An empirical method for prediction of tram noise

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ABSTRACT

An empirical method for prediction of tram noise has been developed based on an environmental noise monitoring program for Oslo's trams. The model is designed to predict noise from individual tram passages. A multivariate regression has been performed based on measurements of acoustical and other parameters for 960 tram passages during 5 years. The estimated SEL and MAX, A-weighted levels from the overall regression have been compared to the measured levels from each passage. Three other investigations have also been made based on the data collected. The first one is an analysis of whether the measurement point has an effect beyond the parameters included in the overall analysis. The second one is an analysis of whether there was any difference between vehicles of the same series. The third one is a control of trams with special spectra against the maintenance records.

1. INTRODUCTION

The trend towards denser and bigger urban areas on the one hand and the desire to avoid modes of transport using fossile fuel on the other will increase the demand for electrically powered mass transport like trams. This leads to more people being exposed to noise from trams, but good results with quiet trams have been reported [1].

The noise monitoring program for the trams of Oslo was originally started in 2007 as part of ISO 14000 certification for Sporveien, the publicly owned company that runs the trams and metros of Oslo. Initially in 2007 the measurements were made in 8 points with at least 10 tram passages in each of the points. The program was designed to uncover longterm trends in the noise emission from the trams of Oslo through yearly measurements. Later, in 2010, the measurements of rail quality were introduced. In 2012 the first prediction method for SEL and MAX, A-weighted sound level from individual tram passages, was presented [2]. There are two main types of tram in Oslo. There are 40 of the older type SL-79, and 32 of the more recent type SL-95.

Different types of track would be expected to results in different noise emission [3]. There are three types of track in Oslo:

- Rails embedded in city streets
- Ordinary ballast track
- "Green track", which is a concrete structure carrying the rails with soil and grass between the rails.

As the data set accumulated over the years, it was decided to investigate whether it could be used for more than an evaluation of a trend in noise emission from Oslo's trams. This article deals with the development of an empirical model for tram noise based on the data set already collected.

Section 2 gives a description of the measurements, how they were performed and which data were collected. Section 3 gives a description of the analysis methods applied for overall statistics. Section 4 gives a description of other types of more detailed analysis. Two types of detailed analysis were made on the A-weighted levels. The first one was made in order to investigate whether some of the measurement points gave different results than would be expected from the overall analysis. The other one was made in order to investigate whether there were especially noisy or especially quiet trams. Finally an investigation was made of whether trams that had a deviant spectrum had a mechanical problem on the given day the noise from it was measured. Section 5 gives a description of the results of comparing the estimated noise from trams with the actually measured values. In Section 6 follows a discussion of results, while finally Section 7 gives suggestions for further research.

2. METHOD OF MEASUREMENT

The method consists of noting all parameters expected to be relevant for the measurements [4]. The measurement series has been repeated every autumn since 2007. A total of 16 points have been used during the years and included in the overall analysis. Table 1 shows a list of the points and the years in which measurements have been made in each point. In each point a series of measurements are made on one day per year. For each day at least 10 tram passages have been measured. The data acquired could be put into three groups:

– Acoustical parameters
– Non – acoustical parameters
– Rail surface corrugation

This information is required in order to develop an empirical model for noise from trams.

2.1. Acoustical parameters

For each passage of a tram the following parameters are noted:

– SEL, A-weighted and in 1/3-oktave bands
– $L_{A(F)max}$ and $L_{(F)max}$ in 1/3-oktave bands

Table 2 shows an example of a part of a measurement log as recorded.

2.2. Non-acoustical parameters

For every site the local geometry is measured once for the site, see figure 1 for an example of the documentation. Most of the immission points have been used every year. Some points have been changed over the years, or they have been suspended for a year or two during construction works on or close to the track. Table 1 gives an overview of the points used each year. In the present article the vertical gradient of the track has been included in our analysis in addition to the parameters previously reported [2].

Every measurement day on a given site the non-acoustical parameters have been noted as follows:

– Weather conditions are noted, temperature, wind speed and wind direction. The measurements are made at close distances, so that the meteorological conditions have minimal influence on the results. It is noted whether background noise is a potential problem.
– For each tram passage the identity of the tram is noted. The identity of the tram is marked with a

Table 1. Measurement points.

#	Point	2010	2011	2012	2013	2014
1	Toftes gate	X	–	–	X	X
2	Grensen	X	–	–	–	–
3	Drammensveien 53	–	X	X	X	X
4	Cort Adelers gate 17	X	X	–	–	–
5	Kirkeveien at Frognerparken	X	X	X	X	X
6	Lilleakerbanen at Hoff	X	X	X	X	X
7	Grefsenplatået	X	X	X	X	X
8	Kirkeveien at Arboes gt	X	X	–	–	–
9	Nygata	X	X	–	–	–
10	Storgata 36 B	X	X	X	X	X
14	Nils Henrik Abels vei	X	–	–	–	–
15	Abbediengveien 5	X	–	–	–	–
16	Thorvald Meyers gt	X	X	–	–	–
17	Forskningsparken	–	X	X	X	X
20	Ekebergbanen	–	–	X	X	X
21	Grefsenveien at Brettevilles gate	–	–	–	–	X

Table 2. Example of part of measurement log.

