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**VOLVO** 1927-2002



Volvo Trucks  
Dept. 26747  
405 08 Göteborg  
Sweden

Telephone: +46 31 3226925

Telefax: + 46 31 666640

email: [christina.keulemans@volvo.com](mailto:christina.keulemans@volvo.com)

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## IMAGINE

### Improved Methods for the Assessment of the Generic Impact of Noise in the Environment

# Sound power measurements on heavy vehicles to study propulsion noise

### WP5: Road noise sources

WP-leader: M+P

Project Co-ordinator: AEA TECHNOLOGY RAIL BV

Partners:	AEAT NL	BUTE	EURO-CONTROL	MBBM	UGent
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Christina Keulemans	05-06-18	Kaj Bodlund	



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## EXECUTIVE SUMMARY

The aim of this project has been to measure the sound power level of the propulsion noise from a heavy vehicle at constant speed. The measurement results have been compared with the Harmonoise/Imagine source model for heavy vehicles. The model will be used for noise mapping purposes.

The influence of driving style, vehicle load and road gradient was also studied. Finally a city cycle test, including different driving modes; acceleration, constant speed, engine braking and low idle, was performed.

The work has been performed indoors at the Noise and Vibration Laboratory at Volvo Trucks, Göteborg. Partly in the powertrain rig where the truck cab, with standard noise muffler and noise shields, was built up around the driveline, and partly in the truck noise chamber where the rear tires were encapsulated (see pictures below). The sound power level in third octave bands was measured according to ISO 3744 using a parallelepiped measurement surface.

The tested vehicle is a typical long distance truck with a 480 hp engine. The simulated load was 30 tonnes and 18 tonnes for the powertrain rig and the truck noise chamber respectively.

The results indicate that the vehicle speed dependent source model shows too high values at higher speeds. The measurements show also that the propulsion noise at constant speed can be modelled as constant below 50 km/h. The sound level increases above 50-55 km/h with the increased engine speed.

A rougher driving style defined as driving with one gear lower than most suitable gear, leads to an averaged noise increase of 2,3 dBA in the powertrain rig and 1,4 dBA in the truck chamber.

Simulating different vehicle load at horizontal road and with constant speed showed no influence on the emitted noise.

Driving on positive and negative road grades in these measurements showed approximately the same noise increase in both up- and downhills due to increased engine load.

The city cycle test showed that the difference between the maximum and minimum sound power level is 14 dBA with the simulated truck.



Picture 1 and 2: Powertrain rig (left) and Truck noise chamber (right) at the Noise and Vibration Laboratory, Volvo Trucks Göteborg

## Table of contents

Executive Summary	3
1 Introduction	6
1.1 <b>Background</b>	<b>6</b>
1.2 <b>Problem definition</b>	<b>7</b>
1.3 <b>Outline of the thesis</b>	<b>7</b>
1.4 <b>Restrictions</b>	<b>7</b>
2 Noise mapping	8
2.1 <b>Road traffic noise</b>	<b>8</b>
2.2 <b>Sound levels</b>	<b>9</b>
2.3 <b>Sound generation and Source modelling</b>	<b>10</b>
3 Propulsion noise source models of the truck	12
3.1 <b>Harmonoise model</b>	<b>12</b>
3.2 <b>Rotranomo model</b>	<b>16</b>
3.3 <b>Updated French traffic noise prediction model</b>	<b>18</b>
4 Propulsion noise	21
4.1 <b>Engine noise</b>	<b>21</b>
4.1.1 <b>Effect of engine speed on the noise emission</b>	<b>22</b>
4.1.2 <b>Effect of engine size on the noise emission</b>	<b>22</b>
4.1.3 <b>Effect of engine load on the noise emission</b>	<b>22</b>
4.2 <b>Fan noise</b>	<b>22</b>
4.3 <b>Transmission noise</b>	<b>23</b>
4.4 <b>Body rattle</b>	<b>23</b>
5 The trucks dynamic behaviour and noise emission	24
5.1 <b>Truck type definition</b>	<b>24</b>
5.2 <b>Road load model</b>	<b>25</b>
5.2.1 <b>Road simulation in truck noise chamber</b>	<b>27</b>
5.3 <b>Vehicle Performance</b>	<b>27</b>
5.3.1 <b>Accelerating from low speed</b>	<b>28</b>
5.3.2 <b>Uphill driving</b>	<b>30</b>
5.3.3 <b>Downhill driving</b>	<b>31</b>
5.3.4 <b>Deceleration</b>	<b>32</b>
5.4 <b>Effect of driving style on noise emission</b>	<b>33</b>
5.5 <b>Driving statistics</b>	<b>33</b>
6 Experimental studies	36
6.1 <b>The test object</b>	<b>36</b>
6.2 <b>Sound power measurement</b>	<b>36</b>
6.3 <b>Propulsion noise study [39 and 40]</b>	<b>36</b>
6.4 <b>City cycle measurement [41]</b>	<b>36</b>

7	Results and Conclusions	37
7.1	<b>Propulsion noise model vs. measured values at constant speed</b>	<b>37</b>
7.2	<b>Driving style influence</b>	<b>40</b>
7.3	<b>Hill driving</b>	<b>40</b>
7.4	<b>Vehicle load influence</b>	<b>41</b>
7.5	<b>City cycle results</b>	<b>42</b>
7.6	<b>Future work</b>	<b>43</b>

	References	44
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**Appendices**

**Appendix 1: Ref. [39], ER-602178, Sound power measurements in the powertrain rig**

**Appendix 2: Ref. [40], ER-602195, Sound power measurements in the truck noise chamber**

**Appendix 3: Ref. [41], ER-602199, City cycle noise test**

# 1 Introduction

Environmental noise is a problem that mostly has been tackled with regulations and restrictions concerning the noise source. Noise mapping on the other hand is a tool to describe the noise from a receptive point of view. The directive 2002/49/EC establishes that all EU-countries shall present strategic noise maps of major cities, roads, railways and airports, until the end of June 2007.

The EU-projects Harmonoise and Imagine aim at developing harmonised models and methods for noise mapping. Volvo Trucks is a partner of Imagine's working group for road noise. As a part of Volvo Trucks' contribution to the project work, this master thesis investigates the propulsion noise source model of heavy duty vehicles.

## 1.1 Background

Several millions of people are affected by noise every day in Europe. It might be irritating sound disturbing the concentration during daytime but also much more severe effects resulting in sleeping disturbances, hearing losses or high blood pressure. Even if the noise emission has prominently reduced since 1970, the number of affected people has not decreased. Although the noisiest sources, heavy vehicles and motorcycles, have improved the emission the increasing mobility and the amount of vehicles counterbalance the technical advances [12, 19].

The Green Paper on environmental noise from the European Commission 1996 [12] was the beginning of the noise abatement on a European level with the goal to have common standards for methods and evaluation of noise exposure. Until then the noise control was mostly restricted to type approvals controlling the maximum sound levels of the noise sources, although some national regulations existed for community area planning.

Further work resulted in the European directive 2002/49/EC requiring that all countries in the European union make a strategic noise map before 30<sup>th</sup> June 2007 showing the noise exposure in cities with a population of more than 250 000 and emissions from all major roads, railways and airports [13]. The next step is to draw up action plans before 18<sup>th</sup> July 2008, in order to reduce noise where necessary. Common noise indicators,  $L_{den}$  and  $L_{night}$ , were also defined.

The Harmonoise project, supported by the European Commission, aims at delivering noise prediction models that use accurate and harmonised methods. The idea is to separate the noise emission in a generation and a propagation model. There are several advantages with this course of action. Imagine (Improved Methods for the Assessment of the Generic Impact of Noise in the Environment) is connected to the Harmonoise project and will provide a database for noise emission data as well as computation methods for aircraft and industrial noise (figure 1, source: www.imagine-project.org).

Harmonoise proposes a division of the road vehicle noise source into a rolling and propulsion source both depending on the frequency and vehicle

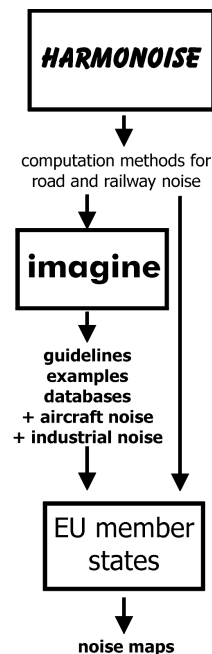


Figure 1

speed. The propulsion noise source is corrected for acceleration and deceleration.

## **1.2 Problem definition**

The aim of the thesis is to investigate and improve the proposed model of the propulsion noise source of heavy duty vehicles. The model is well defined for cars, but it is questioned for heavy vehicles, especially for loaded vehicles accelerating from low speed, e.g. at a stop light in urban traffic or on a slipway on to a motorway. It is also questioned in the case when heavy vehicles drive uphill with lower vehicle speed but high engine speed as well as for downhill driving when retarders and engine brakes effect the noise emission.

The noise source model should be representative, as accurate as possible and applicable in the Imagine-project.

## **1.3 Outline of the thesis**

Firstly, a literature study was performed to investigate partly the current noise mapping methods, partly the trucks dynamic performance and noise emissions. A typical driving behaviour could be worked out and used in the measurements.

The sound power level was then calculated at constant speed from 5-85 km/h, with a step of 5 km/h [39, 40]. The influence of choice of gear, vehicle load and positive as well as negative road gradient was also studied at constant speed. The results were finally compared with the source model of Harmonoise/Imagine.

A city cycle, including different typical urban driving modes, was also performed to study the variation of sound power level over time [41].

## **1.4 Restrictions**

Measurements in this report have been limited to two indoor measurement setups. The sound power level was measured in the powertrain rig and the truck noise chamber at the Volvo Trucks laboratory. The total vehicle and simulated trailer load was 30 tonnes and 18 tonnes respectively in the two rigs. The maximum possible simulated inertia load in the truck noise chamber is 20 tonnes.

The directivity of the source is not studied in this report and the measurement method used, ISO 3744 with a parallelepiped measurement surface, has not been further investigated or compared to other measurement methods.

## 2 Noise mapping

Noise mapping is an important tool when analysing the noise emission in the environment and to ensure that the noise levels are not exceeding the national and EU legislative regulations. It is also of major importance when developing an ambient noise strategy. Through simulating new traffic conditions, for example increase of traffic volume on a highway; it is possible to see the impacts on the surroundings. From an economic point of view it is advantageous to use a noise mapping-tool based on noise emission models instead of continuously performing field measurements.

Noise sources that have to be accounted for when performing a noise map are usually divided into the main categories road, rail, air and industrial-noise. For urban environmental noise the road traffic is the dominating noise source and particularly the heavy-duty vehicles contribute to a higher noise level [1]. Figure 2 shows a noise map of a built-up area close to a trafficked road.

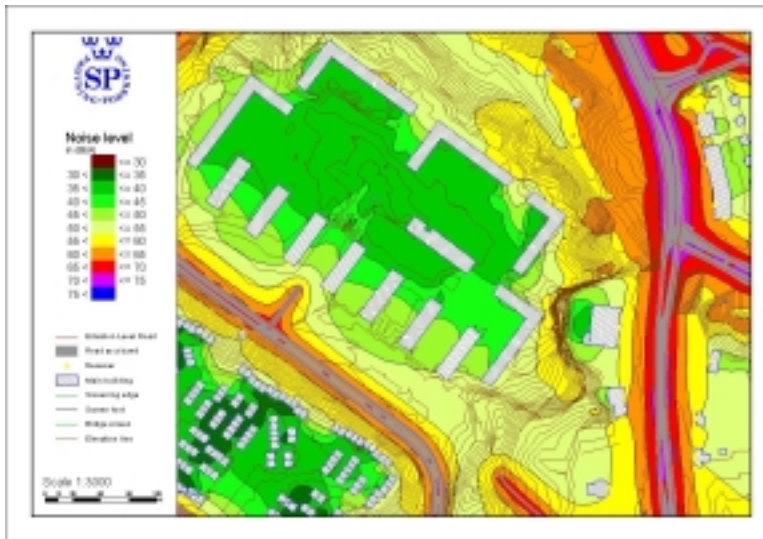


Figure 2: Noise map (source: [www.sp.se/energy/acoustics/omgivningsbuller.htm](http://www.sp.se/energy/acoustics/omgivningsbuller.htm))

### 2.1 Road traffic noise

Cars, buses, heavy vehicles and motorbikes all contribute to the total road traffic noise. Each vehicle can be considered as a point source but it really consists of various sources, engine, transmission, exhaust, cooling system and tyre/road interaction. Depending on the level of accuracy, the different noise sources can be modelled with a sound power level or a sound pressure level at a reference point with or without a described directivity of the source. [1, 14]

There is a range of methods for road noise prediction. Most of them are quite old and do not refer directly to the sound power of the sources counted above. A reference sound level point is often calculated from the relation  $10\lg Q$ , where  $Q$  is the amount of vehicles passing by per hour. Other factors usually taken into account are speed, type of surface, road gradient and amount of heavy vehicles. With help from the reference point and propagation models (which also do vary from method to method) the perceived noise at the distance of interest can be calculated. [14]

There are however some more recent methods, such as the Nordic prediction model Nord2000 [16], that approach the prediction modelling with a focus on the sound generation separate from the propagation. As mentioned above the vehicle is described as a number of point sources and the propagation is described by a physical model, valid for all types of sources.

The Harmonoise-project will present a harmonised prediction model for all European countries. The road traffic model is based on the Nord2000 model. The advantages are, except for a more correct theoretical model, an increased comparability of the results in all countries. A physical correct model of the sound power would also benefit the comparison between future type testing and noise prediction according to the Harmonoise report [2].

## 2.2 Sound levels

There are different ratings or indicators of the noise level as well as different time weightings.  $L_{Amax}$  is for example often used at pass-by tests to determine the maximum A-weighted sound pressure level when a vehicle drives by.

The equivalent continuous sound pressure level  $L_{peqT}$  or  $L_{eq}$  (equation 1) is the average sound pressure level of a sound during a time period,  $T$ .  $p$  is the sound pressure and  $p_0$  the reference sound pressure 20  $\mu$ Pa [27]. The subscript T, usually long-termed, is often omitted or replaced with the time interval, e.g.  $L_{eq8h}$  is the mean sound pressure level over 8 hours.

$$L_{peqT} = 10 \cdot \lg \left[ \frac{1}{T} \int_0^T \frac{p^2(t)}{p_0^2} dt \right] \text{ dB} \quad (1)$$

The sound exposure (E) and sound exposure level ( $L_E$ ) is a more adequate rating to describe a short-time noise event since the sound energy is integrated over the noise event.

$$E = \int_0^\tau p^2 dt \quad (2a)$$

$$L_E = 10 \cdot \lg \frac{E}{E_0} \text{ dB} \quad (2b)$$

$\tau$  is a specified time, normally the time for a single event e.g. a pass-by. The reference sound exposure,  $E_0$ , is  $(20 \mu\text{Pa})^2 \text{ s}$ . [28]

The EU noise indicators  $L_{den}$  and  $L_{night}$  (defined in [13]) together with the future common prediction models will be used to improve the comparability.

