Combined effects of source measures on road traffic noise annoyance in three major European cities

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Source related measures receive increasing attention in road noise mitigation purposes throughout the EU. Broad application of silent roads is stimulated in an increasing number of countries and since road surfaces exhibit a spread of up to 15 dB(A) between the loudest and most silent specimen, effects can be impressive. Silent tyres for passenger cars and heavy vehicles have similar attention. The EU regulation on tyres (2001/43/EC) focuses on phasing out loud tyres. National programs focus on the stimulation of the use of silent tyres without affecting safety and fuel consumption. In the present tyre market a "natural" spread of 6 to 7 dB(A) can be found for passenger cars tyres and 4 to 5 dB(A) for the traction tyres of heavy vehicles. Type-testing of vehicles does result in the application of more silent techniques having an effect on inner-city noise emission of road traffic. Although the effects of individual measures can be found, very less information is available on combined effects of measures. This type of information is nowadays considered essential in the appreciation of noise reducing scenarios. In the present paper scenario-studies were performed to predict the overall effect of the combination of silent tyres, silent vehicles and silent road surfaces in urban situations on the annoyance of the population. The study was performed for three European cities, Amsterdam, Munich and Madrid, each considered representative for a European regional area. The applied source related effects were based on results of research performed within the frame work of other studies within our organisation and performed by third parties.

This project was funded by the Dutch Ministry of Housing, Spatial Planning and Environmental Affairs. It was carried out within the framework of the EU working group on Health and Socio Economic Aspects (WG-HSEA).

1 Introduction

The effect of source measures on the noise production of road traffic in relation to the number of annoyed and highly annoyed people is calculated for three major European cities: Amsterdam, Madrid and Munich.

These calculations are carried out on base of:

- a noise calculation model based on a general accepted propagation calculation method and the Netherlands emission model [1], but modified with the recent information from the EU 5th and 6th framework projects Harmonoise and Imagine in which and rolling noise and engine noise are separated (see §2);
- the general dose effect relations for road traffic noise as developed by the European Commission, and a special one addressing interrupted traffic flows (see §3);
- GIS-based noise maps of Amsterdam, Madrid and Munich made by M+P in a project for the European Environment Agency (EEA) containing figures on inhabitants, vehicle fleet and infrastructure for the year 2010 (see §4).

The calculations are carried out for three scenarios:

- Scenario I: 2010: no extra effort
- Scenario II: 2010: extra effort
- Scenario III: 2010: much extra effort

In this study, the "effort" parameter indicates the amount of effort that is put into the noise source policy for vehicles, tyres and road surfaces. The quantitative definition of the scenarios is given in §5.

The results were then calculated in terms of the exposure of the population in 1 dB classes. With these data and the indicated dose-effect relations the fraction of annoyed and highly annoyed persons in the population was found. These results are presented in §6.

2 Noise emission model

The calculation models for the three cities are built up from the following parts:

- a model describing the noise production of road vehicles, distributed in a rolling noise part and a propulsion noise part, for different speeds, vehicle classes and road surfaces. In this model we distinguish between free flowing traffic and interrupted traffic;

- a model defining the properties of the propagation from source to receiver based on a straight forward propagation in which the effect of screening by housing rows is taken into account in a general way;
- a GIS model of the three mentioned cities, giving for each road section in the city the vehicle fleet composition, vehicle intensity, road surface and speed. Next the distance from the housing facades to the centre of the road and the density of the population, build up from the number of dwellings at each layer per meter, the number of layers and the average occupation per dwelling.