		2014		
Measurement date		27.oct.14		
Temperature:		13	°C	
Wind speed		1,5	m/s	
Wind direction		-		
Background noise		-	dBA	
Vehicle type/Id #	Direction	Vehicle speed (km/h)	LAF(max) (dB)	SEL (dB)
79/108	Inbound	37	90	93
79/125	Inbound	26	87	91
79/127	Inbound	28	84	89
79/120	Inbound	28	86	90
79/116	Inbound	23	85	89
79/136	Inbound	35	88	92
79/124	Inbound	31	88	91
79/126	Inbound	35	85	89
79/119	Inbound	27	84	89
95/152	Inbound	28	85	91
95/161	Inbound	26	84	90
95/144	Inbound	35	89	94
Average				
SL 79		30	87	91
SL 95		30	87	92

three-digit number clearly marked in front, in the rear and on both sides of the tram. The trams of Oslo are of two main types, SL-79 and SL-95 [5]. Table 3 shows the main technical data of each type of tram.

– Vehicle speed is usually measured with a laser.
– The direction of the tram is noted. By convention “inbound” means towards Oslo city centre, “outbound” means away from city centre. Special noteworthy details from each measurement are also noted.

2.3. Rail corrugation measurements

Since 2010 measurements of rail corrugation were included in the noise monitoring program. These measurements have been made according to ISO3095-2005 [6]. Figure 2 shows an example of the measurements of the rail corrugation. Rail corrugation measurements are made with an ATP-RSA for both rails in both directions past the measurement point. The idea that rail corrugation has an influence on noise from rails and wheels is not new. One author states that: “The roughness of the rail is the main source of the noise emission of the tramcar” [7]. A more recent source talking about the effect of rail grindings on railways indicates that the effect is much more pronounced on new and modern rolling stock than on older vehicles [8]. The instrument used for the measurement is suitable for this type of measurement [9]. Danish railway authorities use rail corrugation measurements for maintenance programs as well as for noise control [10].

Table 3. Main technical properties of SL-79 and SL-95.

Property	SL-79	SL-95
Length	22,4 m	33,1 m
Width	2,6 m	2,5 m
Bogie wheel distance	1,8 m	1,8 m
Wheel diameter	680 mm	680 mm
Weight empty	32,8 tonnes	65,0 tonnes
Highest speed	80 km/h	80 km/h
Seats	71	88
Room for standing persons	66	108
Year built	1982-83 & 1989-90	1998-2000

3. METHOD OF ANALYSIS

The analysis of the results has been divided into three parts:

– A main overall analysis using linear regression with 8 predictors onto two different outcome parameters, SEL A and $L_{A(F)max}$.
– Factor analysis to determine: a) whether the individual measurement point gave any significant contribution beyond that predicted by the overall analysis and b) whether each individual tram gave any significant contribution beyond that predicted by the overall analysis.
– Spectrum analysis from each measurement day to see whether there was an anomaly in the noise from any individual tram.

The main overall analysis is described in section 3.1. The other types of analysis are described in section 4.

3.1. Main overall analysis

The parameters, the method of acquisition and the representation in the statistical analysis of parameters are shown in table 4. The principle of the regression is to find the contributing factors to the noise measured. The