$L_{den}$  combines  $L_{Aeq}$  for day, evening and night period ( $L_{day}$ ,  $L_{evening}$  and  $L_{night}$  respectively) of a year with weightings of 5 and 10 dB for the evening and night periods respectively. Day is 12 hours, evening 4 hours and night period 8 hours, with default start at local time 07.00, 19.00 and 23.00 respectively.

$$L_{den} = 10 \cdot \lg \frac{1}{24} \left( 12 \cdot 10^{\frac{L_{day}}{10}} + 4 \cdot 10^{\frac{L_{evening}+5}{10}} + 8 \cdot 10^{\frac{L_{night}+10}{10}} \right) \quad (3)$$

## 2.3 Sound generation and Source modelling

As mentioned in previous paragraphs the work process when developing noise maps can be separated into a noise generation/emission and noise propagation part. Firstly an adequate noise source model has to be developed. Secondly the propagation of the noise has to be described. The variation of the noise level due to the distance to the source, air absorption, weather conditions, scattering and screening diffraction must then be taken into account. The noise propagation models will not be dealt with in this thesis though. Thereafter ratings of the propagated noise can be calculated and further evaluations on the environment and health effects can be accomplished (see figure 3).

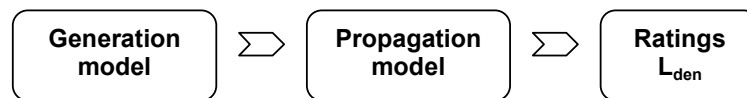


Figure 3

For a given sound power level of a source the sound pressure level can be calculated at a distance of interest. It is therefore of great importance that the model accurately represents the reality. The term “noise emission” is often defined as the sound pressure level measured close to the road from a vehicle passing by (pass-by level) at different speeds, and for different vehicles and traffic flows [4]. According to the Harmonoise position paper [2] the noise emission model is then still dependent on the nearby propagation factors and errors will occur when extrapolating to areas located further away. Noise emission in this thesis will refer to a generation model with a sound power level totally separated from the propagation. A model, with a specified directivity, dependent on the driving mode would be ideal.

There are various types of emission models for heavy vehicles in different countries but a common way to represent the generated noise from a road vehicle is with two or more point sources consisting of rolling and propulsion noise [2, 3, 5, 15]. Measurements with horizontal microphone arrays localise the sound emission to right before and right after the front wheels of the truck, where the engine and gearbox is to be found, as well as to the rear and trailer wheels. The front wheel noise is hard to distinguish since the engine and gearbox noise is dominating [11]. The vertical locations of the point sources do also differ. For cars the strongest engine source is located close to the ground, i.e. the image of the engine source is stronger than the original source. For heavy vehicles the most engine noise comes from a higher levelled point [15].

The propulsion noise is defined as the noise related to the engine, power train, exhaust, air intake and cooling. It is the noise generated from the driving force of the vehicle and sometimes it is named the power unit, mechanical or just engine noise.

The rolling noise refers to the noise generated by the contact between tyre and road surface. It is the dominating source for vehicles travelling with higher speed, in general above 50 km/h for trucks. The noise level is however dependent on type of truck, tyre and road surface. At low speeds the propulsion noise is dominating and influenced by the gear shifting [6]. Propulsion and rolling noise are relatively independent of each other.

There are various factors influencing the propulsion sound generation, directly or indirectly. The driving mode strongly depends on the type of traffic flow. On a busy road or where traffic lights and stop signs frequently occur, the driving is interrupted and *deceleration/acceleration*

characterise the sound. A freely flowing traffic on the other hand, leads to a *constant speed*. This driving condition usually occurs where the speed limits are higher than 50-60 km/h, e.g. motorways, and a higher *gear* is then applied resulting in a lower *engine speed*. [1] The *road gradient* affects the driving condition as well. The vehicle drops/gains speed and to keep a constant speed the driver must use the throttle. How strong the throttle has to be, is depending on the vehicle *mass*. For most models the vehicles are categorized after their mass and axle configuration.

### 3 Propulsion noise source models of the truck

The following models all describe the total sound generated by the road vehicle as an energetic sum of the propulsion and rolling noise source:

$$L_{tot} = 10 \cdot \lg(10^{L_{prop}/10} + 10^{L_{Rol}/10}) \quad (4)$$

The rolling noise,  $L_{Rol}$ , is a logarithmic function of the speed (km/h). The Harmonoise model of tyre/road noise will be presented to give a comprehensive picture. The propulsion noise,  $L_{Prop}$ , is in the Harmonoise model a function of the vehicle speed but in the next following models,  $L_{Prop}$  is a function of the engine speed (rpm). Corrections are made in some cases for acceleration or engine load.

#### 3.1 Harmonoise model

The goal of the Harmonoise and Imagine project is to develop harmonised methods for predicting environmental noise in Europe. Both a reference and an engineering model have been developed, based on the same source description. The reference propagation model is established on theoretical methods for outdoor noise propagation against which the engineering model is compared. [2]

A state of the art-investigation was performed in the project [7] comparing the current engineering models in order to find the most qualified source modelling. According to the report most of the models and data cannot be used since they do not fulfil the requirement on emission-propagation separation.

The model proposes a division of the vehicles into five main categories according to their mass and number of axles. Table 1 shows the heavy vehicle's categories (light vehicles and two-wheelers belong to category 1 and 5 respectively). The different sub-categories are used during the data acquisition. Later on, it might be decided that only the main categories will be used since most authorities do not have such detailed data.

The rightmost column in the table indicates the category according to the EU Directive and ECE Regulations. Category M defines motor vehicles with at least four wheels used for the carriage of passengers. Motor vehicles with at least four wheels carrying goods belong to category N. Sub-categories M1-M3 are defined by the number of passenger seats and vehicle mass and N1-N3 is alone defined by the authorized mass. It would be advantageous to keep a standardised type definition but according to [35] the categorisation for noise prediction demands a different type definition. Each category has been chosen accordingly to receive as low variance of the noise level as possible within the category, but also to keep the difference low to nearby categorises. A typical vehicle of category 2 is a distribution like truck with at least a total mass of 3,5 tonnes and a maximum mass of 12 tonnes. A heavy vehicle in category 3 is a long distance like vehicle with semitrailer and or trailers where the total mass exceeds 12 and may be up to 60 tonnes.

Main category	No	Sub-categories: Example of vehicle types	Notes	EU/ECE Category
<b>2. Medium heavy vehicles</b>	2a	Buses	2 axles (6 wheels)	M2, some M3
	2b	Light trucks and heavy vans	2 axles (6 wheels) <sup>(1)</sup>	N2
	2c	Medium heavy trucks	2 axles (6 wheels) <sup>(1)</sup>	N2
	2d	Trolley buses	2 axles	Possibly M3
	2e	Vehicles designed for extra low noise driving ("Whisper Mode")	2 axles <sup>(2)</sup>	N2
<b>3. Heavy vehicles</b>	3a	Buses	3-4 axles	M3
	3b	Heavy trucks <sup>(3)</sup>	3 axles	N3
	3c	Heavy trucks <sup>(3)</sup>	4-5 axles	N3
	3d	Heavy trucks <sup>(3)</sup>	≥6 axles	N3
	3e	Trolleybuses	3-4 axles	Possibly M3
	3f	Vehicles designed for extra low noise driving	3-4 axles	N3
<b>4. Other heavy vehicles</b>	4a	Construction trucks (partly off-road use) <sup>(3)</sup>		?
	4b	Agr. Tractors, machines dumper trucks, tanks		?

(1) Also 4-wheel trucks, if it is evident that they are >3,5 tonnes

(2) Trucks designed for extra low noise, "Whisper mode", meeting more stringent standards than current EU levels

(3) High exhaust is noted (3a', 3b',...)

**Table 1: Categorisation of heavy vehicles in Imagine [35]**

All the vehicles are dedicated two point sources (as in equation 4) but vehicles with high exhaust should be modelled with a supplemental higher source. According to [16] about 10 % of the heavy vehicles in the Nordic countries have a vertical exhaust around 3,5 m above the road surface.

The two point sources are located at 0,01 and 0,75 m above the ground for heavy vehicles (0,01 and 0,30 m for light vehicles). Most of the engine noise is considered located under the vehicle body. The rolling noise source is mainly to be found close to the ground, but is also emitted at a higher position due to vibration of the tyre sides in the wheel house, hence a weighting is proposed between the two noise sources. 80 % of the propulsion noise is assigned the higher point and 20 % the lower, and vice versa for the rolling noise. The weighting has shown a better agreement with measured values especially at higher frequencies with higher directivity. When measuring the sound power level from a whole vehicle during a pass-by the ratio,  $p$ , of the total sound power associated with the lowest source is given by the following equation [7]:

$$p = \frac{0,8 \cdot 10^{L_{WRot}/10} + 0,2 \cdot 10^{L_{W Prop}/10}}{10^{L_{WRot}/10} + 10^{L_{W Prop}/10}} \quad (5)$$

The rolling noise is modelled accordingly for all road vehicles, with the reference speed  $v_{ref} = 70$  km/h and coefficients  $a_R$  and  $b_R$  given for each third octave band. Correction values are also available, accounting for the impact of extra axles. The default value is 4 axles for heavy vehicles (Category 3).  $L_{WRol}$  is assumed to increase with  $10 \cdot \lg(\text{number of axles})$ . Temperature, tyre and road surface corrections are also defined. [7]

$$L_{WRol}(f) = a_R(f) + b_R(f) \lg \left[ \frac{v}{v_{ref}} \right] \tag{6}$$

The propulsion sound power level at cruising speed,  $v$ , for the frequency in third octave band is modelled for all vehicle categories as the following linear relationship:

$$L_{W Prop}(f) = a_P(f) + b_P(f) \cdot \left[ \frac{v - v_{ref}}{v_{ref}} \right] \tag{7}$$

The reference speed is the same as for the rolling noise. The coefficient  $a_P$  is the unweighted sound power level at 70 km/h. The speed coefficient  $b_P$  is the same for type 2 and 3 vehicles. (The coefficients for category 4 have not yet been established.) Both coefficients are given in 1/3-octave bands 25-10000 Hz (see table 2). The low frequency bands including the third engine order (63 Hz) are independent of the vehicle speed. Above 200 Hz a speed correction is added:

Freq. (Hz)	Category 2		Category 3	
	$a_P$	$b_P$	$a_P$	$b_P$
25	97	0	97,7	0
31,5	97,7	0	97,3	0
40	98,5	0	98,2	0
50	98,5	0	103,3	0
63	101,5	0	109,5	0
80	101,4	0	105,3	0
100	97	0	100,8	0
125	96,5	0	101,2	0
160	95,2	0	99,9	0
200	99,6	0	102,3	0
250	100,7	8,5	103,5	8,5
315	101	8,5	104	8,5
400	98,3	8,5	101,6	8,5
500	94,2	8,5	99,2	8,5
630	92,4	8,5	99,4	8,5
800	92,1	8,5	95,1	8,5
1000	93,8	8,5	95,8	8,5
1250	94,3	8,5	95,3	8,5
1600	95,2	8,5	93,8	8,5
2000	94,9	8,5	93,9	8,5
2500	93,3	8,5	92,7	8,5
3150	91,2	8,5	91,6	8,5
4000	89,3	8,5	90,9	8,5
5000	87,3	8,5	87,9	8,5
6300	85,3	8,5	87,9	8,5
8000	84,3	8,5	81,8	8,5
10000	83,3	8,5	80,2	8,5

Table 2: Coefficients for propulsion noise [7]

The equation 7 is valid for constant speed driving. For acceleration/deceleration  $a$ , ranging from -2 to +2m/s<sup>2</sup> a correction value should be added:

$$\Delta L_{acc} = C \cdot a \quad (8)$$

For medium heavy vehicles and heavy vehicles  $C$  is 5,6. In the driving situation when an engine brake is used for deceleration and consequently raising the noise level the absolute value of  $a$  should be applied.

The coefficients  $a_p$ ,  $b_p$  and  $C$  were calculated with regression analysis on data from a study of urban driving on cars (category 1) and on light trucks and heavy vans (category 2b), the heaviest vehicle weighing 18 tonnes. The noise was measured close to the engine, exhaust and tyre. During the measurements the vehicle speed and engine speed was recorded along with the indirectly measured engine load, through observing the throttle position. Equation 7 and 8 showed to be the most suitable model based on the measured values [29]. For category 3 the coefficients  $b_p$  and  $C$  were assumed to be the same as for category 2.  $a_p$  was increased for the lower frequencies [7].

The directivity influence due to screening of the source by the vehicle body is corrected for with  $dL$  to the sound power level. The integral of the directivity function is approximately zero when integrating over a pass-by. The total directivity is depending on the frequency in Hz and the horizontal  $\varphi$  and the vertical  $\psi$  angle in radians (see figure 4).

$$dL(f, \varphi, \psi) = dL_H(f, \varphi) + dL_V(f, \psi) \quad (9)$$

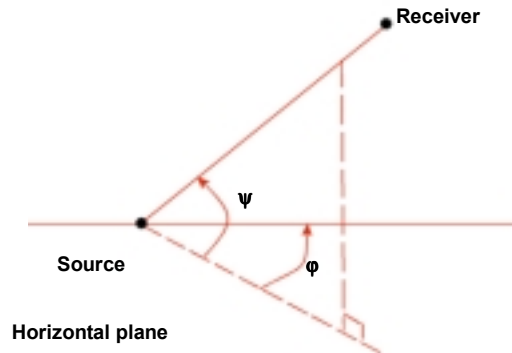


Figure 4: Geometry for the directivity functions as in [7]

The two point sources have different directivity functions. The horizontal directivity is accordingly defined [7], where (10a-b) is valid for the 0,01 m point.

$$dL_H = 0 \quad f \leq 1250, f \geq 8000 \quad (10a)$$

$$dL_H(\varphi) = (-1,5 + 2,5 \cdot \text{abs}(\sin(\varphi)))\sqrt{\cos(\psi)} \quad 1600 \leq f \leq 6300 \quad (10b)$$

The following equation is defined for the source located at 0,75 m above the ground:

$$dL_H(\varphi) = (1,546 \cdot \varphi^3 - 1,425 \cdot \varphi^2 + 0,22\varphi - 15)\sqrt{\cos(\psi)} \quad (11)$$

To prevent problems with pass-by integration when the receiver is located on top of the vehicle ( $\psi = \pi/2$ ) and  $dL_H$  is 0, the horizontal functions are multiplied with  $\sqrt{\cos(\psi)}$ . The square root was chosen to decrease the effect for close to horizontal angles [7].

The functions in Table 3 approximate the vertical directivity  $dL_V(\psi)$ :

Frequency/Source height	0,01 m	0,75 m
50,63,80	0	0
100,125,160	0	0
200,250,315	$-2(1-\cos^2(\psi))$	$-2(1-\cos^2(\psi))$
400,500,630	$-3(1-\cos^2(\psi))$	$-3(1-\cos^2(\psi))$
800,1000,1250	$-4(1-\cos^2(\psi))$	$-3(1-\cos^2(\psi))$
1600,2000,2500	$-4(1-\cos^2(\psi))$	$-2(1-\cos^2(\psi))$
3150,4000,5000	0	$-2(1-\cos(\psi))$
6300,8000,10000	0	$-2(1-\cos(\psi))$

Table 3: Vertical directivity functions at 0,01 and 0,75 m

The idea of the Harmonoise model is to make it possible to predict the noise on different levels of accuracy. To receive more detailed results, corrections have to be added. Some default values will be given in the Harmonoise and Imagine project others might be country or regional specific parameters and should be implemented nationally, e.g. deviant composition of the vehicle fleet or road surface made of local material. Knowing the vehicle type, speed and acceleration one can approximately estimate the propulsion noise.

