HARMONOISE PREDICTION MODEL FOR ROAD TRAFFIC NOISE

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Prepared for: Project Record: Development of a harmonised prediction models for road and rail noise

Client: Roads Policy Division, Department for Transport (Marilyn Waldron)

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Executive summary

The European Directive for the Assessment and Management of Environmental Noise (2002/49/EC) or END demands the production of strategic noise maps and noise action plans for major roads, railways airports and in agglomerations. From 2012, the maps will have to be produced using harmonised prediction methods. The Directive referred to the lack of a harmonised and reliable method for noise prediction and as a consequence a new method was required which could be adopted across Member States. The project Harmonoise (Harmonised, Accurate and Reliable Methods for the European Directive On the Assessment and Management of Environmental NOISE) was designed to fulfil this need. The project was part funded by the European Commission, DG Information Society and Technology, under the 5th Framework Program (IST-2000-28419). The project output is a description of the noise prediction methods for road and railway noise sources that have been developed. It is expected that software suppliers will subsequently supply computer programs for mapping and action plans.

The work was carried out within a number of work packages (WPs) which included the developments of road and railway source models (WP 1.1 and WP 1.2), propagation models (WP2) and an engineering model for use in noise mapping (WP3). Data was collected at 13 sites to validate the models that had been developed (WP4).

TRL’s major input has been in WP1.1 and WP3 with some early involvement in WP2. This report focuses on the prediction of road traffic noise and TRL’s contribution to the project is highlighted where the work has been largely planned and directed by TRL staff. In other cases TRL have contributed but the work has been largely directed by non-TRL staff. The final report based on work by all the partners and project deliverables are available on the Harmonoise web site: www.harmonoise.org

Noise levels are predicted in terms of $L_{den}$ and $L_{night}$ as these are the indices required by the environmental noise directive. The noise index $L_{den}$ is defined as:

$$L_{den} = 10 \log \left[ \frac{12}{24} 10^{\frac{L_{day}}{10}} + \frac{4}{24} 10^{\frac{L_{evening}+5}{10}} + \frac{8}{24} 10^{\frac{L_{night}+10}{10}} \right] dB(A)$$

where $L_{day}$ is the $L_{Aeq}$ level taken over 12 hours during the day, $L_{evening}$ is the $L_{Aeq}$ over 4 hours in the evening and $L_{night}$ is taken over 8 hours during the night time. The weighting factors +5 and +10 in the exponents are designed to take into account the increased annoyance caused during the evening and night-time periods. Consequently, the weighting and averaging over traffic composition and weather conditions are carried out separately for each of these three periods of the day averaged over a year. Average weather conditions are based on several years of meteorological data.

The source model developed in WP 1.1 provides the description of the sound power of various categories of vehicle in terms of speed and acceleration. Corrections are applied for the road surface texture and condition including temperature and for directivity both in the horizontal and vertical plane. The sources on the vehicles are simplified into two point sources: a lower and higher source. The lower source is mainly due to tyre/road noise and the higher source is mainly propulsion noise. The height of the propulsion noise source depends on the vehicle category.

The sound power of the sources in a given direction are then used to calculate levels at any given receiver using a ray based propagation model developed in WP3 of Harmonoise. The road surface acoustic impedance is included in the propagation model. A road segment will be composed of a series of point sources of different types depending on the percentage of vehicles of varies categories and their speed. All these sources are integrated to arrive at the final averaged A-weighted traffic noise level.

The reference propagation model developed in WP2 is concerned with obtaining very precise predictions of sound propagation through different atmospheric conditions and is based on state-of-the-art propagation methods. These are restricted to a limited range of conditions where the developed theory allows the necessary accuracy of prediction. Typically these prediction tools are not appropriate for noise mapping purposes due to the complexity of use and the intensive computer
resources that are required. Note that the propagation component of the engineering model is simpler and uses less computer resources.

The engineering model has been validated against measured results at two road locations where the roads ran on embankments above essentially flat terrain. The differences between predicted and calculated values of $L_{den}$ were never greater than 1.5dB(A) even at a distance greater than 1 km from the road. However, further validation is required for example in the more complex situations typically found in urban areas.

A follow up project called IMAGINE started in December 2003 and funded under the 6th EC Framework Program will enable more data to be collected and added in order to refine the prediction methods developed in Harmonoise. It will also enable methods for data collection to be defined and advice given on the production of noise maps. The prediction method will also be extended to industrial sources and aircraft so comprehensive mapping of noise sources will be possible.
1 Introduction

The European Directive for the Assessment and Management of Environmental Noise (2002/49/EC) or END requires the production of strategic noise maps and noise action plans for major roads, railways airports and in agglomerations. The Directive notes the lack of a harmonised and reliable method for noise prediction and the need for a new method which could be adopted across Member States. The project Harmonoise (Harmonised, Accurate and Reliable Methods for the European Directive On the Assessment and Management of Environmental NOISE) was designed to fulfil this need. The project was part funded by the European Commission, DG Information Society and Technology, under the 5th Framework Program (IST-2000-28419).