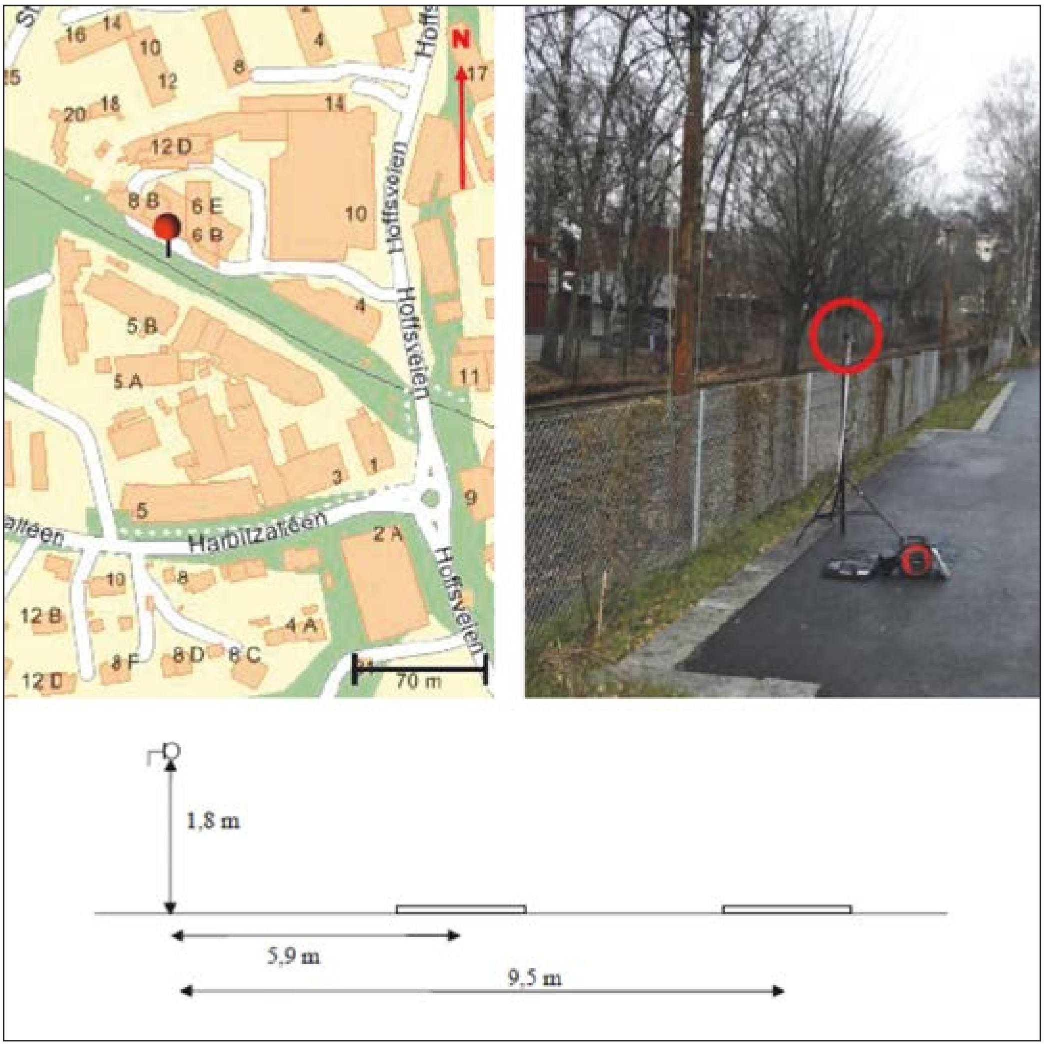

Figure 1. Example of data sheet for measurement point.

Figure 2. Example of field measurement of rail corrugation.

noise level as SEL or MAX, A-weighted, free field, has been defined as an outcome. Other factors have been defined as predictors of the noise. Some of the predictors have been transformed before the run of the regression as described in the following text and in table 4. The assumption has been that the following parameters contribute to the noise level actually measured:

- **Speed of the vehicle,** represented as the base 10 logarithm of the measured speed in km/h. The speed has usually been measured with a laser, and care has been taken to ensure that the speed is measured as the tram is on its way past the microphone. Drivers have been instructed to drive as they would normally do during our measurements. The range of speeds have been between 10 and 70 km/h. The regression factor is termed p_v.
- **Distance** from the track centerline to the microphone. This parameter is only measured once for each measurement point. The distance is represented in the regression by the base 10 logarithm of the distance in meters. The range of distances in the

Table 4. Factors included in overall statistical analysis.

Predictor /factor	Data gathered	Used in analysis after data reduction/ conditioning
Speed (km/h)	Measured with laser	Log_{10} (speed) past the mic
Distance (m)	Distance from track to microphone	Log_{10} (distance)
Year measured	Date	Year, two digits
Tram type (SL 79/SL 95)	Vehicle # (72 trams)	Vehicle type (two types)
Track type	Three types	0,1,2
Rail quality, given as equivalent corrugation spectrum in dB rel. 1 µm	≈ 100 parameters per rail	One number per track
Time since grinding	Number of years	Number of years
Gradient	Approximate vertical height difference per traversed meter horizontally	Gradient in ‰
Outcome / response		
Noise	≈ 60 parameters per passage of vehicle	Single number rating, corrected for influence of buildings, in SEL or MAX A-weighted

measurements presented is 2 to 13 meters. The regression factor is termed p_d.

– The year has been entered as a two-digit number omitting the preceding 2-0. The regression factor is termed p_y.
– Tram type has been entered as 0 for SL95, 1 for SL79. With only two alternatives a linear regression is equivalent to a factor analysis. The regression factor is termed p_s.
– Track type has been entered as 0 for city street, 1 for ballast track and 2 for green track. It was originally assumed that the green track would be the quietest and the city street would be the noisiest. The regression factor is termed p_t.
– **Rail quality** has been entered as the single number rating for the most corrugated one of the two rails on a track. The value ranges from around 15 for the best new track to over 30 for the most worn tracks investigated. The regression factor is termed p_c.
– **Time since grinding** has been entered as an integer number of years since the last grinding, this is normally in the range 0 to 5. Some tracks were ground during the summer before the autumn measurements, sometimes the track was new. For lines with little traffic there may be a 5 year interval between grindings. The regression factor is termed p_g.
– **Gradient** is given in ‰ average vertical height difference per unit of horizontally traversed distance during the measurements. The number ranges from 0, flat, to 75, the steepest descent investigated. The regression factor is termed p_h.