### 3.2 Rotranomo model

On the commission by the European Working Group 8, for road traffic, TRL Limited and RWTÜV Fahrzeug GmbH were assigned the task to develop a noise prediction model for noise control strategies [5]. Their model is based on TraNECam, a model first developed by RWTÜV for the German Environmental Agency (UBA). This model is used together with a traffic flow simulation in the EC-project Rotranomo [9] where different traffic situations are simulated.

In contrast to the Harmonoise model the equation for the propulsion noise is depending on the engine speed and engine load. The output of the model does also differ from the Harmonoise model; overall sound pressure level,  $L_{Amax}$  or  $L_{Aeq}$  at 7,5 m distance from the road and in the middle of the vehicle at 1,2 m height above the ground [9]. The model is hence not separated from the sound propagation. It is more related to a typical noise validation or abatement measurement. The total noise level is expressed as in equation 12.

The vehicle categories are Passenger car, Light duty vehicle, Rigid truck, Trailer truck, Public transport bus and Motorcycle. The subcategories for trucks are depending on the mass and whether traction tyres are used or not. See table 4 for the heavy vehicle categorisation. The noise emission factors are further divided into different age classes of the vehicles: upto 1981, 1982-1984, 1985-1989, 1990-1995, 1996-present and two future noise classes.

Vehicle category	Sub-category
<b>Rigid truck</b>	≤ 7,5 tonnes Gross Vehicle Weight (GVW)
	7,5-14 tonnes GVW
	14-20 tonnes GVW
	20-28 tonnes GVW
	≤ 7,5 tonnes, traction tyres
<b>Trailer truck</b>	7,5-14 tonnes, traction tyres
	14-20 tonnes, traction tyres
	20-28 tonnes, traction tyres
	≤ 32 tonnes GVW
<b>Public transport bus</b>	> 32 tonnes GVW
	≤ 32 tonnes, traction tyres
	> 32 tonnes, traction tyres
	≤ 20 tonnes GVW, standard
	> 20 tonnes GVW, articulated

**Table 4: Vehicle categorization in Rotranomo**

The propulsion noise source,  $L_{pProp}$ , expresses the sound pressure level. It is defined as follows, with a correction for the engine load  $DL_p$ :

$$L_{pProp} = L_{eng} + DL_p \quad (12)$$

For no engine load,  $P_{norm} = 0$ , or load less than 10% of the full load, the sound level of the propulsion noise  $L_{eng}$  is defined as:

$$L_{pProp} = L_{eng} = L_{nidle} + (L_s - L_{nidle}) \cdot n_{norm} \quad (13)$$

Where  $L_{nidle}$  and  $L_s$  is the sound pressure level at idling and rated speed  $s$  respectively.

The engine speed is normalised in order to represent the different vehicle types.  $n$  is the actual engine speed:

$$n_{norm} = \frac{n - n_{idle}}{s - n_{idle}} \quad (14)$$

For increasing load,  $P_{norm} \geq 0,1$ , the noise level increases.  $DL_p$  is calculated as a linear interpolation between low load and full engine load:

$$DL_p = (DL_{p,idle} + (DL_{p,s} - DL_{p,idle}) \cdot n_{norm}) \cdot (P_{norm} - 0,1) / 0,9 \quad (15)$$

$DL_{p,idle}$  and  $DL_{p,s}$  is the noise emission increase at idling speed and at rated speed respectively. The low load model was derived from stationary measurements at 7,5 m from the road centre and 1,2 m above the ground at idling to rated engine speed. Pass-by measurements at full load delivered the full load curve. [5]

The following figure shows an example of the propulsion noise modelling for a newer trailer truck with a maximum mass of 32 tonnes. The idle and rated engine speed was defined as 600 and 1800 rpm respectively. The linear functions are based on coefficients in [5]. The report indicates

however that in the future the linear functions should be replaced by a 6<sup>th</sup> degree polynomial approximation for better curve fitting to measurement results. According to the report this method, low-full load prediction, is commonly accepted by vehicle manufacturers and government bodies.

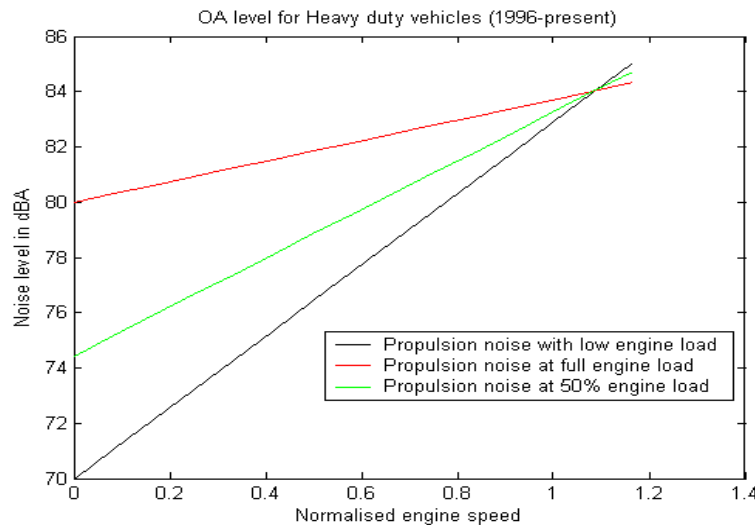


Figure 5: Rotranomo propulsion noise model

Unlike the Harmonoise model the Rotranomo model requires the normalised engine speed and engine load to be pre-calculated for each vehicle category. To convert the vehicle speed into the exact normalised engine speed gearshifts algorithms are demanded and for the engine load full load power curves have to be available. [9] A less accurate conversion would be to denote each vehicle category a normalised engine speed for constant vehicle speed and correct for increased engine load at acceleration and deceleration in different traffic situations.

### 3.3 Updated French traffic noise prediction model

The interim model for emission estimating in strategic road traffic noise mapping, recommended by the European Commission for road traffic noise prediction, is the French method described in "Guide de Bruit des Transports Terrestres". A working group was appointed the revision of the interim models in 2002. At the same time the French government assigned a working group to update the national noise emission data and a new method is being developed in France [3, 4]. It was recommended in [4] that the updated version should be adapted by the interim model.

Only two vehicle categories are used in the French model; the vehicle fleet is divided into light and heavy vehicles (more than 3,5 tonnes net load). The data for heavy vehicles are based on measurements of vehicles with 4 or more axles. The error for smaller heavy vehicles with this assumption is said to be less important on highways (1 dBA) than on urban roads where light vehicles dominates the vehicle fleet.

All vehicles are modeled by a propulsion noise source and a rolling noise source as in equation 4. The rolling noise is vehicle speed  $V$  and road surface  $R$  dependent. The propulsion noise is dependent of the slope of the road  $p$  and the traffic flow type  $a$  (fluid, accelerated or decelerated) of the vehicle.

$$L_{A \max} = 10 \cdot \lg(10^{L_{prop}(p,a)/10} + 10^{L_{Rot}(V,R)/10}) \quad (16)$$

The sound pressure levels were calculated from measured pass-by levels at 7,5 m from the road center and 1,2 m above the ground.

Indifference to the Harmonoise model this model is based on  $L_{Amax}$  or  $L_{Aeq}$  without any separation of the source and propagation. Further simplifications for both light and heavy vehicle, according to the report [4], are that the propulsion noise is said to dominate at lower speeds (below 50-60 km/h) and the rolling noise dominates at higher speeds (50-120 km/h). The propulsion noise,  $L_{Prop}$ , is defined as a constant over the whole speed range. The impact of acceleration is said to be negligible for heavy vehicles driving at higher speeds. For a vehicle driving in a slope in the higher speed range the increased noise emission is said to be insignificant. Further is the implement of an engine climbing a slope at constant speed considered identical to an engine accelerating on a leveled road.

In table 5 the relationship is shown. At the time of the writing of the report no updated information was found for the acceleration-slope relationship. The propulsion noise is considered constant, 73 dBA and corrections are made for acceleration, deceleration and driving in hills.

	Slope		
	$0\% \leq p \leq 2\%$	rising $2\% \leq p \leq 6\%$	falling $2\% \leq p \leq 6\%$
<b>Continuous</b>	73 dBA	$73 + 2*(p - 2)$	$73 + 1*(p - 2)$
<b>Acceleration</b>	ongoing	under development (1)	under development (1)
<b>Deceleration</b>	ongoing	under development (1)	under development (1)

(1) the numerical relationship between slope and acceleration still has to be developed [4, p.46].

**Table 5: New French road traffic noise emission data: engine noise of heavy vehicles.**

Further research has been made by The Transport and Environment Laboratory in France (INRETS) and LRPC Strasbourg. Their results on propulsion and rolling noise from heavy vehicles have been presented in Internoise papers [3, 6, 11].

The papers present models for both noise emission of heavy vehicles when performing traffic noise predictions (given in table 5) and for the different sources of the vehicle itself.

Their study is based on  $L_{Amax}$ -measurements at 7,5 m from the centre line and 1,2 m height at controlled pass-bys with constant speed. The propulsion sound pressure level was measured during low vehicle speeds or high engine speed, when the overall level was considered as equal to the propulsion noise level. The coefficients  $a$  and  $b$  were calculated by regression analysis ( $a = 73,7$ ,  $b = 23,5$  and  $n_{ref} = 1500$  rpm). The model for propulsion noise, a function of the engine speed, is as follows:

$$L_{pProp}(n) = a + b \cdot \lg(n/n_{ref}) \quad (17)$$

Seven different trucks were compared in [3] but the difference in propulsion noise did not vary more than 2 dBA (72-74 dBA). (The rated powers of the trucks were not presented in the paper however.) The influence of vehicle load was studied by comparing a truck without and with a trailer (both loaded and unloaded). According to the paper adding a trailer has little effect on the propulsion noise but increases the rolling noise by 3-5 dBA.

A recent paper from 2004 [11] by the same research group investigates the influence of driving behaviour by running the vehicle at approximately 1200 rpm and one gear lower and one gear higher. For lower vehicle speeds (without rolling noise) the noise increases with a greater gear ratio. For higher vehicle speeds the difference decreases due to the increasing rolling noise. In [6 and 11] a possible third noise source located at the rear axle was also investigated since measurements during cruise-by (i.e. pass-by with the gear engaged and running at constant speed) at higher speeds had shown variations in noise level. A microphone array showed three main noise sources: front zone, driving wheel zone and trailer wheel zone. The driving wheel

zone showed a noise level difference, increasing with vehicle speed, when comparing cruise-by and coast-by (i.e. pass-by with no gear engaged) measurements. The assumption that rolling noise is dominating at higher speeds should however lead to equal noise levels at cruise-by and coast-by driving. According to the paper this might be due to noise from the axle gearbox.

## 4 Propulsion noise

The earlier used traffic noise models are based on statistical parameters (vehicles/hour, % heavy vehicles, mean road speed). If one wants to develop a model which relates to the individual vehicle noise the operating parameters for each source should be considered. As in the Harmonoise model, the main sources can be divided in two groups.

The propulsion noise is noise from the engine, air intake, exhaust, cooling system and transmission. These are the dominating noise sources for heavy vehicles in many driving situations. At higher speeds the rolling noise is becoming dominant, especially when driving with traction tyres. Propulsion noise is related to the engine speed and the engine load. Tyre and transmission noise are related to the vehicle speed and load.

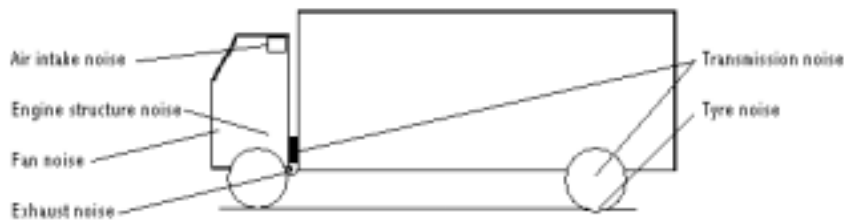


Figure 6: Vehicle noise sources

The exhaust noise; low frequency noise, and the air intake noise are usually well below the engine noise level and the influence on the overall dBA level can be considered negligible. Noise sources that on the other hand set the noise level are body rattle and illegal exhaust systems. Exhaust systems with defected or omitted muffler both on cars and trucks are evident noise problems that greatly affect the overall noise emission.

### 4.1 Engine noise

Engine noise is due to different gas and mass forces during combustion that leads to the so-called combustion noise and mechanical noise that excite the engine structure. The cause of the combustion noise is the gas pressure in the cylinders. Mechanical noise is generated by a mechanical impact such as a piston slap or a gear rattle. There are various parameters affecting the engine noise greatly; engine speed, load, engine size and characteristics such as e.g. type of fuel injection and cylinder- and valve configuration. [1]

In difference to heavy vehicles' engines, light vehicles' are a lot quieter at lower engine (and vehicle) speed. For a heavy vehicle with a typical operating engine speed between 1000-2100 rpm the overall level does not vary as much with vehicle speed as for light vehicles. The table below was published in 1990 and hence only gives an indication of today's noise variation.

Engine Category	Operating speed range, rpm	Range of overall noise min. to max., dBA
D.I. Diesel above 150 kW	1000-2100	10
D.I. Diesel between 75-150 kW	1000-3000	15
I.D.I. Diesel below 75 kW	1000-4000	20
Gasoline engine	1000-6000	30

Table 6: Engine noise variation [33]

#### 4.1.1 Effect of engine speed on the noise emission

Engine noise is mainly decided by the engine speed and the effect of engine speed is depending on the type of engine and engine power. Higher engine speed and power results normally in higher total noise level. In general a light vehicle diesel engine is louder than a petrol engine but since the rated speed for petrol engine is higher, the noise levels approach each other [1]. A reduction of the engine speed would be acoustically favourable. On diesel engines this is performed by compensating the loss of engine power due to speed reduction, with a turbocharger that compresses the air and hence increases the efficiency [22].

The engine speed is dependent on the vehicle speed as well as the applied gear. The engine speed increases with the speed and falls at a gearshift resulting in a saw tooth-like curve.

The relation between the sound power level for a diesel engine and its speed ( $n$  in rpm) is  $10 \cdot N \cdot \lg(n)$ , where  $N$  is determined by the combustion system. For a turbocharged diesel engine  $N$  ranges between 1,5 and 3,5 [30].

#### 4.1.2 Effect of engine size on the noise emission

There is no direct connection between engine power and engine noise. The main factor is the engine speed. Larger engines operate at a lower speed due to limited piston speed. The rated engine speed  $n$  is reduced by  $n \cdot (\text{cylinder capacity in litres})^{0.5}$ . The emitted noise is generally independent of the work done per unit noise (hp). More crucial is the operational speed or the time of the operation of one cycle of events performed by the engine. [33]

The engine power increases with swept volume and combustion air. Engine noise is affected by the cylinder diameter  $B$  (increasing with  $B^5$ ) more than the swept cylinder volume. When increasing the engine power, a larger number of cylinders would be preferable. It will increase the mechanical noise, but reduce the overall noise emission [22].