The main objective of the Harmonoise project is to develop methods that are harmonised, accurate and reliable. The project will not deliver ready to use software but rather a description of the noise prediction methods that have been developed. However, it is expected that software suppliers will develop, supply and maintain computer programs for mapping and action plans. Although some of the partners in Harmonoise are considered software developers, or are closely linked to such organisations, it is the intention that all parties that intend to develop software have equal access to the methods developed in the project. From 2012 it is expected that maps will need to be produced using such harmonised prediction methods.

The work was carried out within a number of work packages (WPs):

WP1.1: Road source description
WP1.2: Railway noise sources
WP2: Reference propagation model
WP3: The engineering model
WP4: Data collection and validation
WP5: Dissemination and exploitation
WP6: Assessment and evaluation

The reference propagation model is concerned with obtaining very precise predictions of sound propagation through different atmospheric conditions and is based on state-of-the-art propagation methods. These are restricted to a limited range of conditions where the developed theory allows the necessary accuracy of prediction. Typically these prediction tools are not appropriate for noise mapping purposes due to the complexity of use and the intensive computer resources that are required. The engineering model was designed for noise mapping and includes a source model. The propagation component of the model is simpler and uses less computer resources. The output from the reference model together with measurements made at thirteen different sites have been used to validate the engineering model.

TRL’s major effort has been in WP1.1 and WP3 with some early involvement in WP2. This report focuses on the prediction of road traffic noise and TRL’s contribution to the project is highlighted where the work has been largely planned and directed by TRL staff. In other cases TRL have contributed but the work has been largely directed by non-TRL staff. The final report based on work by all the partners and project deliverables can be found on the Harmonoise web site: www.harmonoise.org

A follow up project called IMAGINE is already under way (start date December 2003) funded under the 6th EC Framework Program (CT-2003-5035349). This will enable more data to be collected and added in order to refine the prediction methods developed in Harmonoise. It will also enable methods for data collection to be defined and advice on the production of noise maps. The production of Action Plans will also be addressed and the link between traffic flow and noise models will be investigated. The prediction method will also be extended to industrial sources and aircraft so comprehensive mapping of noise sources will be possible.
2 Background and context

As the methods developed in Harmonoise are intended for the application of the END, the methods are particularly suited to predict the noise level in terms of the harmonised noise indicators $L_{\text{den}}$ and $L_{\text{night}}$. The noise index $L_{\text{den}}$ is defined as:

$$L_{\text{den}} = 10 \log \left[ \frac{12}{24} 10^{\frac{L_{\text{day}}}{10}} + \frac{4}{24} 10^{\frac{L_{\text{evening}} + 5}{10}} + \frac{8}{24} 10^{\frac{L_{\text{night}} + 10}{10}} \right] dB(A)$$

where $L_{\text{day}}$ is the $L_{\text{Aeq}}$ level taken over 12 hours during the day, $L_{\text{evening}}$ is the $L_{\text{Aeq}}$ over 4 hours in the evening and $L_{\text{night}}$ is taken over 8 hours during the night time. The weighting factors +5 and +10 in the exponents are designed to take into account the increased annoyance caused during evening and night-time. Consequently, the weighting and averaging over traffic composition and weather conditions are carried out separately for each of these three periods of the day. Average weather conditions are based on several years of meteorological data.

The noise prediction models presently available for noise mapping are semi-empirical methods, combining the physics of sound propagation outdoors with empirical data from repeated experiments. Through interpolation between measured data a particular situation can often be modelled. However the semi-empirical approach has the obvious disadvantage that extrapolation beyond the range of application, leads to large uncertainties. For example within the UK prediction method for road traffic noise, CRTN (Department of Transport and Welsh Office, 1988), the atmospheric conditions are limited to positive wind vectors (wind blowing from source to receiver) and cannot take account of temperature inversions that are known to affect sound propagation particularly over large distances.

“Ambition levels” have been set for the accuracy of the prediction model which forms the main output of the project. Though the term “ambition level” has not been precisely defined it can be interpreted in terms of the root mean square difference between the predicted and measured levels. These differences are:

- $\leq 1$ dB for free field (no objects between source and receiver) at distances up to 100 m
- $\leq 2$ dB for flat terrain at distances up to 2000 m
- $\leq 5$ dB for hilly terrain up to 2000 m
- $\leq 5$ dB for urban areas

It is considered this level of accuracy improves on that for existing models.
3 Components of the model

Figure 3.1 shows the components of the engineering model and lists the main factor influencing noise levels. The source strength will depend on a number of factors including the type of vehicle, its operating condition and the road surface and its condition. Propagation will be affected by wind speed and direction and temperature profiles in the atmosphere as well as obstacles to propagation such as noise barriers. The actual value of $L_{den}$ will take into account average weather conditions.

![Components of the engineering model diagram]

Each of these components will be described in turn and TRL’s contribution will be described in more detail in appendices A to D. Further information can be obtained from the Harmonoise project deliverables that can be downloaded from the Harmonoise website.
4 Source model

The source model entails the description of sound power of various categories of vehicle in terms of speed and acceleration. Corrections are applied for the road surface texture and condition including temperature and for directivity both in the horizontal and vertical plane. The sources on the vehicles are simplified into two point sources: a lower and higher source. The lower source is mainly due to tyre/road noise and the higher source is mainly propulsion noise. The height of the propulsion noise source depends on the vehicle category.