Noise is given as SEL and MAX, FAST, free field, for each immission point. The correction for reflections from building facades has been entered as 3 dB if there are buildings on one side of the track, 6 dB if there are buildings on both sides of the track.

The main analysis of the contribution of each predictor has been performed for both SELA and MAX, FAST AS for three cases:

– All measurements
– All measurements with vehicle speed ≤ 30 km/h
– All measurements with vehicle speed ≥ 30 km/h

Noise from railbound traffic is dominated by different sources at different speeds. There is a minimum noise at standstill, and the contribution of this basic noise is reduced as rolling noise takes over at increasing speed. This means it seems reasonable to split the analysis between different speed ranges. The choice of 30 km/h as a dividing line is made because this is an established convention in the Oslo area. For the Oslo metro, different parameters are already used for noise calculations at speed above 30 km/h and below 30 km/h. It is also part of the consideration that the speed limit for road traffic in purely residential areas in Oslo is often 30 km/h, which is the kind of area where the tram would be expected to be a problem at short range.

The measurement points as distinct entities are not directly included in the overall analysis, only the distance and the parameters of the track (track type, rail corrugation and years since last grind). The overall analysis does not include detailed investigation of the spectrum.

The use of a continuous variable for tram type is not problematic. As long as there are only two distinct values, a linear regression using a continuous variable is equivalent to defining it as a categorical variable. For the track type, however, the situation is a bit more problematic. It seemed natural to assume that city street would be the noisiest type of track, green track the quietest with the ballast track somewhere in the middle. Investigations into this problem using different type of analysis have given inconclusive results. One possible reason is that there are no measurement points with green track where both types of tram run. This may lead to confounding of the results.

4. OTHER ANALYSIS

4.1. Factor analysis

The term factor analysis is used about further analysis focusing on a smaller detail of the overall picture. This type of statistical analysis has been made in order to look for explanations to the uncertainties in the overall analysis. Two possible contributors have been singled out for investigations: measurement points and the individual trams.

4.1.1. Measurement point

This analysis was made in order to investigate whether the measurement points had some distinct influence beyond that included in the parameters given above. This was done by including the measurement point as a categorical variable (called factor in the statistics program R) in the overall regression analysis.

4.1.2. Tram identity

There are only 72 trams in Oslo, and there have been measured 960 passages. All the trams have been measured more than once, some vehicles more than 30 times. This means that running the statistical analysis with the tram identity as a categorical variable (called factor in the statistics program R) might reveal more new information as to whether there is a difference between the vehicles.

4.2. Detail analysis of individual measurement series 2012

It was decided in 2012 to investigate whether there was any clear connection between the spectrum of particularly noisy trams and the state of maintenance. Spectrum analysis has not been included in the overall analysis. The spectrum analysis has been performed for each individual measurement point individually. The purpose of this analysis was to see whether there was any way to reduce noise complaints by adjusting maintenance routines. For each measurement day in a given point the average spectrum was plotted together with the spectrum for particularly noise vehicles. The results were checked against the maintenance records of the trams. Roughly half the cases of a special spectrum could be explained by the maintenance records. One case is shown in figure 3, another in figure 4. The case in figure 3 was found to be due to a leak in a hydraulic system on that measurement day, leading to a compressor running continuously on tram # 101. This compressor normally runs at short intervals only. And thus this tram emitted much more high frequency noise on that day than the other trams operating on that line. The case in figure 4 was not explained by the maintenance records. However the driver complained about noise while braking, so something was most likely wrong with the vehicle.