#### 4.1.3 Effect of engine load on the noise emission

The effect of engine load is normally not greater than 4 dBA (sound pressure level of overall engine noise) over the whole range of engine speed, according to [33]. The peak cylinder pressures are reduced with reduced load but the fact that the initial pressure rise is just as sudden as for full load, leads to almost the same noise level. Noise at low loads may in some cases even be greater, due to cooling of the combustion chambers [30]. For normally aspirated engines the engine noise is greatest at full load, but for a turbocharged diesel engine the noise at half load is greater than at full load [33]. The main factors which determine the noise is therefore speed and size.

### 4.2 Fan noise

Fan noise in heavy vehicles cooling system may contribute extendedly to the overall noise level especially after long-term engine run or high ambient temperature when it is essential to lower the engine temperature. The sound pressure level from the fan increases with the flow velocity  $v$  ( $\text{m}^3/\text{s}$ ),  $L_{pA} \propto v^5$ , and the fan speed (rpm),  $L_{pA} \propto n^5$  [33]. The fans commonly have a speed of 1 to 1,6 times the engine speed. In Europe the fan is normally electrically controlled, regulating the fan speed according to the temperature. Mechanically fixed fans are directly dependent on the engine speed independent of the engine temperature. To examine the worst-case scenario, drive-by tests on different mechanically operated electrical fans showed that the contribution of the fan noise was remarkably high, so that it alone determined the overall noise level [21]. The fan noise can hence not be overseen in situations where the engine temperature is raised during a long period of time such as driving in uphill slopes.

### **4.3 Transmission noise**

Noise from the transmission i.e. gearbox, drive shafts and rear axles, has become more obvious with acoustically improved engine design. The main noise excitation in the transmission is the meshing of gear teeth [1]. Gearbox noise is mainly decided by the engine torque and engine speed.

### **4.4 Body rattle**

Another source of noise that may not come directly into one's mind when thinking about noise from commercial vehicles is body rattle. Body rattle or body noise is noise generated by metal-to-metal impacts (suspension system, door latches, tipper bodies, loose tools and chains etc.) or vibrating body panels, as the vehicle is driven and excited by irregularities in the road surface. There are no regulations or directives that control particularly the body noise; it is much up to the operators and the drivers of the trucks to perform regular servicing and as well as to follow maintenance practices. Measurements at the roadside of an uneven road have been performed by the Transport Research Laboratory (TRL) in UK, to investigate the effect of body noise to the overall noise from a range of commercial vehicles. It showed a major increase of 5-25 dBA compared to the noise on a levelled reference road. [31]

Noise caused by body rattle can not be overlooked when driving on road surface joints that frequently occur on e.g. bridges. These joints excite noise each time an axle drives over the unevenness which is very annoying to neighbouring areas.

## 5 The trucks dynamic behaviour and noise emission

This section will present the truck type definition according to the Volvo standard, as well as the road load model used to describe a truck in motion and a discussion on the vehicle performance. Finally some driving statistics for long distance vehicles is presented.

### 5.1 Truck type definition

In the Volvo truck's standard [20] the vehicles are defined or categorised with a number of parameters; transport cycle, operating environment, vehicle utilisation, transport mission and Gross Combination Weight (GCW).

The *transport cycle* is divided into Long distance, Distribution and Vocational/ Construction like, see table below. High average speed and few stops characterise long distance like transport cycles. Distribution like transport includes many stops, low average speed and short distances covered. Vocational/Construction like transportation cycle involves major load handling and often with extra bodies like tipper, concrete mixer or a crane. Vocational/Construction like transports can be both distribution like (trash collection truck) and long distance like (timber truck).

The *operating environment* regards the road condition, topography, altitude, climate and curve density. *Vehicle utilisation* parameters are driver dependent and consider speed changes (Low, High, Very High), manoeuvring (Low, High) and yearly usage. Low speed changes (and few gearshift, hard brake engagements and stops) and few (low) manoeuvring are typical for long distance like vehicles. Distribution like vehicles are characterised by frequent (high) speed changes and frequent manoeuvring.

The *transport mission* determines the vehicle appearance, with a designed body or extra equipment. The vehicles can also be divided according to their *GCW*, which is the total weight of a vehicle combination (truck + trailers + load).

<b>Transport Cycle</b>	<i>Long distance like</i>	<i>Distribution like</i>	<i>Vocational/Construction like</i>
<b>Operating Environment</b>			
Road Condition	{Smooth, Rough, Very Rough, Cross-Country}		
Topography	{Flat, Predominantly Flat, Hilly, Very Hilly}		
Altitude	{1500 m, 2500 m, 4000 m, 5500 m}		
Climate	{Very Cold, Cold, Temperate, Hot, Very Hot}		
Curve Density	{Low, High}		
<b>Vehicle Utilisation</b>			
Speed Changes	{Low, High, Very High}		
Manoeuvring	{Low, High}		
Yearly Usage	{Usage <25000, <50000, <100000, <150000, ..., >300000 km/year} or {Usage <1200, <3000, >3000 hours/year}		
<b>Transport Mission</b>			
Body	{(Fifth wheel), Swap body, Platform, Van body, Tank, Bulk, Tipper, Dump body, Concrete mixer, Hook lift, Skip loader, Waste Compactor, Timber, Vehicle transport, Special vehicle}		
Equipment	{Tail lift, Crane, Pump/fan for liquids, gases, slurry, sludge, concrete, bulk etc.}		
<b>GCW</b>	{GCW 3.5, GCW 6, GCW 8, ..., GCW 200 t}		

Table 7: Vehicle parameters in Volvo's trucks standards [20]

The four different topographies in table 7 are defined as follows:

<i>Flat</i>	most common on motorways, with up- and down road gradients of 3 % or more during less than 1 % of the total driving distance maximum gradient is 8 %
<i>Predominantly flat</i>	roads with gradients of 3 % for less than 20 % of the distance, less than 1 % of slopes with more than 6 % gradient, maximum gradient of 16 % during the whole ride
<i>Hilly</i>	less than 35 % of the distance with road gradients of more than 3 %, less than 10 % of the distance with road gradients of more than 6 %, less than 1 % of the distance with road gradients of more than 10 %, maximum gradient of 20 %
<i>Very Hilly</i>	if the requirements for Hilly are not reached extreme driving conditions on e.g. mining and dam-building areas

## 5.2 Road load model

Consider the truck in the figure below. Its motion can be described by a simplified road load model where the vehicle is regarded as a lumped mass located at its centre of gravity.

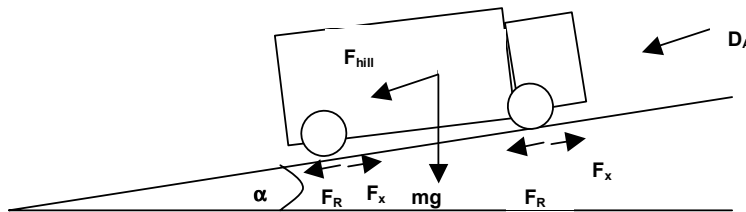


Figure 7: Forces acting on the vehicle

The vehicle with the mass  $m$  (tonnes) driving in the forward direction ( $x$ -coordinate), in constant speed is pulled at the driving wheels by the tractive force  $F_x$  (N). The tractive force has to overcome all driving resistances: rolling resistance  $F_R$ , aerodynamic resistance  $D_A$  and climbing resistance  $F_{hill}$ . A negative value of the road grade  $\alpha$ , i.e. a descending road, is considered a pushing force and adds to the tractive force.  $g$  is the acceleration of gravity. The tractive force at constant speed is defined in equation 18. The acceleration performance, see equation 19, is the difference between tractive and resistance forces. [23]

$$F_x = F_R + D_A + m \cdot g \sin \alpha \quad (18)$$

$$m \cdot a_x = F_x - F_R - D_A - m \cdot g \sin \alpha \quad (19)$$

The driving resistances are defined in equation 20-22 [24]. The rolling resistance (eq. 20) is modelled as independent of the vehicle speed and the number of tyres. The tyre rolling resistance,  $R_m$ , is typically 55-60 N/tonne on an asphalt road surface.

$$F_R = R_m \times GCW \quad (20)$$

$R_m$  (N/tonne) = tyre rolling resistance, GCW (tonnes) = mass of vehicle+load

The air resistance (eq. 21) is proportional to the drag  $C_d$ , vehicle speed  $v$  (km/h) and frontal area of the truck  $A$  (m<sup>2</sup>). The drag coefficient depends among other things on the shape of the vehicle, wind speed and direction and whether airflow equipment is used or not. Typical values for a single truck and semitrailer with and without airflow equipments are 0,5 and 0,7 respectively. For a truck and trailer  $C_d$  is commonly 0,7 and 0,8. The vehicle speed is important at high speeds. The frontal area varies between different truck models from 7 to 10 m<sup>2</sup>.

$$D_A = \frac{C_d \cdot v^2 \cdot A}{21} \quad (21)$$

$C_d$  = drag coefficient,  $v$  (km/h) = vehicle speed,  $A$  (m<sup>2</sup>) = front area

The climbing resistance (eq. 22) is dependent on the road gradient which is defined as the rise of the hill over 100 m distance. For angles less than about 15 degrees the equation can be simplified:

$$F_{hill} = m \cdot g \sin \alpha = Grad(\%) \cdot 98 \cdot GCW \quad (22)$$

$m$  (kg) = vehicle mass,  $g$  (m/s<sup>2</sup>) = gravitational constant,  $\alpha$  = road grade

The relation between vehicle speed (km/h) and engine speed  $n$  (rpm) is stated in next equation 23 [24]. The tyre circumference is nominated  $d$ . The vehicle speed increases with the engine speed, but the engine speed is controlled by the gear ratios of the gearbox,  $r_g$ , and final drive,  $r_f$ . A vehicle speed-engine speed plot has hence the shape of a saw tooth line.

To keep the noise level and fuel consumption low the engine speed at normal vehicle speed should be as low as possible. This is also the engine speed area where the torque output is at maximum. So when designing the driveline, it is important to choose as low final drive ratio as possible to increase the maximum speed and to keep the engine speed low.

$$v = \frac{n \cdot d \cdot 60}{r_g \cdot r_f \cdot 1000} \quad (23)$$

$n$  (rpm) = engine speed,  $d$  (m) = tyre circumference,  $r_g$  and  $r_f$  = gearbox and final drive ratio

The tractive force is increasing with the engine torque  $T_e$  (Nm), gear box and final drive ratio, and efficiency in the drive train,  $\eta_{tr}$  (typically 0,9).  $r$  (m) is the rolling radius of the tyres. The tractive force determines the driving performance at hill climbing and starting capacity in hills from a standing point. The engine torque and power are related by the engine speed. The engine output  $P$  (kW) increases with the engine speed. Consequently, when driving on a hill where the need for engine power is higher, an increased engine speed is needed. The same is valid for downhill driving when the effect of the engine brakes increases with the engine speed.

$$F_x = \frac{T_e \cdot r_g \cdot r_f \cdot \eta_{tr}}{r} \quad T_e = \frac{P \cdot 9549}{n} \quad (24, 25)$$

$T_e$  (Nm) = engine torque,  $\eta_{tr}$  = transmission efficiency,  $r$  (m) = tyre rolling radius,  $P$  (kW) = engine power

The relation between the engine torque and the torque applied on the driveshaft is modelled in the next equation. The engine torque is amplified by the transmission gear ratio but is somewhat reduced by inertial losses in the driveline:

$$T_d = (T_e - L_{et}) \cdot r_g \cdot r_f \quad (26)$$

$T_d$  (Nm) = driveshaft torque,  $L_{et}$  = torque losses in engine and transmission

According to [23] the following equation is often used by road engineers when designing slipways onto the motorways or when investigating the needs for climbing lanes. The great difference between cars and trucks accelerating performance is clear when studying the power-mass relation ( $P$  (kW)- $m$  (tonnes)) in the equation. The acceleration capability decreases with the vehicle speed  $v$  (km/h).

$$a_x = \frac{F_x}{m} = 1,48 \frac{P}{v \cdot m} \quad (27)$$

### 5.2.1 Road simulation in truck noise chamber

A road can be simulated in a vehicle dynamometer rig, with forces representing the rolling, aerodynamic and climbing forces. The road load model for the truck chassis dynamometer at Volvo Trucks is defined in equation 28 [25]. The road load,  $RL$  (N) is the force at the roller surface and is equal to the tractive force (eq. 18) at the tyres.  $F_0$  and  $F_1$  (N) are the friction force coefficients representing the rolling resistance. In difference to equation 18 the model includes a vehicle-speed-dependence through  $F_1$ . The vehicle speed dependent aerodynamic resistance is represented by  $F_2$  (N).

The inertia  $I$ , of the engine, transmission and wheels, when accelerating with acceleration  $a$  is electrically simulated in the rig.  $Grad$  is the road gradient.

$$RL = F_0 + F_1 v^x + F_2 v^n + I \cdot a + mg \cdot (Grad / 100) \quad (28)$$

$F_0$ ,  $F_1$  (N) = friction force,  $x$  (= 0,8 to 1,2) = velocity exponent variable,  $F_2$  (N) = air resistance,  $n$  (= 1,1 to 3,0) = velocity exponent variable,  $I$  = (kg) inertia,  $m$  (kg) = mass,  $g$  (m/s<sup>2</sup>) = gravitational constant,  $Grad$  (%) = road grade

The road load coefficients can directly be entered in the simulation program of the rig, or be calculated prior to the simulation with collected road data. The vehicle inertia ranges 4 to maximum 20 tonnes. If a vehicle load greater than 20 tonnes is to be simulated this can be done by increasing the road gradient.

The gradient ranges from -30 to 30 %. The maximum tractive force, braking power (i.e. simulating uphill driving) and motoring power (downhill driving – the vehicle has to control the speed) is 60 kN, 400 kW and 360 kW respectively.

## 5.3 Vehicle Performance

When a driveline of a truck is to be designed the parameters in table 7 are considered. The goal is to achieve good driveability with low fuel consumption. Low fuel consumption and low noise emission usually go hand in hand. According to [24] good driveability is when driving in normal cruising speed, on a flat road and in top gear, and one is able to drive within the engines most economical revolution range while still having sufficient power in reserve for managing hill and overcoming fluctuations in air drag and rolling resistance. The combination of the engine torque and power output, as well as the power at the driving wheels needs to be specified according to the required vehicle performance.

PERF, a Volvo-owned software, is used to simulate and evaluate the performance of different heavy vehicles. The simulations are based on the vehicle dynamic formulas as explained in

paragraph 5.2. Acceleration and braking sequences on different road grades and for different vehicle masses have been simulated in PERF and are presented in the following paragraphs.

### 5.3.1 Accelerating from low speed

Vehicles in urban areas accelerate from standstill or low speed at e.g. traffic lights and stop signs. On the slipway onto the motorway the vehicles usually accelerate from a higher speed around 50 km/h up to 80 or 90 km/h which is the maximum allowed speed for heavy duty vehicles in most of the European countries.

When studying the noise emission in noise mapping issues, the full load acceleration performance on levelled road is often said to be equal to the performance when driving up a hill at constant speed. As mentioned in paragraph 3.3 a research group aims to find a numerical relation between the two driving conditions.

The following four figures show the full load acceleration, from 0 km/h on a levelled road, of a typical long distance like truck (a single-body vehicle i.e. without extra trailer). Different GCW are simulated; 15, 30 and 45 tonnes. The engine is a 12-liter with 460 hp. The gear selection, most suitable for each GCW, was chosen and noted in the figure. A gearbox with 14 gears (12 + 2 extra crawler gears) was selected and the highest gear, ratio 1:1, is referred to as 6H. The acceleration was studied for a distance of 1 km. Since no speed limiter was possible to apply, the vehicle speed exceeds 90 km/h.