2.1 Noise emission – constant flow

For constant driving conditions the emission formulae of method I (SRMI) of the Dutch calculation scheme are regarded. The noise emission factors for light (*lv*) and heavy (*hv*) vehicles are based on measurements of traffic on several one to three year old dense asphalt road surfaces. The emission factors are given as a function of the average vehicle speed *v* and the number of vehicles per hour *Q*:

$$E_{lv} = 69{,}4 + 27{,}6 * \log (v_{lv}/v_{ref,lv}) + 10 * \log(Q_{lv}/v_{lv})$$
$$\text{with } v_{ref,lv} = 80 \text{ km/h} \qquad (1)$$

$$E_{hv} = 76{,}0 + 17{,}9 * \log (v_{hv}/v_{ref,hv}) + 10 * \log(Q_{hv}/v_{hv})$$
$$\text{with } v_{ref,hv} = 70 \text{ km/h} \qquad (2)$$

For this study the formulae are rewritten in the following form:

$$E_{veh.cat.} = a + b*\log(v_{veh.cat.}) + 10*\log(Q_{veh.cat.}) \qquad (3)$$

resulting in:

$$E_{lv} = 16{,}9 + 17{,}6 * \log (v_{lv}) + 10 * \log(Q_{lv}) \qquad (4)$$

$$E_{hv} = 43{,}0 + 7{,}9 * \log (v_{hv}) + 10 * \log(Q_{hv}) \qquad (5)$$

Now, for both light and heavy vehicles formulae are deduced for the rolling noise and engine noise separately:

$$E_{lv\ rolling} = 7{,}3 + 21{,}5 * \log (v_{lv}) + 10 * \log(Q_{lv}) \qquad (6)$$

$$E_{lv,engine} = 20{,}3 + 13{,}6 * \log (v_{lv}) + 10 * \log(Q_{lv}) \qquad (7)$$

$$E_{hv,rolling} = 15{,}0 + 21{,}5 * \log (v_{hv}) + 10 * \log(Q_{hv}) \qquad (8)$$

$$E_{hv,engine} = 51{,}0 + 2{,}0 * \log (v_{hv}) + 10 * \log(Q_{hv}) \qquad (9)$$

The Harmonoise emission formulae assume a linear relation between the level of the propulsion noise and the vehicle speed but comparison between the two approaches demonstrated that this caused no major difference [2].

The relations between vehicle speed and noise emission are depicted in figure 1 and figure 2 for light and heavy vehicles respectively. The energetical sum of the noise emission of rolling and engine noise in both cases matches the SRMI-values for the overall noise emission for all relevant speeds. Equations (6)-(9) are used in this report to describe the noise emission of light and heavy vehicles.

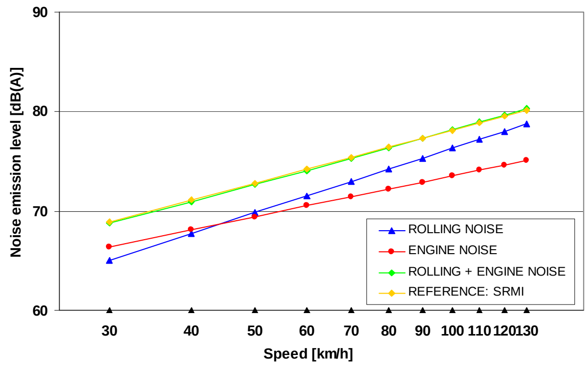

Figure 1: Noise emission of light vehicles

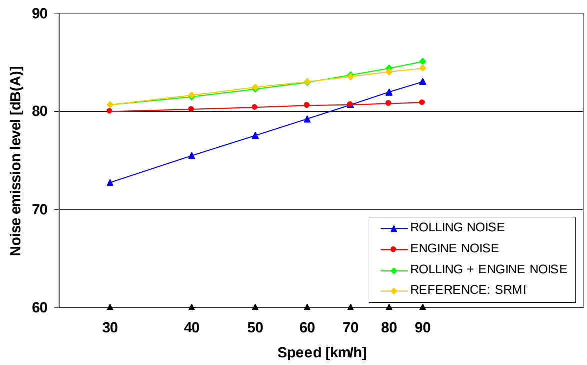

Figure 2: Noise emission of heavy vehicles

2.2 Noise emission – interrupted flow

For a description of the noise emission of an interrupted traffic flow the formulae describing the engine noise are rewritten by adding 5 dB(A) to the engine noise emission formulae (7) and (9) providing the formulae (10) and (11). This factor of 5 dB(A) represents the observed propulsion noise increase due to an acceleration of 0,8 m/s^2 for cars and about 0,4 m/s^2 for HDV's. The rolling noise component remains the same.