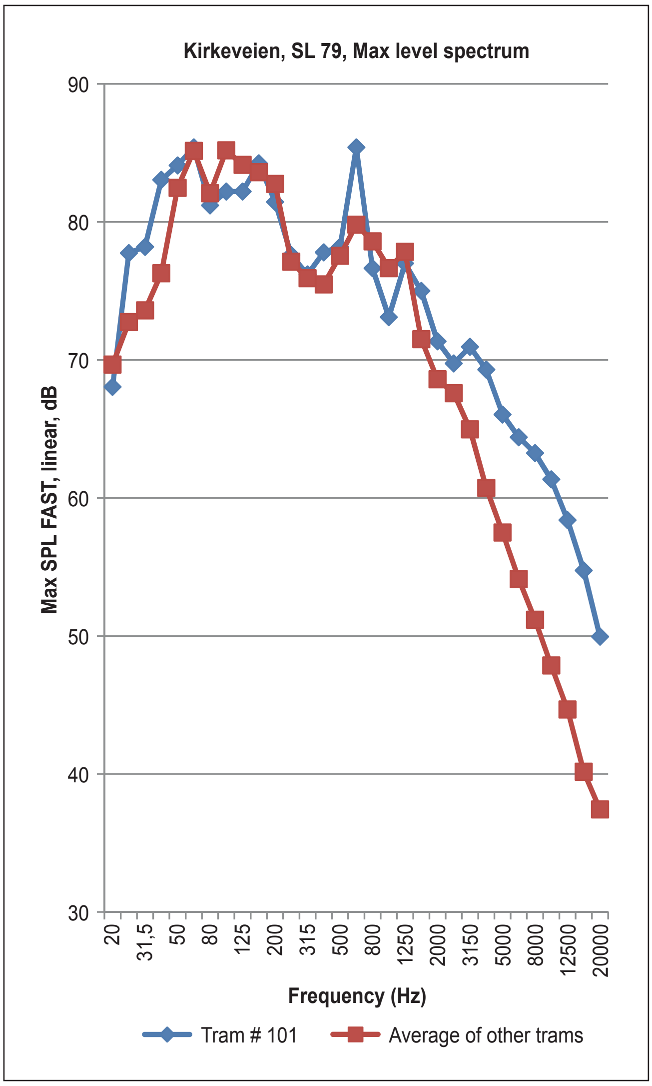

Figure 3. Example of a noisy tram.

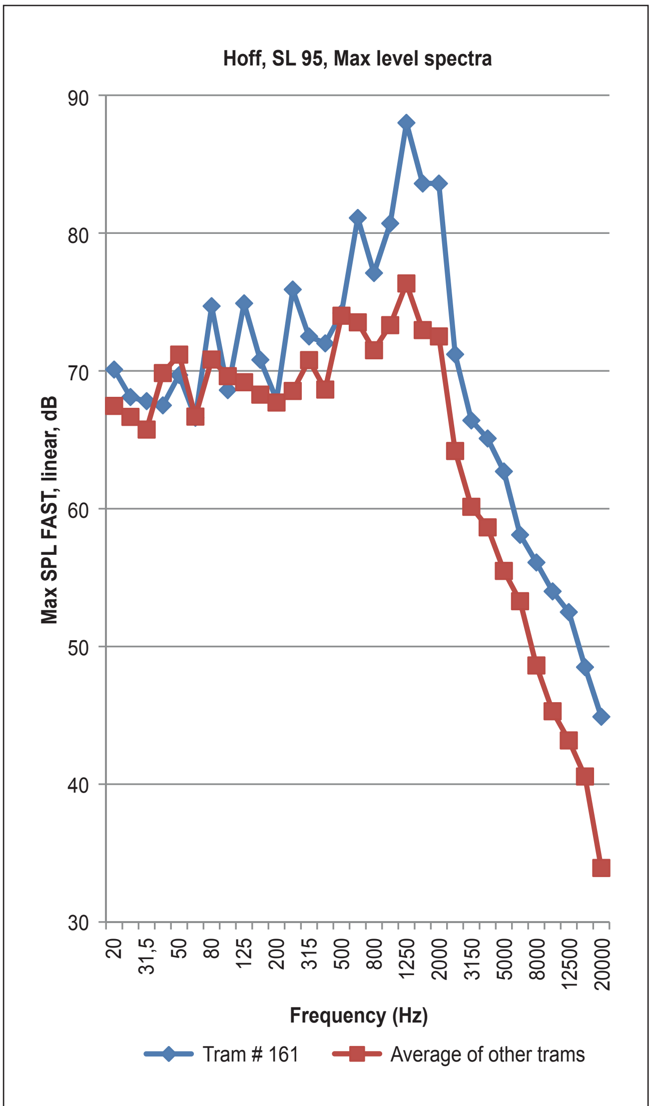

Figure 4. *Example of a noisy tram.*

In 2013 a similar type of analysis yielded no results. No special spectra were found that could be matched with the maintenance data base. A probable explanation could be that the noisy events found in 2012 changed the attitude of the people working in maintenance at the tram garage, so that the trams were generally kept in a better state.

5. DEVELOPMENT OF EMPIRICAL PREDICTION METHOD

The concept of developing a prediction method based on field measurements only is not new [11]. This is an alternative to developing theoretical models especially suited for trams [12, 13]. The main purpose of the present article is to show the results of developing a local empirical prediction method. The resulting formula for the estimated noise level is as follows:

$$
\begin{aligned}
L = L_0 + p_v(\log(10)\text{speed}) + p_d(\log(10)\text{distance}) + \\
+ p_y\ {}^*\text{year} + p_s\ {}^*\text{tram type} + p_t\ {}^*\text{track type} + \\
+ p_c\ {}^*\text{rail quality} + p_g\ {}^*\text{time since grinding} + p_h\ {}^*\text{gradient}
\end{aligned}
$$

Where:

- L_0 is the estimated intercept from the regression analysis
- P_v is the regression factor for the log (base 10) of the tram sped
- P_d is the regression factor for the log (base 10) of the distance from the track to the microphone
- P_y is the regression factor for the year the measurement was made
- P_s is the regression factor for the tram type
- P_t is the regression factor for the track type
- P_c is the regression factor for the rail quality given as corrugation in dB rel. 1 µm
- P_g is the regression factor for the time since last grinding of the track
- P_h is the regression factor for the vertical gradient

The other parameters have been described in detail in section 3.1.