The acceleration performance of all vehicles is strongly dependent on the power and the mass of the vehicle. It can be seen in figure 8 that the acceleration is maximum  $2 \text{ m/s}^2$  and decreases logarithmical with gained speed. It is clear that the greater the mass the slower is the acceleration performance. The effect of acceleration on the noise emission from heavy vehicles travelling at higher speeds is said to be negligible to the overall noise emission in [4]. This is most likely true for loaded vehicles since the drivelines are designed as mentioned earlier, to have their maximum driveability at the most common speed (80-90 km/h) and with a buffer power output to manage 1-2 % road grades. Hence the acceleration performance is limited at higher speeds.

Heavy vehicles are also often vehicle speed limited to 90 km/h to maintain permitted speed.

In figure 9 and 10 the vehicle speed and engine speed are shown. It can be seen that maximum speed is reached by the 15-ton-truck during the 1 km distance, but not for the heavier vehicles. It is shown in the engine speed figure that the acceleration course is different at lower vehicle speed. The vehicle is accelerated up to higher engine revolutions between 1200 and 2000 rpm. Above 40-50 km/h, for the heavier vehicles, the engine speed is reduced with increasing vehicle speed and gear up-shifting. It varies between 1400 and 1800 rpm. The propulsion sound power is hence greatest at start. The maximum vehicle speed at the direct gear 6H is 1950 for this vehicle.

In figure 11 the torque from the engine on the driveshaft is shown. The relation between the engine torque and driveshaft torque is stated in equation 26. The engine torque increases with the gear ratio, i.e. at lower speed. The engine load is hence greatest at start.

It can be seen that the gear selection is dependent on the vehicle load. For lower load the acceleration is performed with fewer gears. If a different driving style was used; more gears applied during the acceleration, the acceleration would probably take longer time since at each gear a certain upper engine speed has to be reached.

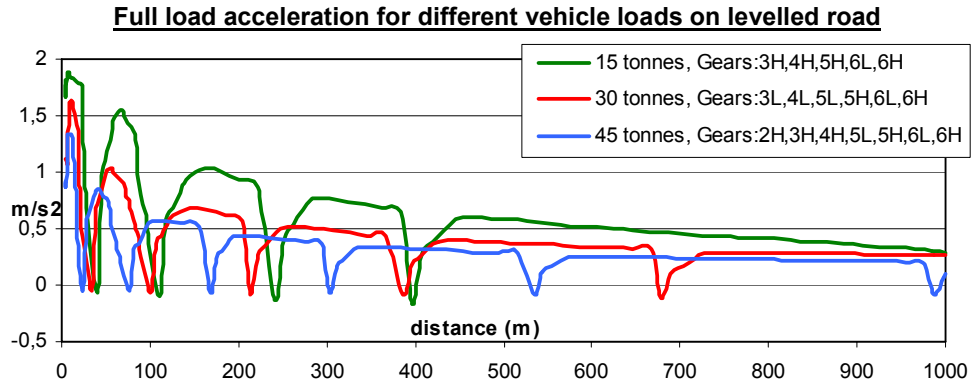


Figure 8: Acceleration (m/s<sup>2</sup>) vs. distance (m)

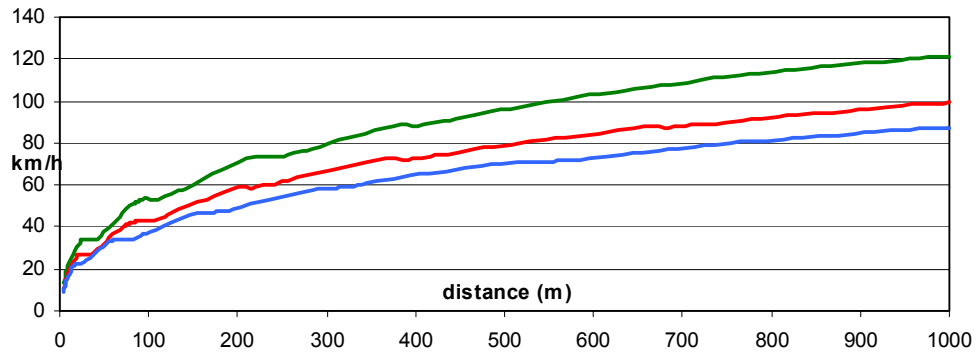


Figure 9: Vehicle speed (km/h) vs. distance (m)

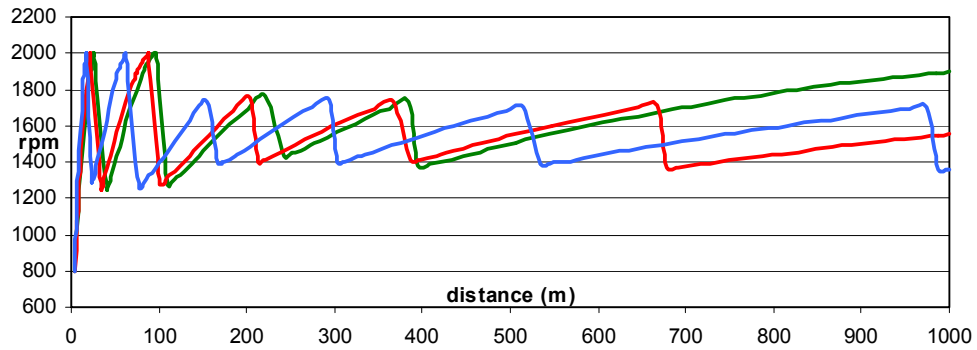


Figure 10: Engine speed (rpm) vs. distance (m)

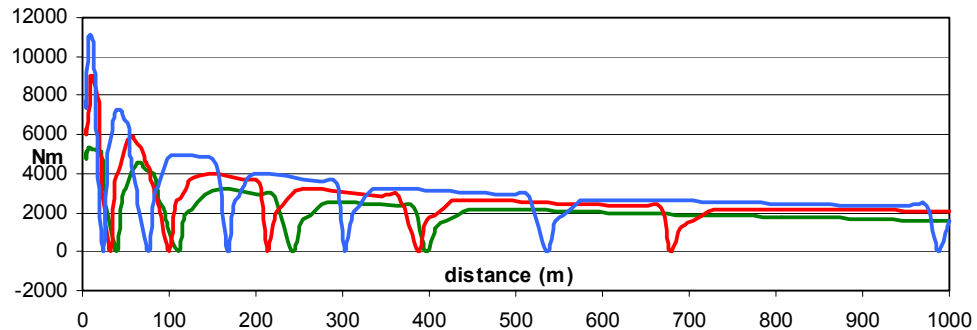


Figure 11: Driveshaft torque (Nm) vs. distance (m)

### 5.3.2 Uphill driving

Figure 12-15 show the full throttle acceleration of the same vehicle with a GCW of 30 tonnes on different road grades 0, 4 and 8 %, all 1 km long. The truck reaches the start of the hill with a speed of 80 km/h. Road grades of 8 % are not common on motorways but do exist. Uphill driving increases the tractive effort immensely according to the road load model in equation 18.

The acceleration values are shown in figure 12. Since no speed limiter is set the vehicle accelerate to about 110 km/h on flat roads. In the 4 % slope the vehicle is able to keep constant speed when downshifting one gear from top gear (6H to 6L). It can be seen that in the steepest hill the truck decelerate and loses speed until the downshifting to 4H where it is possible to remain at constant driving course at 37 km/h with the specified vehicle load. This clearly points out the importance of including climbing lanes in larger hills for heavy vehicles.

The engine speed, figure 14, increases with a downshifting pattern as the engine torque increases to maintain the forward movement. It can be seen that engine speed is much higher than when driving at constant speed which is about 1250 rpm at 80 km/h for this vehicle. Since the vehicle in the 8 % hill has to downshift two gear-steps at one occasion the increase in engine speed leads to top engine speed of 1750 rpm. The engine fan starts when the engine load and the engine temperature are high, as when driving in long uphills. Since the engine fan is related to the engine speed (1:1-1,6) it will reach much greater fan speed on graded roads compared to constant speed on horizontal roads.

The driving behaviour or gear-shifting is hence dependent on different parameters; the load of the vehicle, the hill gradient but also the length of the hill.

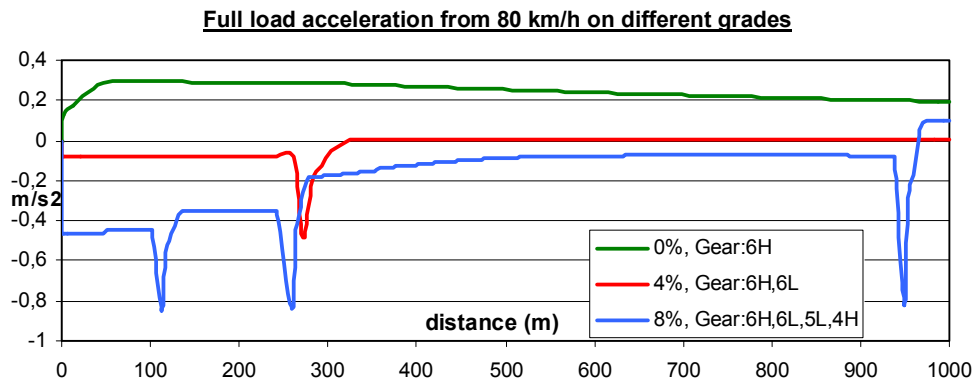


Figure 12: Acceleration (m/s<sup>2</sup>) vs. distance (m)

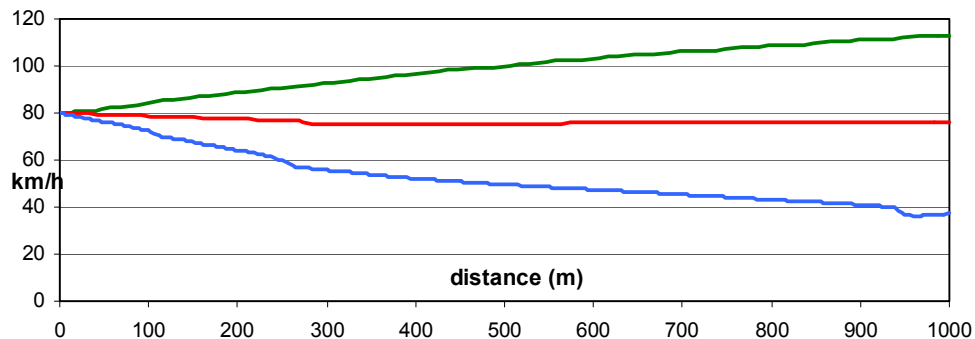


Figure 13: Vehicle speed (km/h) vs. distance (m)

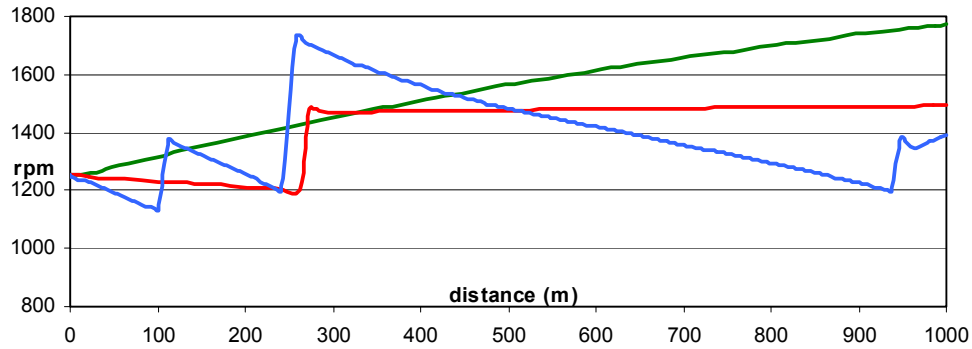


Figure 14: Engine speed (rpm) vs. distance (m)

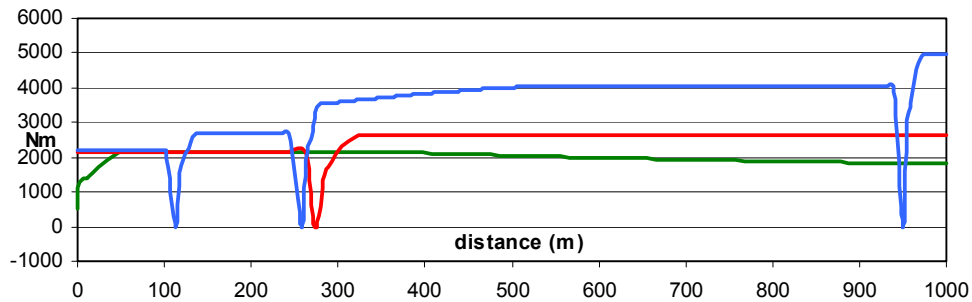


Figure 15: Driveshaft torque (Nm) vs. distance (m)

### 5.3.3 Downhill driving

Downhill driving increases the vehicle speed but to not exceed allowed speed the vehicle is being decelerated with engine brakes or retarders; only using the wheel brakes would result in immediate worn out brakes due to the high temperatures.

There are different types of engine brakes [32]. The exhaust brake (EPG, exhaust pressure governor) and compression release brake are the most common ones. The EPG is mounted on the exhaust outlet on the engine and builds up the exhaust pressure by closing a pressure valve, resulting in a braking force on the piston in the compression phase. Volvo Engine Brake (VEB) is a combination of the exhaust and the compression brake. The main idea of the VEB is to release the air right before the top dead centre to prevent the return of force in the work phase of the piston. As the high pressured air is released into the exhaust manifold the noise increases. Generally, engine brakes generates about as much noise during the brake performance as a vehicle in full load acceleration. But the variation of the engine brakes is large however.

Engine brakes are also present when driving on horizontal road. When driving with the cruise controller the engine brakes are engaged each time the throttle pedal is released.

Engine brake noise is greatly related to the engine speed and brake torque. To obtain as great brake torque as possible, the engine has to change down the gear, resulting in a full load situation for the vehicle. That is the case in a long moderate downhill slope or a short steep slope when the vehicle mass is pushing on the wheels. The following graph shows the maximum brake performance at different vehicle speed for the vehicle with a 12-liter engine and engine brakes (with EPG and EPG + VEB).

To be able to keep constant speed in a downhill of -8 % the driver must shift to gear 4L or 2H if the truck is equipped with exhaust brake only. The vehicle will then maintain the speed of about 20 and 40 km/h respectively without accelerating (see the "X" marks).

