Despite the sufficiently low noise levels, a large number of complaints have been made by local residents. The complaints were unlikely to be related to the fact that local residents were experiencing noise from a trafficked road that was not there before. The complaints mainly concerned the nature of the noise and in particular that of heavy vehicles (trucks). The Noise Nuisance Act does not take this typical effect into account.

From the majority of the complaints it seemed that the noise from trucks is perceived as “tonal”. In general, this kind of tonality is a rare phenomenon with this type of road surfaces, as followed from hundreds of measurements on comparable road surface types. However, there are a limited number of cases in which tonality occurred.

4. Subjective Impression of Traffic Noise

4.1 Introduction

It is customary to express the strength of noise in an objective (physical) measure. The obvious physical quantity here is the sound pressure. In this way a dimensionless (non-physical) quantity, so-called level with unit decibel (dB), is created. However, it is known that people are almost unable to perceive constant stimuli, including sound. Stimuli can be constant in time or frequency. In the daily environment, sounds may vary both in time and frequency. Theoretically, this is almost identical in higher processing centres in the brain, because the processing of auditory stimuli is performed in narrow bands where time and frequency are uniquely related through phase. In yet higher centres, the different spectral information is merged into one percept again [5].

Two psychophysical measures were applied in this study. The first is tonality which works in narrow frequency bands and the second is saliency which works in a broad frequency band.

4.1.1Tonality

Psychophysically, tonality is a difficult concept. Every signal that is briefly listened to is tonal due to roving spectra. Human hearing is very selective when it comes to tonality. Therefore, even short stimuli of white noise can be considered as tonal [6]. Also signals without distinct frequency components (spectral lines) can be tonal. Examples of this are "coloured" or repeated noises [7] that are often used in electronic music. In general, it can be said that with a tonal sound it is possible to play a recognisable melody. Tonality (presence of more or less pure tonal components) is calculated in a similar way to loudness.

The ISO standard 1996: 2, annex C [8] contains a method to determine tonality on basis of a detection algorithm. For the exact mathematical formulations, refer to the text of the standard. Figure 1, left panel shows the algorithm graphically.
In the case of 1/3 octave band measurements, a simplified algorithm may be used. Figure 1, right panel shows this algorithm graphically. To determine the tonality, an earlier study for the Province of North Holland [9] shows that the optimum measurement time is around 2 s. Tonality is narrow-band based and determined locally. A weighting has, therefore, hardly any influence on tonality.

4.1.2 Auditory saliency

It is often (rightly) claimed that the various "subjective" noise measures correlate better with each other than with the human perception. That is why a new method has been developed which is based on higher processes in the human auditory system. It often appears that the global forms of the two frequency distributions (spectra) are comparable. That is why loudness-based methods add little to nothing compared to the standard dB(A) concerning “smooth” spectra. However, the differences can be as high as 5 dB per frequency band. Based on psychophysics, a theory has been developed that predicts the so-called Auditory Saliency A0 [10]. This theory was especially developed for room acoustics in which small spectral differences are very important [11]. The A0 criterion determines the prominence of (small) differences as detected by human hearing. The A0 criterion is determined by analysing the differences of two spectra in each frequency band (see Fig. 2).

For thin wearing courses, like the paving on the N201, earlier studies have shown that this method corresponds well with results from surveys [12]. Although the method looks at differences per frequency band, saliency is broadband and is therefore determined globally. A weighting has, therefore, hardly any influence on saliency.
5. Questionnaire

Simultaneously with the acoustic measurements a questionnaire had to be filled in by a selected group of inhabitants. The questionnaire was based on research performed in Copenhagen [13] with additional standard questions from the province. 35% was annoyed by noise of trucks from which 22% severely. The most unfavourable wind direction was North (50%). The majority indicated that the annoyance was the highest in the early morning.

6. CPX measurements

6.1 Method

First, the performance of the asphalt has been tested by using the Close-Proximity (CPX) method according to ISO 11819-2 [14]. It is not very common to use only the CPX method in relation to Noise Acts and complaints. The main reason for this is that the method is essentially designed for product type approval. However, it possible to apply the method in a wider scope [15].

No noise-reducing asphalt has been applied in the tunnel and on the crossing sections. These parts are therefore excluded in the analysis. The transitions of the different pavements were not perceptible at the measuring points. Also, in absolute sense, the transition appears not to be too large and complies with the Dutch Joint Directive [16].

6.2 Conformity of Production Noise

Based on a general calibration the measured CPX values have been converted to the Conformity of Production (COP) of the N201. This yields the average noise reduction relative to the Reference from the prevailing Publication 200 [4]. The results are shown in Table 1 with the current specification requirement for 2 years after construction.

Table 1: Average noise reductions at 80 km/h 2 years after construction.