$$E_{lv,engine} = 25{,}3 + 13{,}6 * \log (v_{lv}) + 10 * \log(Q_{lv}) \qquad (10)$$

$$E_{hv,engine} = 56{,}0 + 2{,}0 * \log (v_{hv}) + 10 * \log(Q_{hv}) \qquad (11)$$

In figure 3 and figure 4 the resulting noise emission of light and heavy vehicles at different speeds is shown graphically.

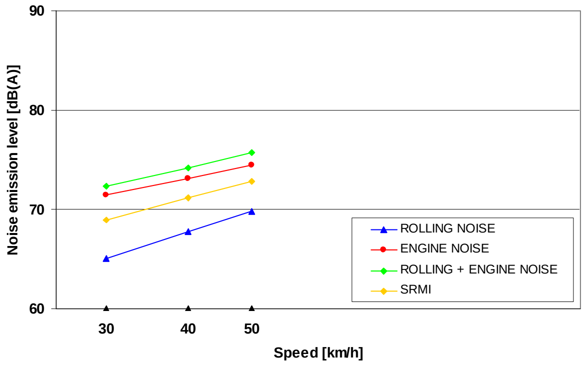

Figure 3: Noise emission of accelerating light vehicles

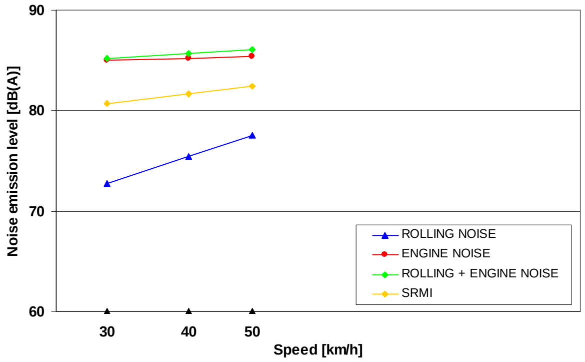

Figure 4: Noise emission of accelerating HDV's

3 Noise exposure

The noise nuisance is calculated using the dose-effect relations for road traffic noise exposure [3]:

$$\%A = 1.795{*}10^{-4}\ (L_{den}-37)^3 + 2.110{*}10^{-2}\ (L_{den}-37)^2 + 0.5353\ (L_{den}-37) \qquad (12)$$

$$\%HA = 9.868{*}10^{-4}\ (L_{den}-42)^3 - 1.436{*}10^{-2}\ (L_{den}-42)^2 + 0.5118\ (L_{den}-42) \qquad (13)$$

in which %A denotes the percentage of annoyed people and %HA denotes the percentage of people who are highly annoyed.

Based on the conclusion in [4] in urban situations interrupted vehicle flows cause higher annoyance than free flow road traffic at comparable L_{DN} levels. At levels of around 65 dB(A) the % highly annoyed (%HA) is stated to be 6% higher than for constant speeds. This finding is included in this model by adapting the formulae (12) and (13) in such a way that in both cases at levels of around 65 dB(A) the % (highly) annoyed is 6% higher than for the condition at constant speed, resulting in:

$$\%A = 1.795{*}10^{-4}\ (L_{den}-37)^3 + 2.110{*}10^{-2}\ (L_{den}-37)^2 + \mathbf{0.7353}\ (L_{den}-37) \qquad (14)$$

$$\%HA = 9.868{*}10^{-4}\ (L_{den}-42)^3 - 1.436{*}10^{-2}\ (L_{den}-42)^2 + \mathbf{0.7618}\ (L_{den}-42) \qquad (15)$$

The four dose-effect relations which are used in this study are presented graphically in figure 5.