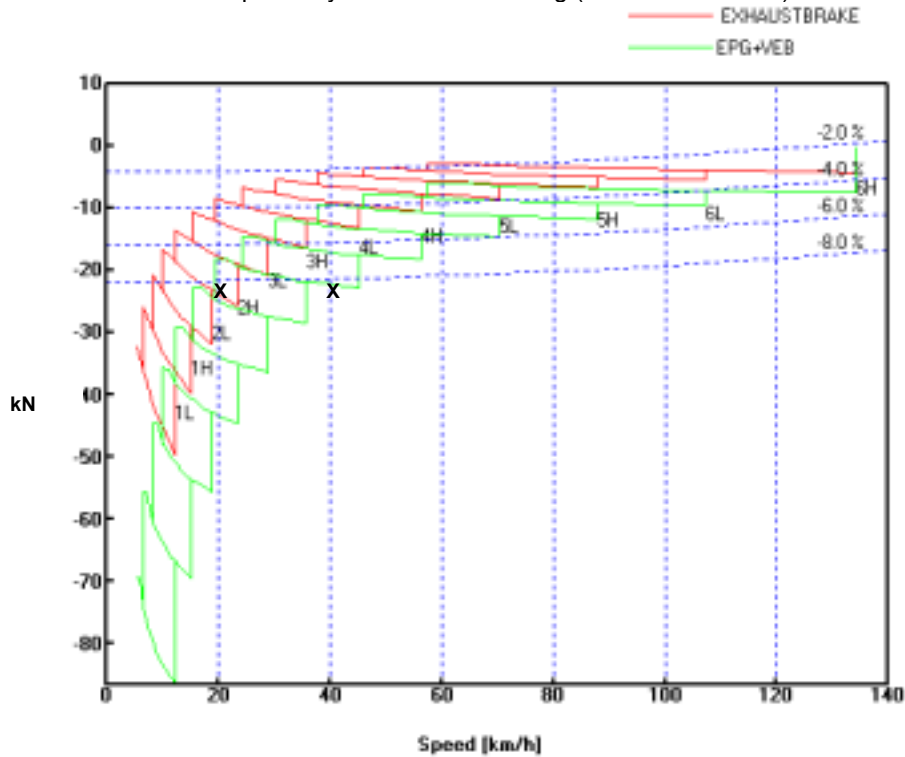


Figure 16: Max. engine brake (kN) at different vehicle speed (km/h) and gear

### 5.3.4 Deceleration

In urban traffic at crossings and traffic lights when decelerating to standstill, wheel brakes are frequently used. Brake squeal noise might occur in older vehicles or vehicles that have been poorly serviced. But according to [19] this type of irritating sound is fortunately seldom a big problem nowadays.

As the wheel brake pedal is released or the parking brake is used compressed air is released from the air brake tanks resulting in a raised sound level. The so-called air pressure release noise is not allowed to exceed 72 dBA in Europe at 7 m from the vehicle side.

There are no common European regulations on the brake noise. In Austria, however, there are requirements on retardation noise tests and the results must not exceed 80 dBA, when decelerating from 40 km/h and 1800 rpm. The level is independent of the type of engine brake installed on the vehicle.

## 5.4 Effect of driving style on noise emission

The recommended driving style for commercial vehicle drivers, to maintain minimum fuel consumption, results in both environmental improvements (decreased noise and green house gas emission), road safety and decreased noise emission.

The main recommendations are, according to the ECO-Driving Europe [36]:

- Shift into a higher gear as soon as possible
- Maintain steady speed at the highest gear possible
- Predict the traffic and keep the distance, to be able to plan the driving
- Decelerate smoothly by releasing the throttle well in time

It is often wrongly considered that a fast acceleration demands more fuel. It is rather the opposite, since shifting through all gears (including split gears, Low to High) does not improve the acceleration performance. Another common mistake is to use the wheel brakes frequently instead of planning the deceleration in time and predict the motion of the vehicle. The kinetic energy of a heavy vehicle is often underestimated; a 40-tonne-vehicle driving at 80 km/h roles 1 km without throttle on a horizontal road before reaching 65 km/h. [37]

Many commercial vehicles are also equipped with a software program to control and study the fuel consumption. Although automatic gearboxes are less fuel efficient than manual gearboxes under the same driving conditions; automatic can still save a lot of fuel in the end since it is controlled by a computer that analyses and adjusts the operating functions according to the driving conditions.

However, even if the economical gain is obvious many drivers do not apply to the eco-driving. They are considered to drive more aggressively, characterized by using a lower gear than appropriate and to give full throttle too long which prolongs the acceleration course, which clearly increase the noise emission.

The driving style-influence on the noise emission has been investigated in [11]. The pass-by levels were measured at different constant speeds on a truck with a loaded trailer. An aggressive driving style, with a lower adapted gear, normal driving, selected by the driver and passive driving, with one gear higher than by normal driving. (It might be questioned however whether a passive driving style is possible since it would lead to too low engine speed, presumed that normal driving is within the green area-economy range of the engine speed). A propulsion noise source model based on the measurements showed a difference of about 4 dBA between the normal driving style and the aggressive style at a vehicle speed ranged 20-50 km/h.

## 5.5 Driving statistics

A long distance like transport vehicle is said to spend about 80 % of the driving time in the highest gear and at constant speed. With this in mind the vehicles have been designed to be within the most fuel-efficient engine speed range at the normal driving speed of the vehicle.

In the following statistics it can be seen that the most common engine speed range is 1350-1500 rpm i.e. in the middle of the green speed area of the tachometer (figure 18). The statistics is based on data gathered by Volvo Trucks during summer and autumn 2004. The engine control unit of the truck logged the time that the engine spent in different engine speed and engine load combinations as in the example rpm-Nm-matrix in table 8.

The table shows the driving definition of the different types of driving in the logged data; Engine Brake, Idle, Full load, Constant speed and Coasting [38].

Engine braking occurs at different speeds. Low idle is idling at stand-still, e.g. waiting on a traffic light. But many drivers leave their truck with the engine on when taking a brake. PTO was read from another parameter in the software. PTO-time is when using auxiliaries like concrete mixer, crane or lift. Idle and PTO is hence also associated with work-station-noise. The full load range moves up in torque output with the engine speed, see the table. But at 1350 the full load is defined by lower torque again. Constant speed or cruise is defined as driving with the gear engaged. Coasting, in this study, is defined as driving with the gear engaged, but without using the auxiliary engine brake. The engine torque has a negative value. The distribution between engine brake and coasting was based on a program-specific parameter. In figure 17, remaining time is the time in the rpm-Nm-matrix that does not fit into the defined categories.

Nm	rpm	0	750	950	1150	1350	1500	1650	1800	1950	2100-
<b>Negative</b>											
<b>0</b>											
<b>300</b>											
<b>600</b>											
<b>900</b>											
<b>1200</b>											
<b>1500</b>											
<b>1800</b>											
<b>2100</b>											
<b>2400-</b>											

Engine  
brake/Coasting
  Low idle
  Full load
  Constant speed

Table 8: An example of Engine speed (rpm) - Engine Torque (Nm) matrix

The definition above for constant speed is 1000-1800 rpm for smaller engines (9-liter) and 1000-1600 rpm for larger engines (16-liter). As indicated in the previous paragraphs, the propulsion noise increases with the engine speed and the engine torque, both tractive and braking torque.

The vehicles in these data were mainly 12-liter-engines, as the vehicle studied in appendix 1-3, with varying output power (420-500 hp). The total logged time varied from at least 3 months up to several years, i.e. both new and some years older trucks were studied. The trucks, Swedish and some Spanish, were driven in different parts of Europe. The vehicles can be divided in three main categories; Long distance, Distribution and Construction. These were further divided into:

- Long distance max 44 tonnes:* Tractors with semitrailer
- Long distance max 60 tonnes:* Only rigids driving with extra trailer at night in Sweden where the vehicle length 25,5 m is allowed.
- Distribution Regional:* Rigids
- Distribution City:* Rigids
- Construction On road:* Rigids with auxiliaries
- Construction Off road:* Rigids with auxiliaries

In figure 17 it can be seen that the three long distance categories follow each other well. At first sight constant speed or cruise might be considered low, but when regarding the fact that the data was logged constantly, not only during road driving, low idle takes up a great part of the time. Further is coasting and engine brake often part of the constant speed. If the cruise controller and engine brake is on it will interfere each time the throttle is released. This explains the low part constant speed compared to 80 % discussed at the beginning.

The distribution and construction vehicles have less constant speed time but more low idle and PTO-time. The construction off-road vehicles and distribution city vehicles have a remarkable larger time spent in idling. This might be due to extra equipment, e.g. lifts, that demands the engine to run during use.

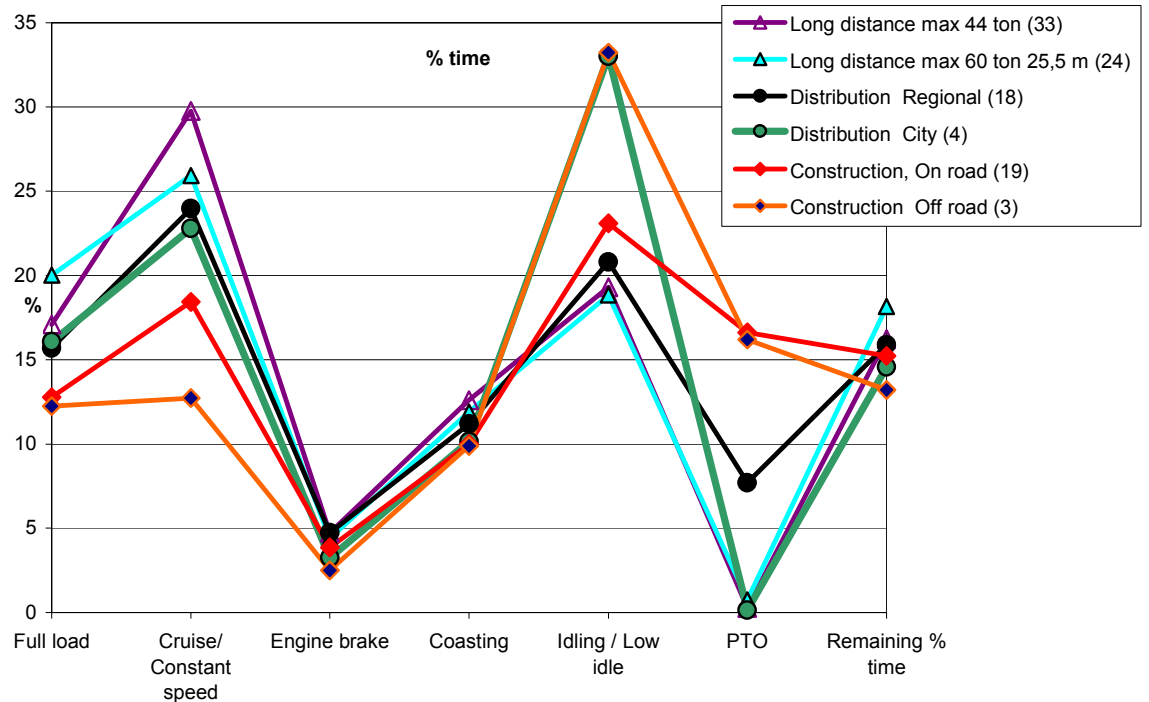


Figure 17: % of time in each driving mode

Figure 18 shows the same driving modes but divided in each rpm-range (0 to 2100 rpm is called speed range 1-10). It can be seen that at full load, constant and coasting the most common speed range is number 5, i.e. 1350-1500 rpm independent of the transportation cycle. It is also seen that the construction-vehicles deviate the most from the rest of the vehicles.

Engine brake does not have as clear peak as full load and constant speed. The time in different ranges is much more spread out over the engine speed range.

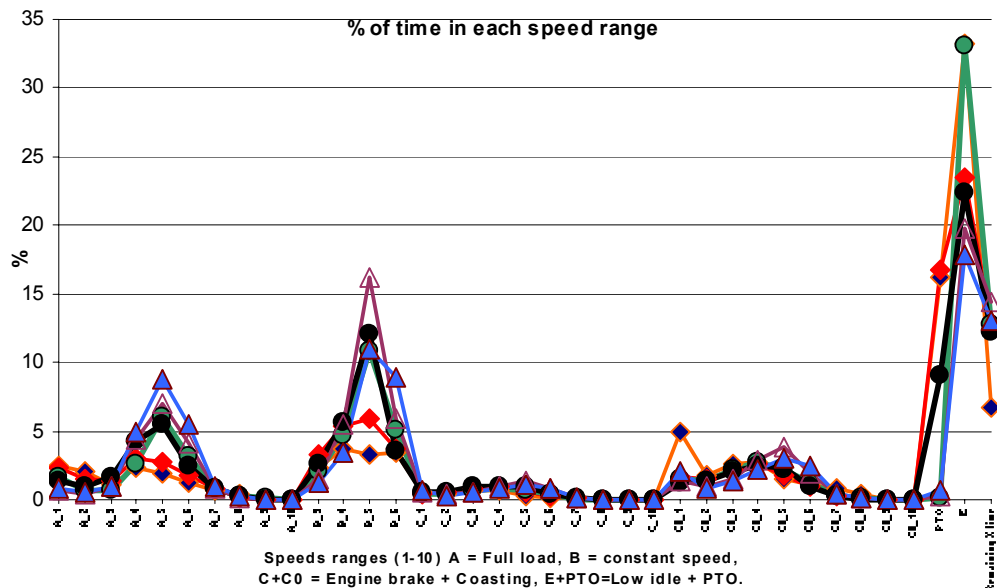


Figure 18: % of time in each driving mode

## **6 Experimental studies**

Three different sets of measurements were performed to study the propulsion noise. They are thoroughly presented in the measurement reports [39, 40 and 41] included as **appendix 1-3** in this report.

### **6.1 The test object**

In all cases a long haul or long distance like truck was simulated with the same type of engine: 480 hp 6-cylinder in-line, but different gearboxes: an automatically controlled manual gearbox (I-shift) in the first case and a manual gearbox in the second and third measurement. In the first set of measurements the truck was built up around the engine and gearbox in the powertrain rig at the laboratory (explained on page 3 in [39]) see the photos in appendix 1 of [39].

The measurements in [40] and [41] were performed in the truck noise chamber on a complete vehicle (explained on page 3 in [40]). Photos of the vehicle are included in appendix 1 in [40 and 41]. The simulated total vehicle load was 30 tonnes in the powertrain rig and 18 tonnes in the truck chamber.

### **6.2 Sound power measurement**

The sound power measurement according to the standard ISO 3744 was chosen as test method in both rigs. The method is described on page 4 in [39] and [40]. In the first set of measurements 16 microphones were positioned around a parallelepiped reference box enclosing the test object. In [40] and [41] 14 microphone positions were used. The microphone positions are pictured in appendix 2 of all reports.

### **6.3 Propulsion noise study [39 and 40]**

In the first two reports the propulsion noise was measured during constant speed from 5 to 85 km/h with an interval of 5 km/h with most suitable gear, i.e. the gear which results in an engine speed within the economy range. In some runs a lower gear was selected to resemble a more aggressive driving style. The influence of vehicle load and road gradient was also studied.

The results are presented both as overall levels versus vehicle speed and engine speed and as sound power level for each third octave band. Regression analysis was made based on the overall levels in uphill and downhill driving.

### **6.4 City cycle measurement [41]**

The equivalent sound power level, in third octave bands, was measured during a designed city cycle in the truck noise chamber. The city cycle is described on page 6 in appendix 3. It included constant speed driving at different velocities as well as starting and turning of the engine, acceleration, engine braking and low idling.

The overall sound power variation with time, with a time resolution of 2,3 seconds, is also presented together with the recorded engine speed, dyno roller speed (considered equal to the vehicle speed) and the tractive force of the roller (equal to the tractive force that the vehicle has to overcome). A correlation study of the sound power level and the different recorded parameters is presented in appendix 5 of [41].