The sound power of the sources in a given direction are then used to calculate levels at any given receiver using a ray based propagation model developed in WP3 of Harmonoise. The road surface acoustic impedance is included in the propagation model. A road segment will be composed of a series of point sources of different types depending on the percentage of vehicles of varies categories and their speed. All these sources are integrated to arrive at the final averaged A-weighted traffic noise level.

4.1 Vehicle categories

The vehicles are divided into the categories shown in Table 4.1. It is likely that initially only the main categories will be used. Later, data on subcategories will become available. It can be seen that separate categories have been reserved for low noise vehicles and electric vehicles. It is to be expected that the proportion of these vehicles will grow over time and relevant data can be added.

There are three main categories corresponding to light (category 1), medium heavy (category 2) and heavy vehicles (category 3). Category 1 and 2 vehicles all have two axles except in the case of vehicle/ trailer combinations. Generally category 2 vehicles have 6 or more wheels (4 on the rear axle). Category 3 contains the heaviest vehicles which have more than 2 axles.

At the present time limited data is available to describe the emission from sub-classes and consequently predictions are only available for the main vehicle classes. An exception is that rolling noise sound power levels are given as a function of the number of axles for category 3 vehicles.

Vehicles with high exhausts (stack exhausts) are placed in sub-categories since the effective position of the propulsion noise source is likely to be significantly higher above ground than for vehicles with exhausts mounted close to the chassis.

Electric vehicles are also placed in a sub-category since the characteristics of the propulsion noise will be significantly different from diesel or petrol fuelled vehicles.
Table 4.1: Vehicle categories

<table>
<thead>
<tr>
<th>Main category</th>
<th>No.</th>
<th>Sub-categories</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light vehicles</td>
<td>1a</td>
<td>Cars (incl MPV:s up to 7 seats)</td>
<td>2 axles, max 4 wheels</td>
</tr>
<tr>
<td></td>
<td>1b</td>
<td>Vans, SUV, pickup trucks, RV, car+trailer or car+caravan</td>
<td>2-4 axles(^{(1)}), max 2 wheels per axle</td>
</tr>
<tr>
<td></td>
<td>1c</td>
<td>Electric vehicles, hybrid vehicles driven in electric mode(^{(2)})</td>
<td>Driven in combustion engine mode: See note</td>
</tr>
<tr>
<td>Medium heavy vehicles</td>
<td>2a</td>
<td>Buses</td>
<td>2 axles (6 wheels)</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td>Light trucks and heavy vans</td>
<td>2 axles (6 wheels)(^{(3)})</td>
</tr>
<tr>
<td></td>
<td>2c</td>
<td>Medium heavy trucks</td>
<td>2 axles (6 wheels)(^{(3)})</td>
</tr>
<tr>
<td></td>
<td>2d</td>
<td>Trolley buses</td>
<td>2 axles</td>
</tr>
<tr>
<td></td>
<td>2e</td>
<td>Vehicles designed for extra low noise driving</td>
<td>2 axles(^{(5)})</td>
</tr>
<tr>
<td>Heavy vehicles</td>
<td>3a</td>
<td>Buses</td>
<td>3-4 axles</td>
</tr>
<tr>
<td></td>
<td>3b</td>
<td>Heavy trucks(^{(4)})</td>
<td>3 axles</td>
</tr>
<tr>
<td></td>
<td>3c</td>
<td>Heavy trucks(^{(4)})</td>
<td>4-5 axles</td>
</tr>
<tr>
<td></td>
<td>3d</td>
<td>Heavy trucks(^{(4)})</td>
<td>≥6 axles</td>
</tr>
<tr>
<td></td>
<td>3e</td>
<td>Trolley buses</td>
<td>3-4 axles</td>
</tr>
<tr>
<td></td>
<td>3f</td>
<td>Vehicles designed for extra low noise driving</td>
<td>3-4 axles(^{(5)})</td>
</tr>
<tr>
<td>Other heavy vehicles</td>
<td>4a</td>
<td>Construction trucks (partly off-road use)(^{(4)})</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4b</td>
<td>Agr. tractors, machines, dumper trucks, tanks</td>
<td></td>
</tr>
<tr>
<td>Two-wheelers</td>
<td>5a</td>
<td>Mopeds, scooters</td>
<td>Include also 3-wheel motorcycles</td>
</tr>
<tr>
<td></td>
<td>5b</td>
<td>Motorcycles</td>
<td></td>
</tr>
</tbody>
</table>

\(^{(1)}\) 3-4 axles on car & trailer or car & caravan. \(^{(2)}\) Hybrid vehicles driven in combustion engine mode: Classify as either 1a or 1b. \(^{(3)}\) Also 4-wheel trucks, if it is evident that they are >3.5 tons. \(^{(4)}\) If a high exhaust is noted, identify this in the test report. Categorize this as 3b', 3c', 3d' or 4a'. \(^{(5)}\) For example, low noise (“whisper mode”) delivery trucks and buses.