It should be noted that the model actually predicts the noise from each individual tram passage. The accuracy to be expected from a calculation of an aggregated level like L_{den} or $L_{eq,24h}$ should be much better than the accuracy for an individual passage of trams. The same goes for the prediction of $L_{5AF,}$ which is meant to be the expected second highest maximal level from 20 passages of trams.

The development of a method consisted in finding which parameters to include in the regression model. In principle this can be done by including more parameters in the regression as long as the r^2 continues to increase [2]. These first attempts at a regression used the first 7 parameters described in section 3.1: Speed, distance, tram type, corrugation, year of measurement, track type and time since grinding. Later the vertical gradient has also been included, as this has been shown to be of importance in the development of an empirical prediction method for another city, Kosiçe, Slovakia [11].

The results from the regressions at speeds up to 30 km/h and at speeds from 30 km/h upwards were compared with the actually measured noise level in each individual case for both SEL A and $L_{A(F)max}$. The residue has been plotted for each tram passage. The residue is defined as measured level minus estimated level.

6. RESULTS AND DISCUSSION

The results of the analysis are discussed below. The results are divided into overall linear regression, factor analysis and empirical prediction.

6.1. Overall linear regression

The results of the overall linear regression are shown in table 5. The regression factors have been calculated for all the 6 investigated cases from section 3.1, SEL and MAX, A , FAST. Some characteristics of the regression coefficients are reasonable. For both SEL and MAX the overall correlation is higher at speeds from 30 km/h upwards than at lower speeds. The speed dependence is steeper at higher speeds. This agrees with intuition, since some noise from the tram is present even at standstill. The faster the tram goes, the smaller the contribution of noise from machinery that is independent of driving speed becomes. The distance attenuation is essentially the same independent of speed. Distance attenuation will not necessarily be attributable to a line source or point source, since all the measurements have been made at a distance shorter than the greatest dimensions of the tram. The greatest measurement distance is 13 meters, and the smallest of the trams has a length of 22 meters. This is a limitation regarding the theoretical description of the sound field, since all measurements have been made in the near field of the source. It also seems clear that the difference in noise between the two types of tram is greater at higher speeds.

There is a theoretical problem in running the analysis on MAX, A –weighted level. Normally with railbound noise sources like trams the maximal levels in different frequency ranges will occur at different times. For example noise from braking or curve squeal could easily come at different times than noise from bogie resonances. This means that the maximal A-weighted level is usually slightly lower than the A-weighted sum of maximal 1/3-octave band levels. In our as yet unpublished experience this discrepancy usually amounts to 2-3 dB.

6.2. Factor analysis

The results of the two types of factor analysis made on the whole data set will be described below.

6.2.1. Measurement points

The factor analysis of measurement points showed that some of the measurement points had a statistically significant effect on the noise beyond that which could be explained by the overall statistical analysis. The presented difference is the difference left after correction for all other parameters that change from immision point to immision point, distance, track type, rail corrugation and gradient. A full printout of these results is shown in table 6. Points 7 and 9 are slightly noisier than the others, points 5, 6 and 10 are slightly quieter. Further investigation will include horizontal curvature in the statistical analysis which may help to explain these local differences .

6.2.2. Individual vehicles

There are 960 passages of 72 vehicles included in the database of this investigation. It was decided to look for whether any of the trams were particularly quiet or noise even when corrected for all other factors included in the analysis. Factor analysis using the tram identity gave as a result that the trams 110, 131, 132 and 138 have been

Table 5. Regression coefficients.

PARAMETER	SEL A – regression factors			MAX A – regression factors		
	All	Up to 30 km/h	30 km/h and faster	All	Up to 30 km/h	30 km/h and faster
Intercept, p_0	67,187077	76,538546	59,461542	60,235397	73,359345	50,80419
Logspeed, p_v	13,310782	8,929057	15,318161	18,415826	12,124811	20,926071
Logdist, p_d	–4,79454	–4,661183	–4,218583	–7,091294	–6,303489	–6,645283
Year, p_y	–0,037599	–0,283036	0,253725	–0,067452	–0,410346	0,28885
Train, p_s	–2,262893	–1,510515	–2,973198	–2,559884	–1,22345	–3,640547
Track, p_t	0,76528	0,84514	0,690741	0,830644	0,911343	0,78178
RSA, p_c	0,144813	0,099541	0,198706	0,050191	–0,022064	0,119541
Lastgrind, p_g	–0,372942	–0,11018	–0,614146	–0,494909	–0,234422	–0,744633
Gradient, p_h	0,015315	0,019999	0,015661	0,021583	0,029522	0,0207036
			Correlation			
r^2	0,531	0,4241	0,4663	0,5708	0,3935	0,5234

Table 6. Estimated influence of the measurement point.