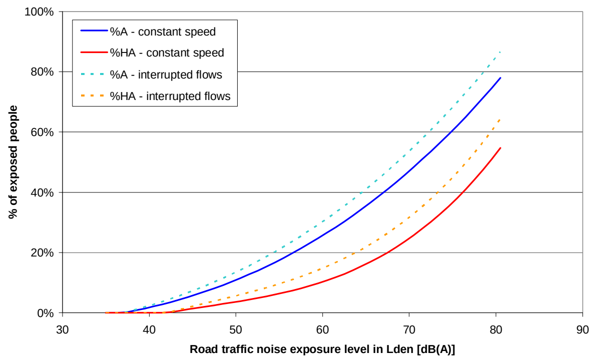

Figure 5: Road traffic noise dose-effect relations for flows with a constant speed and interrupted flows

4 Noisemaps

The M+P-noisemaps of Amsterdam, Munich and Madrid are described in previous reports [5][6]. Examples are shown in figure 6, 7 and 8 respectively. The noisemaps are made in a Geographical Information System (GIS). The noisemaps are street-orientated, which means that all relevant data on traffic, population and infrastructure are designated to street sections from crossing to crossing. All data on traffic, population and infrastructure are based on predictions for the year 2010. The input data in the noisemaps include:

- number of light/heavy vehicles per day/evening/night;
- speed of light/heavy vehicles;
- road surface type (dense or porous);
- average distance to first line dwellings;
- noise barrier between road and first line dwellings;
- number of inhabitants on first/second line dwellings (the effect of a noise barrier is estimated to be on average 10 dB(A)).

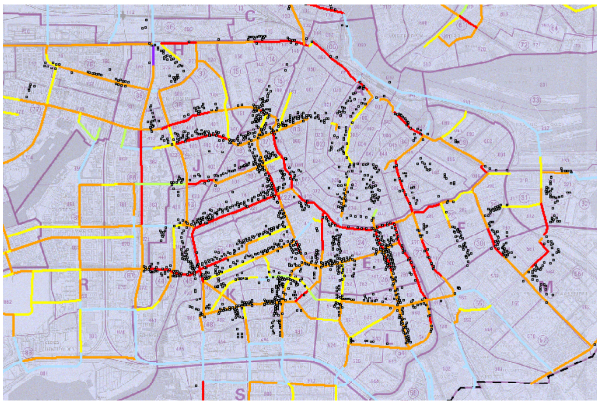

Figure 6: M+P noisemap of Amsterdam

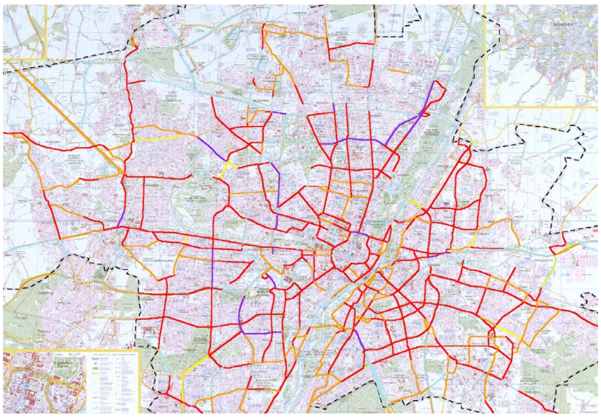

Figure 7: M+P noisemap of Munich

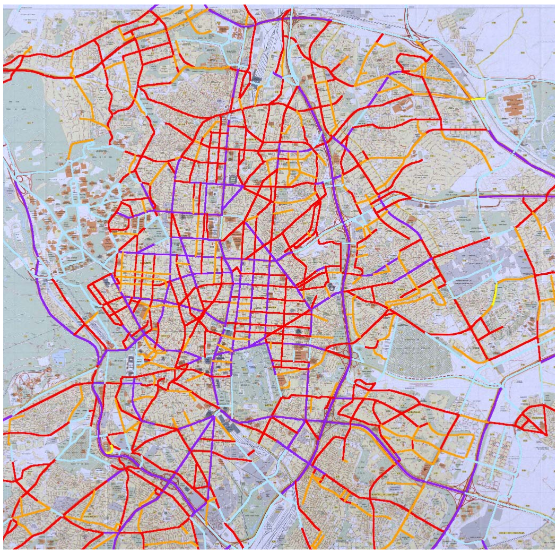

Figure 8: M+P noisemap of Madrid

For this study some refinements were introduced in the noisemaps to enable a more detailed investigation on the effects of source measures on the noise exposure:

- The overall noise emission of light and heavy vehicles is divided into a rolling noise part and a engine noise part;
- The street sections are divided into a start and end segment of 100m for acceleration/deceleration driving conditions and the remaining part for cruising driving conditions. The 100m sections are chosen in relation with the assumed acceleration values and the average vehicle speed after 100m. For the first and last 100m-segment of every road the noise emission formulae for acceleration conditions are used and for the remaining part the noise emission formulae for the cruising conditions are used;
- Originally the noisemaps were used to determine L_{dn} levels and therefore the vehicle population was divided into the day and the night period; now based on default values for the vehicle distribution a proportion of all vehicles is designated to the evening period to be able to calculate the L_{den};
- The noise exposure of dwellings is reported in 1 dB(A) instead of 5 dB(A) classes;
- Dose-effect relations are included in the noisemaps.

In the noisemaps typical cruising speeds of 30 to 120 km/h for light vehicles and 30 to 80 km/h for heavy vehicles are used. For acceleration conditions a typical average speed of 30 km/h for light and heavy vehicles is used, providing a more reliable lower rolling noise level at these first meters of a road section.

5 Definition of scenarios

In this study the effects of source measures are defined for three scenarios:

- Scenario I, no extra effort: a slight reduction of tyre noise caused by choice of slightly less noisy tyres by a relatively small group of consumers and transport companies for comfort reasons and limited application of low noise roads by authorities to meet citizens complaints;
- Scenario II, extra effort: a reduction of tyre and engine noise caused by choice of less noisy tyres and vehicles by the consumers and transport companies for comfort reasons, broader application of low noise roads by authorities to meet citizens complaints;
- Scenario III, much extra effort: all potential of silent techniques is deployed by both a broad phasing out of noisy tyres, vehicles and surfaces and by broad application of low-noise techniques due to public awareness.

The effects of source measures in the three defined scenarios are given in table 1, table 2 and table 3 as a reduction of the values *a* in the source description formulae (4) and (5).

Table 1: Effects of source measures in scenario I

	Engine noise dB(A)		Rolling noise dB(A)	
	lv	hv	lv	hv
Silent road surface (dense)	-	-	1	0
Silent road surface (porous)	0	1	1	1
Silent tyres	-	-	1	0
Silent engine	0	1	-	-

Table 2: Effects of source measures in scenario II

	Engine noise dB(A)		Rolling noise dB(A)	
	lv	hv	lv	hv
Silent road surface (dense)	-	-	2	1
Silent road surface (porous)	1	2	3	2
Silent tyres	-	-	2	1
Silent engine	1	3	-	-

Table 3: Effects of source measures in scenario III

	Engine noise dB(A)		Rolling noise dB(A)	
	lv	hv	lv	hv
Silent road surface (dense)	-	-	3	2
Silent road surface (porous)	1	2	4	3
Silent tyres	-	-	3	2
Silent engine	2	5	-	-

The noisemap of Amsterdam contains road surfaces which are already porous. These road surfaces have been added an additional 2 dB(A) reduction for light and heavy vehicles in the calculations for scenario I.

6 Results

In table 4 the number of inhabitants is given for the three cities as well as a percentage of this total number indicating the exposure of inhabitants to road traffic noise of either mainly free flowing traffic or interrupted traffic.