4.2 Basic source model

In order to be able to combine the source model with an appropriate propagation model it is necessary to describe the source as a number of point sources. In Harmonoise two source heights are used for each vehicle category. One is 0.01 m above the road surface and the other is either at 0.3 m for light vehicles or 0.75 m for heavy vehicles. For heavy vehicles with high exhausts (stack exhausts) an additional position at 3.5 m should be used. However, emission data for these vehicles are not yet available. 80% of the rolling noise is assumed to radiate from the lower source whereas 20% is assumed to radiate from the higher source. This allows for some “smearing” of the source which in practice rarely takes the form of a discrete point source. The rolling noise for the reference condition is described by the equation:

\[
L_{R_{\text{ref}}} (f) = a_R (f) + b_R (f) \log \left( \frac{v}{v_{\text{ref}}} \right)
\]

where \(v_{\text{ref}}=70\) km/h. The coefficients \(a_R(f)\) and \(b_R(f)\) for each main vehicle category are contained within a Harmonoise WP1.1 report (not yet published). The difference between category 2 (2 axle medium heavy vehicles) and category 3 (heavy vehicles with >2 axles) depends on the number of
axles. It is assumed that $L_W$ increases as $10 \log$ (number of axles). The default assumption is that a category 3 vehicle on average has 4 axles. Large city buses will often have 3 axles and long distance freight trucks will on average have at least 5 axles. The adjustment across all frequency bands is given by:

$$\left( a_R \right)_{\text{Category 3}} = \left( a_R \right)_{\text{Category 2}} + 10 \log \left( \frac{\text{number of axles}}{2} \right)$$

Note that there is no adjustment to the coefficient $b_R$.

For propulsion noise 80% is assumed to radiate from a source at a height of 0.3 m for light vehicles and at a height of 0.75 m for heavy vehicles. Figure 4.1 shows a plot of the sound emission of a stationary goods vehicle indicating the distribution of the propulsion noise based on measurements with a microphone array carried out at TRL by TNO of the Netherlands (Watts et al., 2003). A Harmonoise technical report of the measurements that were carried out by TRL and TNO is given in Appendix A.

Note that 20% of the sound power is assumed to radiate from the low source 0.01 m above the road surface. In contrast to rolling noise it has been found that propulsion noise is best described as a linear function of speed:

$$L_{app}(f) = a_P(f) + b_P(f) \left[ \frac{v - v_{ref}}{v_{ref}} \right]$$

where the speed coefficient $b_P(f)$ is the same for category 2 and category 3 vehicles whereas $a_P(f)$ varies across all categories. The reference speed $v_{ref}$ is again at 70 km/h.

![Figure 4.1: Third octave band level contours at 1 kHz for a stationary test on Ford Cargo indicating position of engine source and image in the road surface](image)

As would be expected propulsion noise is assumed to be independent of the road surface. The effect on the radiation of propulsion and rolling noise over a porous road surface is taken into account by
introducing an appropriate road surface impedance into the propagation calculations. In Figure 4.2 some examples of rolling and propulsion noise for light and heavy vehicles on a stone mastic surface (SMA) with 16mm maximum size chippings at a typical urban speed of 50 km/h are shown.

**Category 1 (light)**

**Category 3 (heavy with more than 2-axles)**

![Figure 4.2: Sound power levels for rolling and propulsion noise at 50 km/h on SMA (0/16)](image)

It can be seen that below about 500 Hz propulsion noise dominates whereas at mid frequencies rolling noise becomes relatively more important and dominates propulsion noise in the case of light vehicles. It can be shown that for light vehicles the rolling noise is in fact 7.7 dB(A) higher than the corresponding sound power for propulsion noise. In the case of heavy vehicles it is the propulsion noise which is higher than the rolling noise. The difference (rolling noise-propulsion noise) in this case is -4.9 dB(A).

The situation at the higher speed of 100 km/h on the same surface is given in Figure 4.3. Rolling noise becomes even more dominant in the case of light vehicles. The difference is 11.6 dB(A). For heavy vehicles the difference between rolling and propulsion noise was found to narrow with a difference of -2.2 dB(A).

**Category 1 (light)**

**Category 3 (heavy with more than 2-axles)**

![Figure 4.3: Sound power levels for rolling and propulsion noise at 100 km/h on SMA (0/16)](image)

At higher speeds the contribution of rolling noise to the total sound power radiated is greater across all vehicle classes.
4.3 Source model corrections

A number of corrections are made to the basic sound power levels. These include corrections for surface type and condition, acceleration and directivity of the sources and corrections for tyres.

4.3.1 Road surface corrections

The road surface taken as the reference for calculating rolling noise sound power has a maximum chipping size of 11 mm and is a surface having the acoustic characteristics based on the average of dense asphalt concrete (DAC) and stone mastic asphalt (SMA) with an age of more than 2 years but showing no signs of deterioration. Table 4.2 gives the correction to the rolling noise sound power levels for category 1 vehicles in terms of a simple dB correction across all frequency bands by surface type and maximum chipping size. Note that due to lack of appropriate data there are no corrections for heavy vehicles. In addition there is at present no reliable correction for hot rolled asphalt (HRA). It is hoped to extend the range of corrections in the EC part funded IMAGINE project which will build on the results obtained in Harmonoise.

As an example of the correction a 14 mm SMA greater than 2 years old would have a correction to rolling noise of +0.3 + 3\times0.25 \text{ dB} \text{ i.e. } +1.05 \text{ dB}. The corrections are made to each third octave band.