Estimate Std. Error t value Pr(>|t|)
MP(MP01) 0.10710 0.55643 0.192 0.847413
MP(MP02) 0.06366 0.82141 0.078 0.938240
MP(MP03) -0.16124 0.60002 -0.269 0.788201
MP(MP04) -1.11884 0.71385 -1.567 0.117376
MP(MP05) -2.64880 0.64395 -4.113 4.24e-05 ***
MP(MP06) -2.46146 0.50404 -4.883 1.23e-06 ***
MP(MP07) 1.85212 0.50156 3.693 0.000235 ***
MP(MP08) -1.25658 1.07513 -1.169 0.242796
MP(MP09) 2.95450 0.81764 3.613 0.000318 ***
MP(MP10) -1.34858 0.38285 -3.522 0.000448 ***
MP(MP14) 1.60001 1.10588 1.447 0.148281
MP(MP15) -1.80250 1.00982 -1.785 0.074589 .
MP(MP16) -0.89565 0.71667 -1.250 0.211707
MP(MP17) 1.03587 0.53955 1.920 0.055177 .
MP(MP20) 1.08895 0.61228 1.779 0.075644 .
MP(MP21) 2.99 Not yet valid data

quieter than predicted from the overall analysis. Trams 153, 163, 164 and 166 have been noisier. All the apparently quiet trams are of the SL-79 series, and all the apparently noisy trams are of the SL-95 series. A possible explanation is that the SL-95 series is generally of a poorer mechanical quality than the SL-79 series, even though the trams of the SL-79 series are older.

6.3. Empirical prediction

One possible way of determining the practical applicability of the work is determined by how well the models actually can predict noise from an individual tram passing. In figure 5 through 8 are shown the differences between the estimated and measured level for each passing tram. The estimate is based on the overall regression for the 4 selected subcases:

– Measured vs. estimated noise – SEL A, v ≤ 30 km/h, shown in figure 5
– Measured vs. estimated noise – SEL A, v ≥ 30 km/h, shown in figure 6
– Measured vs. estimated noise – MAX A, v ≤ 30 km/h, shown in figure 7
– Measured vs. estimated noise – MAX A, v ≥ 30 km/h, shown in figure 8

The figures show that the estimated level lies within ± 5 dB for about 85% of the individual passages. The

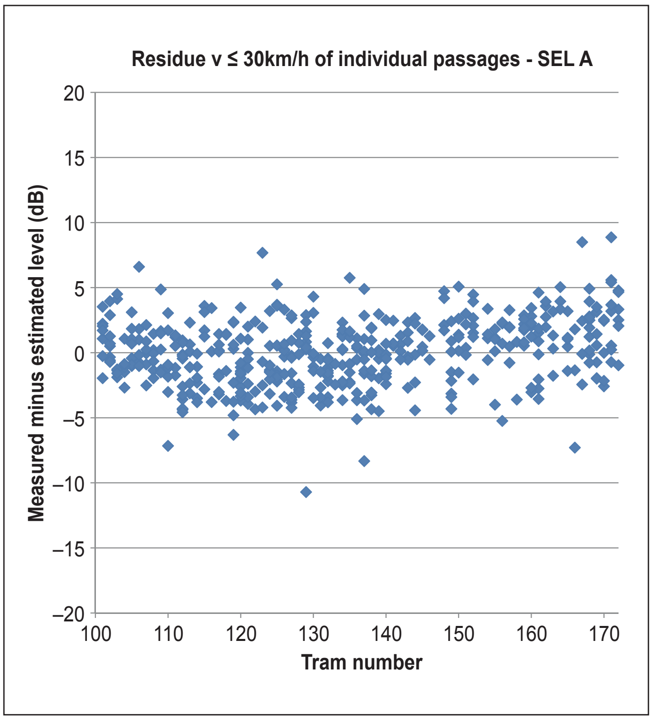

Figure 5. Measured vs. estimated noise – SEL A, v ≤ 30 km/h.

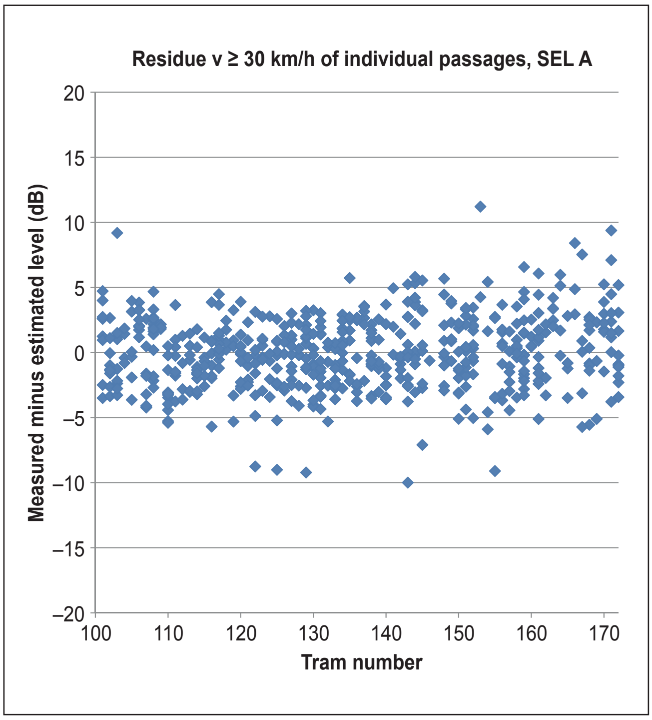

Figure 6. Measured vs. estimated noise – SEL A, v ≥ 30 km/h.

passages where the measured maximal level exceeds the estimated level by 10 dB or more are exceptional cases. This means the formulas obtained can be used for prediction of aggregate measures of equivalent levels like L_{eq} or L_{den}. They can also be used for estimates of L_{max} or L_{5AF} as long as all the parameters are inside the range that has been in use.