<table>
<thead>
<tr>
<th>road</th>
<th>direction</th>
<th>noise reduction [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N201</td>
<td>east</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>west</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>requirement after 2 years</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 1 shows that the average noise reduction of Microflex on the N201 was 4.1 dB(A) at 80 km/h two years after construction. The road surface thus met the relevant contract requirements. The same paragraph in the contract also contains a requirement for the initial noise reduction. This has never been measured (see §2.2) but can be estimated from the current measurement results. It is assumed that the noise reduction of a thin wearing course decreases 0.5 dB(A)/year on average.

Table 2: Estimated noise reductions after construction at 80 km/h.

<table>
<thead>
<tr>
<th>road</th>
<th>direction</th>
<th>noise reduction [dB(A)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N201</td>
<td>east</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>west</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>requirement after construction</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 2 shows that the estimated average noise reduction of Microflex on the N201 was 5.1 dB(A) at 80 km/h just after construction. Therefore, the road surface would probably have met the relevant specification requirements.

6.3 Further analysis

The acoustic homogeneity is an important measure of the quality of a road surface. The CPX measurements show that the noise reductions vary as a function of distance. However, these variations cannot explain the cause
of the complaints. The data are further analysed spectrally per section of 20 m length. The results are shown in Fig. 3.

![Graph showing sound levels](image)

Figure 3: Left panel: The A weighted sound levels per octave band as a function of distance (“positie”). The left part is located in the province of North Holland and the right part in the province of Utrecht. Right panel: The sound level per octave band for all distances. All approximately 200 spectra represent a measurement every 20 m.

Figure 3, left panel, shows that the overall sound levels vary over the distance. However, the energy in octave bands vary much more. This effect is perceived as a changing timbre over the distance. Due to an interruption in the surface, this is hardly noticeable. Figure 4 shows the octave band spectra for all the sections.

Figure 3, right panel, shows the spectral discontinuity near the border of the two provinces can be recognized again. The spectral discontinuity has civil engineering significance but it is not sufficiently explanatory for the occurrence of the complaints. Also, during the immission measurements (see §6) this effect was not audible due to varying spectral transfer functions as a function of the observation direction. The varying spectral distribution indicates that some parts seemed to be more clogged during the 2 years under traffic; which is a normal phenomenon. Clogging (soiling) causes a change in spectrum [17]. Cleaning the road surface will therefore have little or no influence on the number of complaints. But it does have an effect on the total (functional) lifespan. It also seems that the layer thickness deviates slightly from what is normal practise for this type of road surface (25 mm).

7. Emission and immission measurements

7.1 Method

At two positions with an obstacle free view on the N201, short-time (measuring time 2 s) analyses were carried out very early in the morning (see §5). During these measurements there was a heading northern wind (see again §5) from the north which is not most common direction. At these positions, there is no influence of interfering reflections from adjacent buildings. The measurements with a clear view of the N201 can therefore be considered as quasi-emission measurements. A number of measurement positions in two neighbourhoods have been chosen behind the measurement positions with clear view. These neighbourhood positions can be considered as immission points. Every passing truck is measured at the emission and the immission position, simultaneously. Because each measurement is 100% correlated, the mutual accuracy is optimal. The speeds of the trucks were also measured at both emission positions. It was shown that a large proportion of the trucks drove faster than the speed limit.

7.1.1 Tonality

Figure 9 shows a typical example of a 1/3 octave band spectrum of a passing truck.
Figure 4: Measured 1/3 octave band spectrum in dB of a passing truck.

The analysis showed that almost all passages were tonal at both the emission and immission positions. The correlation between the results at the emission and immission points is therefore 1, which of course has no statistical significance. All this means that the freight traffic on the N201 emits a clear tonal noise. This is obviously the cause of the complaints of the local residents.

7.1.2 Saliency A0

The Saliency A0 has been calculated based on the same data set as for tonality. The average spectrum of all passages per measurement point was determined as a reference. Next, the saliency was calculated for each passage. To prevent the (unexpected) large number of tonal passages affecting the results, the spectra have been converted to octave bands, using a moving average (convolution) of three 1/3 octave bands (this is not equal to adding three 1/3 octave bands into one octave band). It followed that a number of passages were salient. However, the saliency was at maximum 5 dB. This is only a little more than the just noticeable limit of 3 dB. All this means that the freight traffic on the N201 showed a normal spectrum that hardly varied. This corresponds with the spectral analysis of the performed CPX measurements (see §5).

8. Frequency Analysis

8.1 Method

Because the emission and immission measurements were performed in 1/3 octave bands, the precise frequencies that cause the tonality are not known. Therefore, extra frequency-selective measurements were carried out and the nature and origin of the noise was determined on the basis of Fast Fourier transformation (FFT), which means that the strength of the individual frequencies can be measured much more precisely. Measurements were carried out at the same emission positions and at an additional reference point with a dense asphalt type (AC Surf 16) and a 2 layered Porous Asphalt (PA). Figure 6 shows a result from the thin wearing course on the N201. It can be concluded from these results that at dominant frequencies the sound pressure level can be 6 dB(A) up to 10 dB(A) higher above the ambient noise, which is quite substantial.