<table>
<thead>
<tr>
<th>Road surface</th>
<th>Correction relative to the reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harmonoise reference with chip size 11 mm, (mean value of DAC and SMA)</td>
<td>±0 dB</td>
</tr>
<tr>
<td>DAC</td>
<td>-0.3 dB</td>
</tr>
<tr>
<td>SMA</td>
<td>+0.3 dB</td>
</tr>
<tr>
<td>Chip size (valid range 8-16 mm)</td>
<td>+0.25 dB/mm above 11 mm</td>
</tr>
<tr>
<td></td>
<td>-0.25 dB/mm below 11 mm</td>
</tr>
<tr>
<td>Age (T years)</td>
<td>- (0.2T^2 -1.2T+1.6); T\leq 2</td>
</tr>
</tbody>
</table>

For other surfaces outside this range of reference surfaces tables are given, based on Dutch data, listing corrections by third octave band centre frequency for cars and trucks. However the corrections are independent of speed and therefore must only be viewed as interim corrections pending further research. Corrections currently available included those for porous asphalt, surface dressing and brushed and exposed aggregate concrete.

For porous surfaces clogging causes an increase in noise with age. A suitable equation to describe this change is:

$$\Delta L_T = \Delta L_0(1 - (0.25T - 0.016T^2)), T \leq 7 \text{ years}$$

where $\Delta L_0$ is the sound pressure level for the individual frequency bands relative to the reference surface at the time $T=0$ years. Corrections are made to each frequency band of the rolling noise component of vehicle noise.

Rolling noise is affected by temperature. Both asphalt and tyres become softer with increasing temperature thus decreasing the rolling noise sound power level. This correction should be frequency dependent. However, due to lack of detailed data the correction to be applied equally on all frequency bands is

$$\Delta L_{WR}(\theta) = K(\theta_{ref} - \theta)$$

where
\[ \Delta L_{WR} = \text{sound power level correction due to rolling noise, dB} \]

\[ \theta = \text{the measured air temperature, } ^\circ\text{C} \]

\[ \theta_{ref} = \text{the reference temperature, } 20^\circ\text{C} \]

\[ K = \text{the temperature coefficient} \]

There are a wide range of temperature coefficients for many different road surfaces. For category 1 vehicles it is normally 0.1 and 0.06 for DAC and SMA surfaces respectively. For category 2 and category 3 vehicles the coefficients to apply are 50% of that of category 1.

There is also a correction for passenger cars travelling on wet surfaces i.e. when there is a distinct layer of water on the road. The increase relative to a dry surface \( \Delta L_{\text{wet}} \) is given by:

\[
\Delta L_{\text{wet}} = 10 \log \left( \frac{110}{v} \right) + 20 \log \left( \frac{f}{2000} \right); f > 2000 \text{ Hz}, 30 < v < 110 \text{ km/h}
\]

\[
\Delta L_{\text{wet}} = 5 \log \left( \frac{110}{v} \right); f = 1600 \text{ Hz}
\]

\[
\Delta L_{\text{wet}} = 2.5 \log \left( \frac{110}{v} \right); f = 1250 \text{ Hz}
\]

Note that due to insufficient information there are no corrections for heavy vehicles.

### 4.3.2 Acceleration corrections

Propulsion noise increases during acceleration and decreases during deceleration. The correction is given by:

\[ \Delta L_{\text{acc}} = C \cdot a; \quad -2 \text{ m s}^{-2} < a < 2 \text{ m s}^{-2} \]

where \( a \) = the acceleration/deceleration in m s\(^{-2}\) and the coefficient \( C \) is given by Table 4.3. For category 3 vehicles an engine brake is often applied and in such cases the absolute value of the deceleration should be used thus increasing the level also when decelerating.

<table>
<thead>
<tr>
<th>Vehicle category</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category 1</td>
<td>4.4</td>
</tr>
<tr>
<td>Category 2</td>
<td>5.6</td>
</tr>
<tr>
<td>Category 3</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Corrections are made to each frequency band of the propulsion noise component.

### 4.3.3 Directivity corrections

The vehicle point sources are assigned both horizontal and vertical directivity. When integrated over a pass-by the integral of the directivity function is close to zero. The reference is the omnidirectional sound power level which, using the propagation model and integrated during a complete pass-by, yields the correct sound exposure level in the horizontal direction. It will be assumed that the vertical directivity is the same for all horizontal angles. Different directivity functions are used for rolling and propulsion noise. For example the horn effect is specific to rolling noise and a correction is given at the lowest source height at frequencies above 1.6 kHz.
The directivity function which is a function of angles, see Figure 4.4, and frequency, f is given by:

$$\Delta L(f, \phi, \psi) = \Delta L_H(f, \phi) + \Delta L_V(f, \psi)$$

and it is normalized to yield 0 dB contribution when integrated during pass-by and $\Delta L_V(0) = 0$ dB. Suffixes $H$ and $V$ refer to the horizontal and vertical directions.