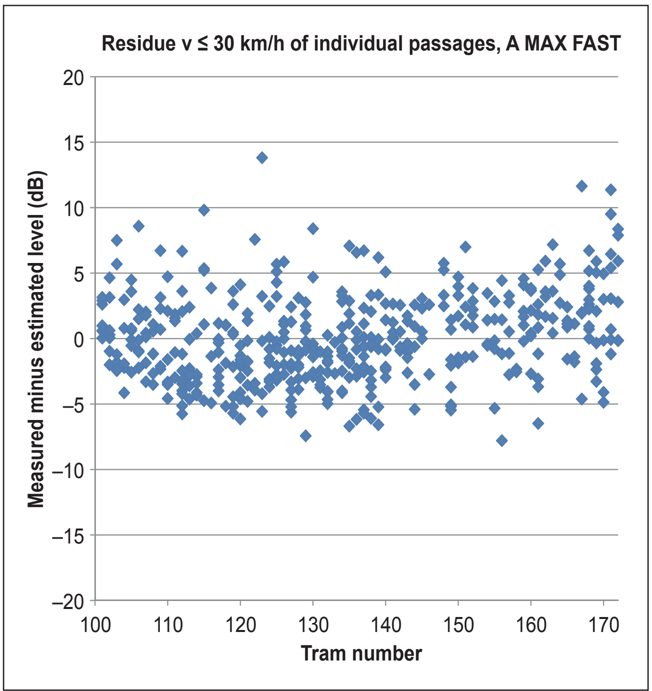

Figure 7. Measured vs. estimated noise – MAX A, v ≤ 30 km/h.

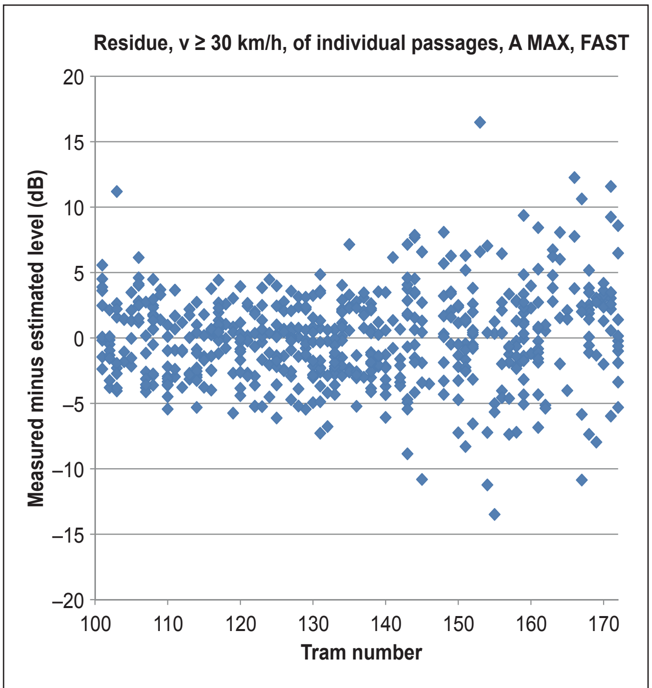

Figure 8. Measured vs. estimated noise – MAX A, v ≥ 30 km/h.

It is generally not advisable to remove especially noisy or escpecially quiet tram passages (outliers) from a multivariate statistical analysis unless there is something clearly wrong in the measurement in question. The largest difference between estimated and measured SEL is 11,2 dB. The largest difference between estimated and measured MAX is 16,5 dB. Both these are from the same passage of tram # 153, which has been identified as a noisy tram.

7. FURTHER RESEARCH

The results as given are only applicable to the trams of Oslo. However the methods described are applicable to any urban railbound transport system. It would be of great interest to try the methods in other cities. A program for noise monitoring of the metro trains of Oslo is under planning and expected to start in the spring of 2016.

8. CONCLUSIONS

An environmental noise monitoring program has been described. It has been shown that this environmental noise monitoring could be developed into an empirical model for noise prediction using multivariate statistics.

9. ACKNOWLEDGEMENTS

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Statistical analysis has been performed with the program package R, which is available for free and widely used in many fields of research. The user interface R Commander from NMBU (The Norwegian University of Bioscience, at Ås) has also been applied. This user interface is also available for free.

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