Figure 5: Example of an FFT measurement showing peak hold spectra.
8.2 Analysis

For trucks of the observed type, tractors from various manufacturers with a short wheelbase ranging from 3.6 m to 3.9 m, the final reduction takes place in the rear axle. In this rear axle there is in all cases a so-called hypoid toothing. The transmission ratio of the hypoid toothing for trucks of the observed type is between 2.5 and 3.5. The speeds of the observed trucks were measured between 60 km/h and 85 km/h (see §6.1). Since trucks typically have tyres of the size 315/80 R22.5 or 315/70 R22.5, it follows that at speeds of around 80 km/h, a tooth engagement frequency occurs approximately between 300 Hz and 400 Hz. These frequencies correspond with the tonal part in the immission measurements (see §7.1). The measurement data showed that this fundamental tone is observed at locations 1 and 2, but also that the 1st and the 2nd harmonic tone is observed much stronger than usual. The harmonic levels are clearly lower at location 3 with the standard dense asphalt than at locations 1 and 2. Additionally, comparable trucks have been measured on a 2-layered PA (80 mm total thickness). Here, the tonal sounds are hardly visible and audible. This makes the road surface/tyre interaction as the sometimes proposed cause of tonal noise [18] very unlikely. With 2-layered PA, the absorption peak coincides with the harmonics in the differential sound. With Microflex, the frequency range around the frequency of the differential sound is muted precisely due to the lower layer thickness, which makes the tonal peak stand out.

9. Proposed measures

Based on measurements and analyses, the following measures could be applied to reduce tonality. It should be noted that it is currently not known precisely why the tonality is so strong on the N201. The source is well known (differential noise from trucks), but why is it so dominant in this very case is unclear. It is necessary to perform an objective, detailed, and quantitative research on trucks and their tonal noise emission. Furthermore, a monitoring is advised to see the change in spectra resulting from changed properties of the surface like texture and porosity. The surveys have to be repeated regularly.

A sound barrier dampens higher frequencies better than lower frequencies. However, this spectral effect is quite gradual and will therefore have little or no influence on tonality and saliency. The immission values of the traffic noise are around 50 dB(A). By applying a barrier, these values would be about 45 dB(A). This will reduce the number of detected passages, but the rest will remain unchanged in terms of tonality. If the road surface would be replaced by a Stone Mastics Asphalt (SMA), the observed tonality would probably disappear. However, the accompanying lower noise reduction of SMA must be compensated by undesirable sound barriers.

In order to be able to significantly damp the differential noise of trucks, the maximum speed for freight traffic could be reduced to 60 km/h. Dump trucks and tractor/trailer combinations do not show any tonal noise around 60 and 70 km/h, respectively. The measurements show that many trucks are speeding (see §6.1). This measure is not really necessary for the other categories of traffic because all requirements with regard to noise levels at the façades are already met (see §2.2). This measure tackles tonality in a very targeted manner. However, the expected effect has not yet been determined objectively with sufficient accuracy.

Applying 2-layered PA will reduce the overall noise level, but that is not necessary in this case. However, the absorption peak will fit much better with the differential noise, making it less dominant (see §7.2). This measure therefore tackles tonality more accurately than sound barriers. 2-layered PA needs cleaning every year to maintain its functionalities (like water drainage and sound absorption). This applies also, but to a lesser extent, to the current road type.

Since the emissions from trucks are tonal, diffractors that are tuned to the typical frequencies in differential noise can be used along the roadside. This development is relatively new and it has a claimed overall noise reduction of 2-3 dB(A). However, if the diffractors are tuned to the tonal components as found in this study, an estimated 5 dB(A) reduction could be achieved for these components. This could significantly reduce the number of tonal passages without affecting the necessary clear view on the road. This measure, therefore, tackles tonalities more targeted than a noise barrier but also more targeted than 2-layer PA. However, at this moment there is discussion about the accuracy and reproducibility of the claimed noise reductions.

A cost study was conducted for the three technical measures as described earlier. The purpose was to show the differences between the variants and to be able to make a trade-off for a variant. The estimations provide insight into the costs of the three technical variants. The cost estimations are shown in Table 3.
Table 3: Estimated costs of the noise measures.

<table>
<thead>
<tr>
<th>measure</th>
<th>costs [million €]</th>
</tr>
</thead>
<tbody>
<tr>
<td>sound barriers 2 m</td>
<td>5.8</td>
</tr>
<tr>
<td>2-layer PA</td>
<td>1.5</td>
</tr>
<tr>
<td>resonators</td>
<td>1.7</td>
</tr>
</tbody>
</table>

10. Conclusions

Heavy traffic on the N201 cause serious annoyance assigned to tonal effects. Measurements of the road surface showed no deviations that could lead to tonal sounds. Immission measurements showed that 100% of the passing trucks emitted a tonal sound. FFT measurements indicated that these sounds correlate with the reductions in the rear axle of trucks. The most effective and durable measures for reducing reduce tonality and, therefore, the number of complaints, are speeds limit and tuned resonators.

REFERENCES