![Figure 4.4: Geometry for directivity correction](Image)

As an example the horizontal directivity at the lowest source height is given by

$$\Delta L_H(\psi) = 0; f \leq 1250 \text{ Hz}, f \geq 8000 \text{ Hz}$$

$$\Delta L_H(\phi) = (-1.5 + 2.5 \times \text{abs}(\sin(\frac{\pi}{2} - \phi))) \times \sqrt{\cos(\psi)}; 1600 \leq f \geq 6300 \text{ Hz}$$

### 4.3.4 Tyre corrections

Tyre dimensions tread block pattern and tyre construction have an influence on tyre/road noise generation. For example in a recent study of the effects of car tyre dimension it was found that on hot rolled asphalt with maximum chipping size of 20 mm and stone mastic asphalt with a maximum chipping size of 14 mm the average increase in noise level per 10 mm increase in tyre section width was approximately 0.5 dB(A) (Abbott and Watts, 2003). It is likely that the average tyre width will vary across Member States being perhaps wider in northern Europe than in southern Europe. Hence there may be a need to apply a vehicle fleet correction to take any such systematic variations into account.

For winter tyres with studs a default correction in the form $a + b \log(v)$ is given. Note that the new EC part-funded project IMAGINE may provide vehicle fleet correction factors for tyres and possibly for road surfaces.
5 Reference propagation model

The reference propagation model is designed to achieve the highest possible accuracy without the restriction of flexibility, ease of use or computation time. In contrast the propagation model in the engineering model is primarily designed for large scale use on a routine basis and focuses on calculation speed and versatility. The reference propagation model has been used to check the output of the engineering model and can be used to enable predictions to be made where the road cross-section is too complex for the simpler engineering model to produce accurate results.

The reference propagation model is based on theoretical modelling methods because any model based on empirical data or on approximations of theory loses its validity in situations that are not covered by the measured data or the approximate theory. For this reason extrapolation outside the validated range will lead to large uncertainties in prediction accuracy. For example in the Calculation of Road Traffic Noise (CRTN) (Department for Transport and Welsh office, 1988) predictions beyond a distance from the road of 300 m have not been fully validated and it is only capable of predicting for positive winds (i.e. wind blowing from source to receiver).

From a state-of-the-art review of propagation models it was concluded that the linearised Euler model and the Parabolic Equation (PE) models are preferable in terms of accuracy and applicability. However the Euler and 3-D PE models demand much computational resources and therefore the 2-D version of PE was chosen as a component of the reference propagation model. This means that only problems where the cross-section does not vary along the length of the road can be solved. In addition the PE method cannot calculate propagation at large angles of elevation and complex geometries e.g. close to a noise barrier and for complex barrier profiles. In these cases to overcome the deficiencies in the source region, i.e. in the road cross-section, the method requires either the boundary element method (BEM) or a straight ray model. Therefore in the source region it has to be assumed that because propagation distances are small, refraction by the atmosphere can be neglected. In these cases the BEM or straight ray model is coupled with the PE model to produce a hybrid prediction model. The prediction proceeds in two stages; the output of the BEM or straight ray models are used to calculate the complex sound pressures along an imaginary vertical surface just outside the road cross-section. These levels are then used as input to the PE model so that the calculations can be made in the far-field beyond the road cross-section taking account of atmospheric conditions.

TRL have contributed to this work by producing a specification of their BEM (Appendix B). They have also described the problem of turbulence near diffracting edges and theoretical and practical methods to obtain solutions (Appendix C).

5.1 Modelling of line sources and directivity

The reference propagation model assumes a point source with a certain sound power level and directivity. To calculate for a traffic stream a series of point sources spaced at equal subtended angles at the receiver position are defined. To account for the different source heights that are included in the source model described above a series of point sources at the relevant heights are defined. Consequently there are a large number of point to point calculations required to fully predict for a traffic stream. The directivity of the sources in terms of the sound power in different horizontal and vertical directions is obtained from the source model.

5.2 Treatment of ground absorption and absorptive barriers and claddings

The impedance of the ground and absorptive road surfaces such as porous asphalt and concrete as well as fibrous material in absorptive noise barriers can be modelled in a number of different ways depending on the degree of information that is available for the characterization of the absorbent. The models that may be used include the Delany and Bazley and Attenborough models (see section B1.1 of Appendix B). The input data including descriptors such as porosity, specific flow resistivity, thickness etc may be assessed by measurement or modelling or may be derived from a table of typical values that will be supplied with the model description.
5.3 Meteorological effects

The influence of wind speed gradients and temperature gradients which cause refraction in the atmosphere due to the resulting changes in sound speed gradients is illustrated in Figure 5.1. Under still conditions at night, heat is radiated away from ground surfaces resulting in a relatively cold layer of air near the ground with warmer layers above (temperature inversion). Under these conditions sound waves are refracted downwards which facilitates sound propagation. Conversely during the day under still conditions the ground warms the lower air layers resulting in a decrease in temperature with height (lapse). For these conditions refraction is upwards resulting in a sound shadow where noise levels are significantly reduced. A wind produces similar effects due to the fact that the air layer in contact with the ground moves slower than air layers at greater height. The result is that upwind a sound shadow is created while downwind conditions are favourable to propagation and noise levels are relatively high.

![Figure 5.1: Refraction of sound waves due to temperature and wind gradients](image)

The sound speed gradient is taken into account in the PE model. A given meteorological condition can be represented for each propagation direction by one of 25 effective sound speed profiles that approximates the actual sound speed profile for this condition and direction. The closest fitting profiles result from using linear-logarithmic functions. Meteorological influences over longer periods can be computed by using a weighted combination of these 25 profiles for each propagation direction. The weighting factors are based on meteorological statistics for the specific location and period.