Table 4: Inhabitants exposed to road traffic noise

city	total number of inhabitants in 2010	mainly exposed to noise from	
		free flowing traffic	interrupted traffic flow
Amsterdam	750.000	78%	22%
Munich	1.325.000	82%	18%
Madrid	3.090.000	84%	16%

All calculated L_{den} levels per street, separating the free flowing and the interrupted traffic, taking into account the number of people living in dwellings facing the road and those living behind the most-exposed first line of dwellings, taking into account also the dose-effect relations as mentioned, result in the figures presented in table 5, table 6, and table 7 for the percentage of (highly) annoyed people in Amsterdam, Munich and Madrid respectively. Base year is 2005, predictions are made for 2010.

Table 5: Noise annoyance: Amsterdam

	2005	Scenario I	Scenario II	Scenario III
Annoyed	17,0%	15,6%	12,5%	10,8%
Highly annoyed	7,0%	6,3%	4,8%	4,0%

Table 6: Noise annoyance: Munich

	2005	Scenario I	Scenario II	Scenario III
Annoyed	32,5%	29,9%	25,1%	22,2%
Highly annoyed	15,4%	13,8%	10,9%	9,4%

Table 7: Noise annoyance: Madrid

	2005	Scenario I	Scenario II	Scenario III
Annoyed	34,7%	31,9%	26,8%	24,0%
Highly annoyed	17,1%	15,2%	12,0%	10,4%

If only the separate source measures on the engine, tyres or road surfaces are regarded, the resulting effects of the three scenarios are given in table 8, table 9 and table 10 for the reduction of the number of annoyed and highly annoyed people in Amsterdam, Munich and Madrid respectively for the year 2010.

Table 8: Reduction of noise annoyance due to noise source measures: Amsterdam

	Scenario	Roads	Tyres	Engine	Combined
%A	I	1,0%	0,4%	0,2%	1,4%
	II	2,9%	0,8%	1,1%	4,5%
	III	3,4%	1,1%	1,9%	6,2%
%HA	I	0,5%	0,2%	0,1%	0,7%
	II	1,4%	0,4%	0,6%	2,2%
	III	1,6%	0,6%	1,0%	3,0%

Table 9: Reduction of noise annoyance due to noise source measures: Munich

	Scenario	Roads	Tyres	Engine	Combined
%A	I	1,8%	0,7%	0,3%	2,6%
	II	4,8%	1,5%	1,6%	7,4%
	III	5,7%	2,1%	2,5%	10,3%
%HA	I	1,1%	0,4%	0,2%	1,6%
	II	3,0%	0,9%	1,0%	4,5%
	III	3,5%	1,3%	1,6%	6,0%

Table 10: Reduction of noise annoyance due to noise source measures: Madrid

	Scenario	Roads	Tyres	Engine	Combined
%A	I	1,9%	0,9%	0,2%	2,8%
	II	5,2%	1,7%	1,3%	7,9%
	III	6,3%	2,5%	2,3%	10,7%
%HA	I	1,3%	0,6%	0,2%	1,9%
	II	3,4%	1,2%	0,9%	5,1%
	III	4,1%	1,7%	1,5%	6,7%

7 Discussion and conclusions

The effect of source measures on the noise production of road traffic in relation to the number of annoyed and highly annoyed people was calculated for three major European cities: Amsterdam, Madrid and Munich. In general it can be concluded that:

- All applied source measures provide a reduction of the number of annoyed and highly annoyed people caused by road traffic noise;
- The combined effect of source measures is larger than the sum of the separate effects: both tyres, engine and road surface should be regarded to obtain an effective noise policy.

Although the modeling lacks the precision of highly detailed models, being developed now within the framework of the EU noise directive, it gives the advantage to be able to predict effects over a wide population within a short time and with on base of general used GIS software.

The modeling has demonstrated to be a reliable tool to appreciate scenarios of noise reducing policies in terms of its effect on annoyance. Since quantitative data on vehicle type, vehicle number and road length are available within the model, it is easy to extend the model with cost estimations to be able to study cost-benefit relations of scenario’s. Furthermore the model exhibits the possibility to extend it with air quality effects, so that combined measures can be appreciated.

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