## 7 Results and Conclusions

It is obviously hard to make a simple model of a source that is dependent on different parameters as well as different sub-sources. In this study the noise from a tractor, with a simulated trailer, was investigated. It is a typical combination for a long distance like transport vehicle. The vehicle would be categorised as 3b or 3c depending on the axle configuration of the vehicle. However, driving without trailer the tractor (GCW 8t) would be categorised as 2c, a medium heavy vehicle (3,5-12t). But as commented in 4.1.3 and 5.3.1 the tractor will produce as much or even more noise than a loaded truck. There are also rigid trucks categorized as the EU/ECE definition N3 with two axles.

In the proposed Harmonoise vehicle categorisation [7] the EU/ECE definitions were not included. Adding the EU/ECE definition would be of practical use to improve the harmonisation between standard type approvals and the data collection for noise mapping and ease the classification for single trucks. To avoid wrongly categorized vehicles, category 3b should also include 2-axled vehicles.

### 7.1 Propulsion noise model vs. measured values at constant speed

The measured third octave band levels and overall sound power levels at constant speed were compared with the levels of the Harmonoise/Imagine model. A Matlab-function based on the functions in 3.1, made by Hans Jonasson at SP (version as of 04-11-30), was used to calculate the Imagine values. The coefficients were updated to be identical to table 2. The third octave band levels of the propulsion noise according to the model, for category 3, are shown in figure 19. It can be seen that the low frequencies are modelled as independent of the vehicle speed.

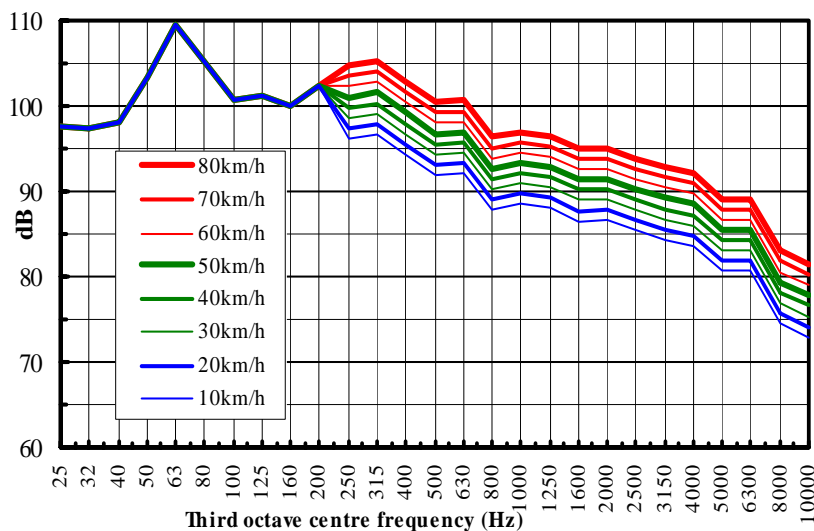


Figure 19: Sound power level, dB, in third octave bands according to the Imagine model

Figure 20 and 21 compare the values measured in the powertrain rig and the truck noise chamber, to the Imagine model (black curves). The vehicle load was 18 tonnes in the powertrain rig and 30 tonnes in the truck chamber, but at constant speed this does not have any influence (see 7.4). The difference in low frequency noise of the measured values is discussed in [40]. It is due to the exhaust outlet noise that was not included in the powertrain rig. In appendix 7 of [40] a comparison at constant speed of 70 km/h is shown. Above 100 Hz the measured values in the powertrain and truck chamber show good resemblance (the 30<sup>th</sup> engine order, 630 Hz, is less prominent in the powertrain rig however due to the exclusion of exhaust noise).

The levels are in general much greater in the model and in particular in the frequency range 80-500 Hz and 3150-10000 Hz. The measured levels do not show the same increase due to vehicle speed as in the model. From the measurements in the truck chamber, with the exhaust outlet noise included through exhaust evacuation nozzle, it can be seen that it is correct to model the noise below 250 Hz as independent of the vehicle speed.

The difference in noise level over the vehicle speed in the powertrain rig is probably only due to the engine speed difference. Appendix 3d of [39] shows the clear gear/vehicle speed independence of the propulsion noise. The measurements in the truck chamber show a somewhat increased vehicle speed dependence however (see figure 22 and appendix 3d in [40]).

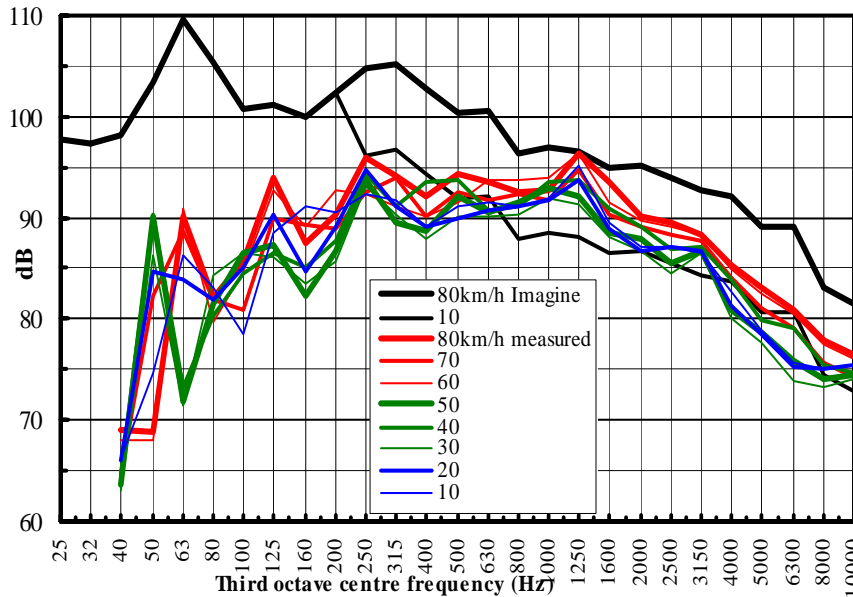


Figure 20: Sound power level, dB, in third octave bands Imagine vs. Powertrain rig

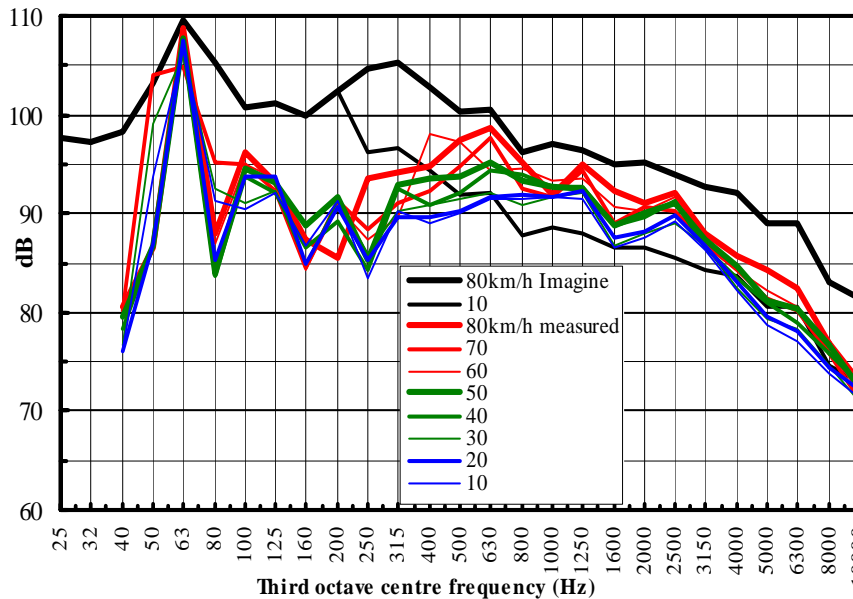


Figure 21: Sound power level, dB, in third octave bands Imagine vs. Truck noise chamber

Figure 22 and 23 show the overall sound power level at constant speed in dBA, both for the so-called most suitable gear choice (the engine speed is within the lower part of the green area on the tachometer i.e. about 1100 rpm) and one gear below. Downshifting leads to a higher engine

speed and hence raises the noise level. A saw-tooth like curve is seen. The squared correlation factor is  $R^2 = 0,81$  for the most suitable gear in the truck noise chamber and  $R^2 = 0,45$  in the powertrain rig. The overall levels measured in the truck chamber show hence the highest vehicle speed dependence. This is to be compared with  $R^2 = 0,48$  during the city cycle, which consisted of 40 % constant speed [41].

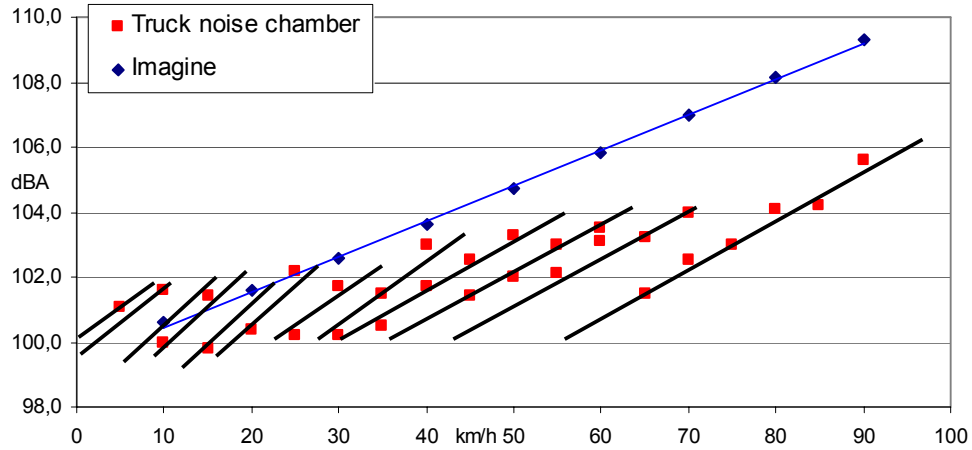


Figure 22: OAL in dBA in Truck noise chamber and Imagine model

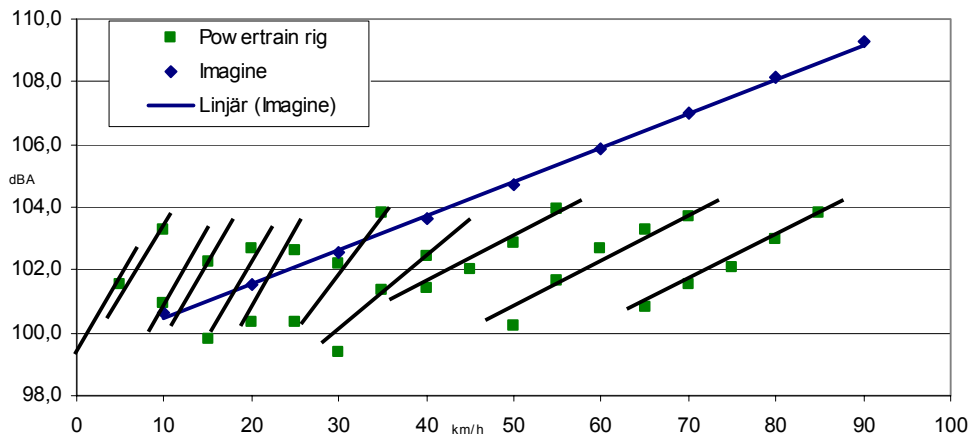


Figure 23: OAL in dBA in Powertrain rig chamber and Imagine model

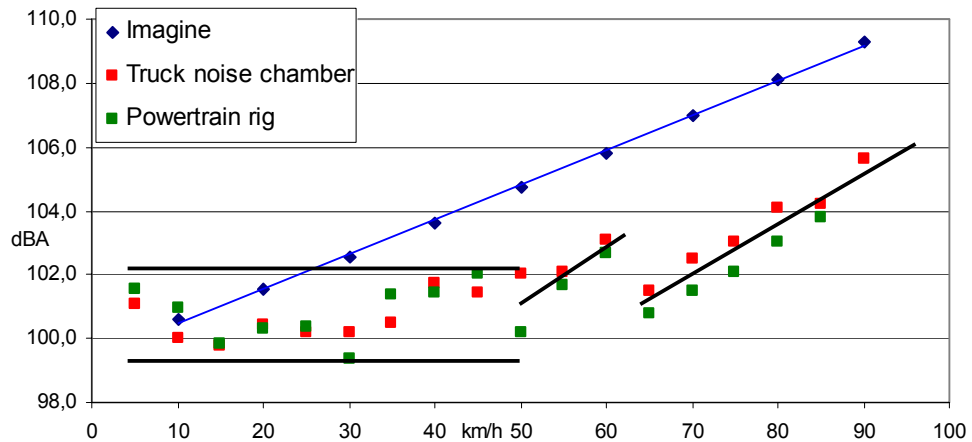


Figure 24: OAL in dBA for most suitable gear in Powertrain rig and Truck noise chamber

The overall levels according to the Imagine model in figure 22 and 23 show the influence of the high frequency bands' levels which raise the overall level prominently with the increased vehicle speed. According to the measured values, see figure 24, the noise can be modelled as constant below 50 km/h. The difference is due to the engine speed which varies between about 1000 to 1200 rpm. At higher vehicle speeds the engine speed increases and consequently raises the overall sound level.

## 7.2 Driving style influence

By choosing a lower gear, an aggressive driving style was simulated in appendix [39] and [40]. The averaged increase in sound power level was 2,3 dBA (2,7 dB) in the powertrain rig, and 1,4 dBA (0,8 dB) in the truck noise chamber. In appendix 3c of [39] and [40] the third octave spectra are plotted. It can be seen that the third engine order moves up in the octave bands.

The difference between the two averaged values is partly due the gearbox ratios which differed between the two measurement installations. In the powertrain rig a gearbox with 12 gears was used and in the truck noise chamber 14 (12 gears + 2 crawler gears). The changed gearbox design used in the truck noise chamber leads to a minor engine speed increase when downshifting in gears. Since the engine noise is mainly engine speed dependent the emitted noise decreases.

The driving style at an acceleration from 0 km/h can be seen in [41] when performing the city cycle. The difference between a full and part throttle is shown in appendix 4a-c. The vehicle was more carefully accelerated in run 2, which decreases the noise level, since the engine speed is not too high, but on the other hand it prolongs the acceleration distance.

## 7.3 Hill driving

The measured noise levels when simulating driving at constant speed in 50-55 km/h on positive road grades and 35-50 km/h on negative road grades are presented in figure 24 and 25 respectively. Since different vehicle loads were simulated, it is not possible to directly compare the sound power levels. The load on the engine increases proportional to the vehicle load and road grade, see equation 22. It can be seen that the heavier vehicle, 30 tonnes, in the powertrain rig produces greater sound levels which leads to a stronger correlation to the road grade, for both positive and negative grades, than the vehicle in the truck noise chamber.