5.4 Modelling of complex barrier shapes

The screening performance of complex barrier shapes such as multiple edge and T-shaped barriers can be assessed by using the 2-D hybrid model involving the BEM in the road cross-section and a PE method in far field. The BEM is able to take into account the effects of complex barrier profiles while the PE model can be used to assess the propagation through the atmosphere. However, the barrier affects the wind speed gradient in the vicinity of the barrier and introduces turbulence which scatters sound which cannot be taken into account. In addition the 2-D approximation can cause prediction errors for horizontal angles of incidence larger than 60 degrees. By using curved ray paths in the source region it is possible to overcome some of these effects but only at the expense of much greater use of computer resources and in many cases this is not a feasible option. Testing the performance of barrier shapes at full scale under different wind conditions allows predictions to be made but only for
receiver and source distances and heights within the range of the collected data. Appendix C gives a measurement method developed by TRL for this purpose.
6 Engineering model

The Engineering model uses the source model described above. The propagation model is simpler and faster to execute than the reference propagation model but accuracy is expected to be less but adequate for noise mapping purposes. All calculations are carried out in third octave bands from 20 Hz to 10 kHz but reduction to octave bands is an option for reducing computation times. The building blocks of the propagation model in the engineering model is a point to point model. Thus only one point source and one receiver position is treated at a time although there may be more than one propagation path due to reflected sound. The contribution from the different point sources (including vehicle sub-source) is assessed one after the other. The calculation is repeated for all relevant meteorological classes. The long term average per period of the day/night is computed from weighting the results from each meteorological class considered by the frequency of occurrence of that class. Finally the results for the three periods day, evening and night are combined into a single index $L_{den}$ taking into account the penalties for evening and night time periods.

6.1 Segmentation

To increase calculation speed the traffic source which can be approximated by a source line is divided into a number of segments along the road. For noise mapping purposes a reasonable value for the maximum angle each segment subtends at the receiver position (angle of view) is 5 degrees. This can be decreased where greater precision is required. The contribution of each segment is represented by point sources placed in the middle of the segment. The point source has the correct sound power and height in order to simulate the vehicle flow and speed on that segment.

![Figure 6.1: Segmentation of traffic stream](image)

The contribution of the segment to the sound level at the receiver is determined by calculating the attenuation along the propagation path. The overall level is then obtained by summing the contributions from all segments.

6.2 Engineering propagation model

The total noise attenuation between source and receiver is affected by geometrical spreading, atmospheric absorption and attenuation due to barriers and ground surface. There may be several propagation paths as illustrated in Figure 6.2. Note that for clarity reflections from the ground planes are not illustrated. If reflected propagation paths are possible due to the presence of building facades, barriers etc., a correction is made for each successive reflection. The attenuation by the atmosphere is calculated according to the method described in ISO 9613-1 (International Organisation for standardisation, 1996) with ambient, temperature, pressure and humidity as input parameters.
6.2.1 Reflections and diffraction

For the computation of excess attenuation the approach adopted by the Nordic prediction model Nord2000 has been utilised with some further developments. The attenuation of sound over absorptive ground uses the model of Chien and Soroka based on the spherical reflection coefficient. (Chien and Soroka, 1980). However the point of reflection is no longer a mathematical point but an area bounded by an ellipse or Fresnel zone (Hothersall and Hariott, 1995). The lower the frequency the larger the zone. Where the ground is mixed the reflection coefficient is based on the weightings of coefficients for the different ground types within the zone.

Where reflections from buildings or other obstacle occur (see Figure 6.3) a relatively simple approach to determining attenuation is taken. In this method the energy reflection coefficient $\rho_E$ of the surface is taken into account together with the size of the reflecting surface $S_{\text{refl}}$ compared to the area of the Fresnel zone $S_F$. This contribution is small where the reflecting surface is small compared with the area of the Fresnel zone.

The attenuation on reflection is given by:

$$A_{\text{refl}} = 10 \log \rho_E + 20 \log \left( \frac{S_{\text{refl}}}{S_F} \right)$$

The value of $\rho_E$ is 1.0 (totally reflecting) for brick, stone and concrete walls but is assumed to be 0.8 for building facades with windows, doors and small irregularities. A value of 0.4 may be assumed for...
a factory wall with 50% of the surface area with openings and lengths of pipe work and pieces of plant in close proximity.

Rough terrain with vegetation can be described by a combination of terrain roughness and ground impedance.

Diffraction effects of barriers and earth mounds etc are taken into account by the Deygout approximation (Deygout, 1966). The method can be extended to predict the attenuation using multiple diffracting edges and for earth bunds.

### 6.2.2 Meteorological effects

In order to assess the effects of meteorological refraction the radius of curvature from source to receiver is determined for each propagation path based on wind speed, wind direction and atmospheric stability estimated from cloud cover and period of the day.

A combined linear/logarithmic sound speed profile is assumed:

\[
c(z) = c_0 + A z + B \log \left( \frac{z}{z_0} \right)
\]

where \( c(z) \) is the speed of sound at a height \( z \) and \( A, B, c_0 \) and \( z_0 \) are constants. These profiles can be converted to equivalent linear sound speed gradients.