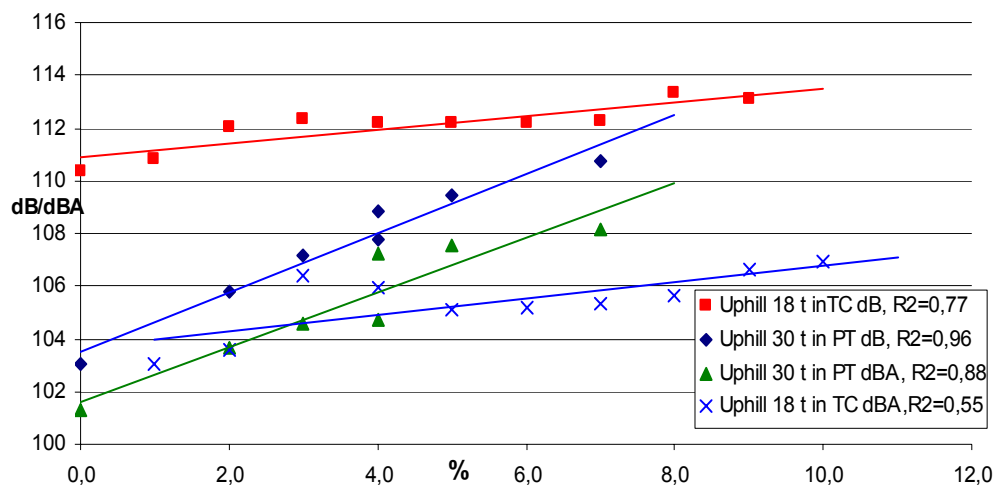


Figure 24: OAL for increasing road grade % in Powertrain rig (PT) and Truck noise chamber (TC)

The noise increases with 0,3 dBA/% road grade in the powertrain rig and 1,0 dBA/% road grade in the truck noise chamber.

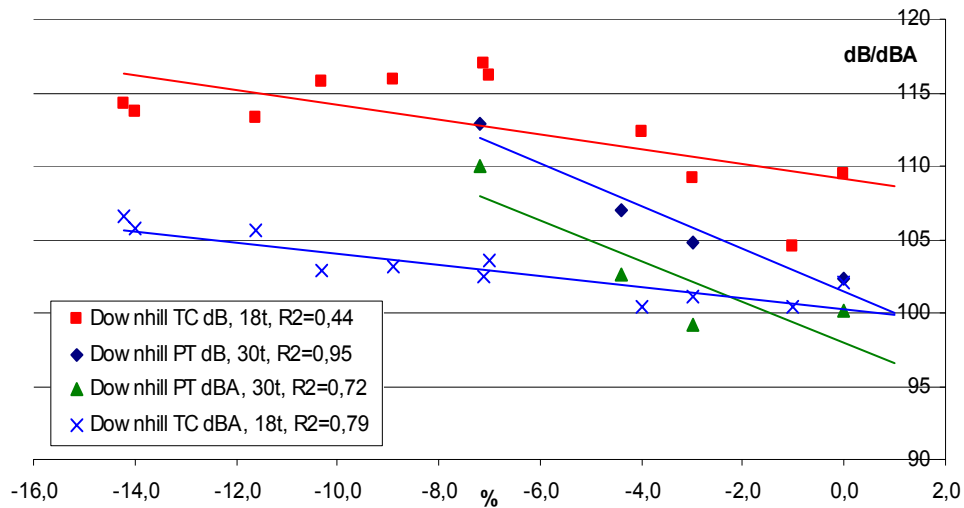


Figure 25: OAL for decreasing road grade % in Powertrain rig and Truck noise chamber

For negative road grades the noise increased with 0,4 dBA/% road grade in the powertrain rig and 1,4 dBA/% road grade in the truck noise chamber. It should be remarked on that the vehicle in the truck noise chamber was not equipped with a second engine brake system. This would have increased the noise level. The fact that the engine fan did not interfere during the measurements makes the values appear low. More measurements are needed to study the influence of the fan which is dependent on the engine temperature and hence effected by the length of the road grade.

It must also be commented that during the measurements the target was to remain at the same constant vehicle speed on the same gear (to avoid influence of changed engine speed) at all grades. At larger slopes however, a downshifting in gear would most likely been performed rather than stay at the same gear. This would have decreased the vehicle speed and increased the engine speed to have greater engine torque for the traction or braking situation.

For road grades less than 2 % the driving performance should not be affected (see 5.3.1), but for greater slopes a correction to the model would be needed. In the Harmonoise/Imagine model there is a correction for the acceleration/deceleration (equation 8). It is recommended that a correction is applied also when driving in up- and down hills where the vehicle speed is low but the engine speed is high to have greater torque.

## 7.4 Vehicle load influence

The measurements in [39] and [40] show that the vehicle load has a negligible influence on the propulsion noise during constant speed (see appendix 4 in both [39] and [40]). Figure 8-11 show that the vehicle load has a major effect on the acceleration performance however. Since increased vehicle load demands a gear-shifting through more gears and hence prolongs the acceleration it will increase the noise duration. To what extent the noise level will increase due to the vehicle load has not been investigated, but it is expected to be low (see 4.1.3).

The vehicle load influence when driving on graded roads is important see 7.3.

## 7.5 City cycle results

The simulated urban driving ([41]) presents the sound power variation over time for a 5-minute long cycle. A correlation analysis of the sound power level and vehicle speed, engine speed and tractive force respectively shows that the sound power level is strongest correlated to the engine speed,  $\rho = 0,91$  and the squared value is  $R^2 = 0,83$  (averaged over three runs) (compare figure 26 and 27). For the tractive force and the vehicle speed the correlation is  $R^2 = 0,50$  and  $R^2 = 0,48$  respectively. This demonstrates the difficulties to make a correct propulsion noise model without involving the engine speed.

The difference in sound power level between full throttle acceleration and constant speed is obvious (see appendix 4c in [41]) and stresses the importance of including an acceleration correction to the model. This is also important at deceleration when the engine brake is used and raises the overall level. The tested vehicle was however only equipped with one type of engine brakes. It is common that heavy trucks especially in hilly area are supplied with at least two braking system. This would increase the braking torque and the emitted noise. In the performed city cycle downshifting in gear resulted in enough braking force to reach target speed, hence the EPG system did not interfere at the measurement.

When not including the idle part, the difference between the maximum and minimum sound power level during the cycle is about 14 dBA.

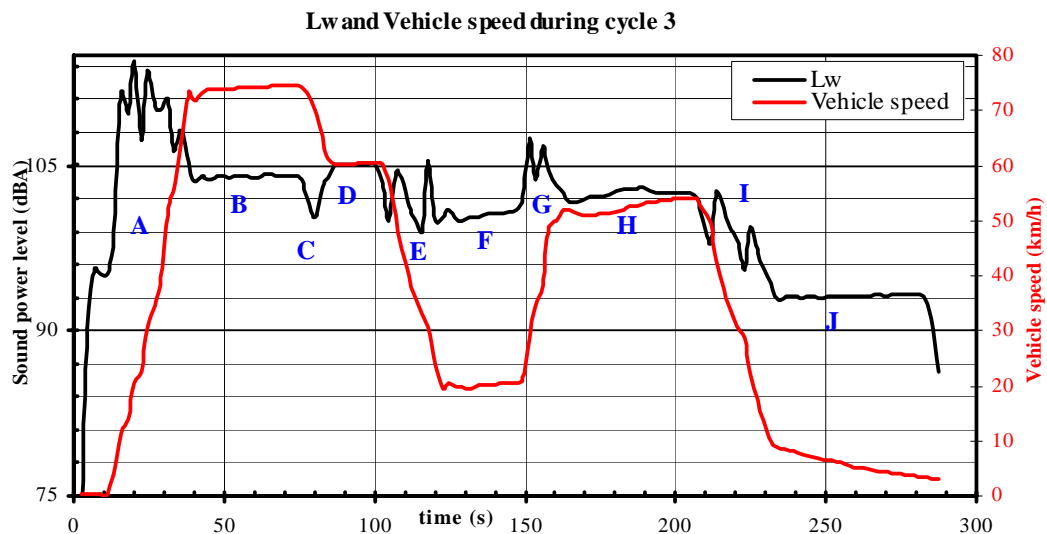


Figure 26: Sound power level during the cycle (A = accel, B, D, F, H = const speed, C, E, G, I = eng.brake and downshifting, J = low idle)

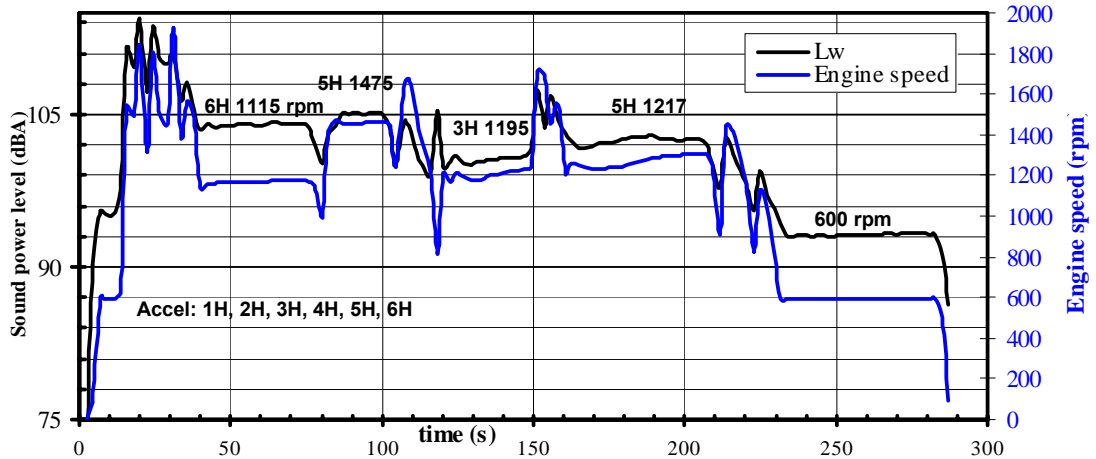


Figure 27: Sound power level during the cycle, gears and engine speeds are shown in the graph

## 7.6 Future work

During the summer of 2005 measurements on heavy vehicles will be performed outdoors at the proving ground of Volvo Trucks, both during constant speed and simulating city traffic situations. Three different vehicles will be used. One typical distribution like vehicle, one long distance like rigid vehicle and one long distance like tractor and trailer. The results in this report can advantageously be compared with the outdoor driving measurements.

It is further recommended that the Harmonoise/Imagine model should be developed to cover the noise increase when driving on graded roads.

## REFERENCES

- [1] P.M. Nelson, *Transportation Noise Reference Book*, Butterworth & Co. 1987
- [2] Position paper from Harmonoise project, "Harmonised Accurate and Reliable Methods for the EU Directive on the Assessment and Management of Environmental Noise", HAR70TR-030709-AEA03, 2003
- [3] J-F. Hamet and V. Steimer, "Modelling Pass-by noise of heavy trucks by power unit noise and rolling noises", in *Proceedings of Inter-Noise 2001*, The Hague 2001
- [4] Report from European Commission, DG Environment, Final Report Part A, Contract B4-3040/2001/329750/MAR/C1, "Adaptation and revision of the interim noise computation methods for the purpose of strategic noise mapping", 2003
- [5] Report from TRL Limited and RWTÜV, "Integrated assessment of noise reduction measures in the road transport sector", PR SE/652/03, 2003
- [6] J-F. Hamet, M-A Pallas, S. Doisy, J.Lelong, "Modelling noise emission of heavy trucks: do a power unit and rolling noise suffice?", in *Proceedings of Inter-Noise 2004*, Prague 2004
- [7] Report from Harmonoise project, "Source modelling of road vehicles", HAR11TR-020614-SP09v8 and v9draft, 2004
- [8] H.G. Jonasson, G. Watts et al., "The Harmonoise source model for road vehicles", in *Proceedings of Inter-Noise 2004*, Prague 2004
- [9] <http://www.rotranomo.com>, 2004-10-19
- [10] M-A. Pallas and S. Doisy, "Localisation and analysis of the noise sources of a truck", in *Proceedings of Inter-Noise 2002*, Dearborn, MI, USA, 2002 <http://www.calm-network.com/db/view.php?id=623>, 2004-10-19
- [11] M-A. Pallas, "Acoustic behaviour of the noise sources of a truck", in *Proceedings of Inter-Noise 2004*, Prague 2004
- [12] Green Paper of the European Commission, COM(96)540 "Future Noise Policy", Brussels 1996, <http://europa.eu.int/en/record/green/gp9611/noise.htm>
- [13] Directive 2002/49/EC relating to the Assessment and Management of Environmental Noise, 2002
- [14] A. Garcia et al., *Environmental Urban Noise*, WIT Press 2001
- [15] H. Jonasson, *Measurement and Modelling of Noise Emission of Road Vehicles for Use in Prediction Models*, SP Report 1999:35, Borås 2000
- [16] H. Jonasson, *Nord 2000, New Nordic Prediction Method for Road Traffic Noise*, SP Rapport 2001:10, Borås 2001
- [17] Report from Harmonoise project, "Road Sources, Comparison of methods for measuring power train noise", HAR11TR-021231-TRL03, 2003
- [18] Report from Harmonoise project, "Test method for the whole vehicle", HAR11TR-020301-SP06, 2003
- [19] Final Report 01-1, I-INCE WP-NERV, Ulf Sandberg, "Noise emissions of road vehicles - Effect of regulations", 2001
- [20] Trucks Standard GDI 966-07 Volvo 3P, P-O Fryk, "Global Truck Applications – GTA", 2003
- [21] Internal classified report, Geir Andresen, Volvo Trucks, ER-600964, 2004-08-16
- [22] R. Hickling and M. Kamal, *Engine Noise - Excitation, Vibration and Radiation*, Plenum Press, New York 1982
- [23] T.D. Gillespie, *Fundamentals of Vehicle Dynamics*, Society of Automotive Engineers Inc., 1992
- [24] Volvo ppt-presentation, "PERF – Performance Calculations", 1999
- [25] Operators manual for nvh truck chassis dynamometer Froude Consine, "Instruction manual: IM 00500/2A, Issue 1", 2001

- [26] ppt-presentation, Jacobs Vehicle Systems, "On Engine Brake Noise"  
<http://www.jakebrake.com/ppt/noise.ppt>, 2004-11-19
- [27] Swedish standards SS-EN ISO 3740, "Acoustics – Determination of sound power levels of noise sources – Guidelines for the use of basic standards (ISO 3740:2000)", SIS Förlag AB, 2000
- [28] Committee draft ISO/CD 80000-8.2, "Quantities, units, symbols, conversion factors", 2004
- [29] Report from Harmonoise project, "Coefficients and data", HAR11TR-031027-MP02v2, 2003
- [30] L. Beranek and I. Vér, *Noise and Vibration Control Engineering – Principles and Applications*, John Wiley & Sons Inc., 1992
- [31] Department of Transport UK, "Control of body noise from commercial vehicles", 2002
- [32] Volvo Truck Parts AB, *Grundläggande fordonsteknik, Lastvagnar del 2*, Göteborg 1995
- [33] Southampton University ISVR, Course Notes "Engine Noise & Vibration Control", 1990
- [34] Committee draft ISO/CD 362, "Acoustics – Measurement of noise emitted by accelerating road vehicles – Engineering method", 2002
- [35] Draft for Final Tech. Report in the Harmonoise project, "Vehicle categories for description of noise sources", HAR11TR-030108-VTI04, 2003
- [36] [www.ecodrive.org](http://www.ecodrive.org), 2005-05-24
- [37] Claes-Göran Sandblom, Åkeri&Transport Nr.5-03: "Stefan lär dig köra ekonomiskt", 2003
- [38] Internal classified report, Eugen Joss, Volvo Trucks, ER-600977, 2004-12-14
- [39] Open engineering report, Christina Keulemans, Volvo Trucks, ER-602178, 2005-03-08
- [40] Open engineering report, Christina Keulemans, Volvo Trucks, ER-602195, 2005-05-17
- [41] Open engineering report, Christina Keulemans, Volvo Trucks, ER-602199, 2005-05-17