Under such conditions ray paths are transformed into circular arcs that can be constructed analytically. Figure 6.4 gives an example for propagation over flat ground. However, it has been found that rather than curving the sound rays there are computational advantages in curving the ground and maintaining straight ray propagation. Curved ground analogies have been applied successfully to a range of techniques including BEM, scale models and ray tracing techniques. It has been proved that the errors in the angle of incidence and the phase differences between the direct and ground reflected waves are small and have little influence on predicted ground effect (Almgren M (1987)).

![Figure 6.4: The use of curved rays to model a refracting atmosphere](image-url)

### 6.3 Statistical variations of vehicle speed

Information is required on the statistical description of the input data and the influence of their variations on the outcome of the calculation of the Harmonoise engineering model. For example, it would clearly be useful to use average speeds if the actual speed distribution was insignificant.

Variations in speed are known to effect the overall pass-by level but the effect of the statistical variation about a mean value on the long term average noise level are not well understood. Consequently there is a need to examine the extent of the effect since for example it is not known to what extent the additional noise produced by relatively fast moving traffic cancel out the benefits of lower speed vehicles. There is also the variation of speed along a section of road where there is a junction, pedestrian crossing or traffic calming device. A similar situation arises where it is possible that the extra noise arising from accelerating vehicles leaving the junction or traffic calming device is compensated by the lower noise of vehicles required to decelerate.
As an illustration Figure 6.5 shows the change in the average noise level $L_{Aeq}$ for light vehicles that have been predicted following the introduction of a junction where vehicles are required to stop. Close to the junction there is up to 3 dB(A) increase in noise whereas beyond a distance of 50m from the stop line the increase levels are less than 1 dB(A). Appendix D gives details of an analysis that was carried out by TRL to determine the effects on noise predictions of speed variations.

Figure 6.5: Increase average level $L_{Aeq}$ for light vehicles approaching at 50 km/h.
7 Validation

The reference propagation model has been validated through comparison with results from measurement surveys carried out at a number of sites. The measurement sites for road traffic noise are described in the Table 7.1 below.

At each measurement site, acoustic and meteorological data were measured over intervals of 15 or 30 minutes. Acoustical data are recorded in 1/3-octave bands from 50 to 4000 Hz. Meteorological measurements were performed with an ultrasonic anemometer, traditional cup-anemometers and thermometers. In addition impedance measurements of the surrounding terrain were carried out. Traffic data was collected during the measurement interval including the number of vehicles and their speeds along each carriageway of the road.

The total measurement period at one measurement site ranged from 1 to 13 weeks. The microphones were located at approximately 25 m, 150 m, 300 m, 600 m and 1200 m from the edge of the near side carriageway.

Table 7.1: Overview of the measurement sites

<table>
<thead>
<tr>
<th>Measurement site</th>
<th>Sound source</th>
<th>Geometry</th>
<th>Measurement period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ladenburg, Germany</td>
<td>4 lane motorway</td>
<td>flat terrain</td>
<td>02.08.02-11.09.02 and 18.03.03-25.04.03</td>
</tr>
<tr>
<td>La Crau, France</td>
<td>Road</td>
<td>flat terrain</td>
<td>18.10.02-25.10.02 and 08.04.03-15.04.03</td>
</tr>
<tr>
<td>Unna, Germany</td>
<td>6 lane motorway</td>
<td>flat terrain with 4 m noise barrier</td>
<td>03.09.03-06.10.03</td>
</tr>
<tr>
<td>Uttrichshausen, Germany</td>
<td>4 lane motorway</td>
<td>hilly terrain</td>
<td>12.06.02-30.07.02</td>
</tr>
</tbody>
</table>

The results of these validations for the road sites are currently only available for Ladenburg and Unna. In addition the predictions of the engineering model have been checked against the corresponding results from the reference model. In particular the point-to-point excess attenuation in the engineering model has been compared with reference propagation computations for over 25,000 geometries for homogeneous meteorological conditions using a standard road traffic source. The results show for a road embankment an average difference in $L_{Aeq}$ of less than 0.1 dB(A) and a standard deviation of just over 0.5 dB(A).

7.1 Ladenburg

This site is a 4 lane motorway (A5 in Germany) of total width 23 m on a 1 to 3m high embankment. The surrounding is essentially flat farmland. Measurements were made in the autumn and again in the spring of the following year in order to span a range of meteorological conditions. Figure 7.1 gives the comparisons between the measured and predicted $L_{Aeq}$ at 5 microphone positions (M1 – M5) at distances of 26, 153, 305 547 and 1104 metres from the edge of the carriageway. All microphones were positioned at a height of 4m above local ground level except the closest microphone which was set at a height of 6m.

Figure 7.1 shows that the differences between predicted and measured values in both measurement periods did not exceed 1.5 dB(A) even at the furthest distance of over 1 km. The average difference (predicted – measured) was -0.22 dB(A) in the spring and 0.02 dB(A) in the autumn.
Spring

![Spring Comparison Chart]

Autumn

![Autumn Comparison Chart]

**Figure 7.1: Comparison between predicted and measured L_{den} at Ladenburg**

### 7.2 Unna

The site at Unna in Germany is the A5. The road is a 4 lane motorway which runs on an embankment 6m above flat agricultural land. At the edge of the road is a 4m high noise barrier. Microphones M1 to M4 were placed at a height of 4m above local ground level at distances of 25, 150, 300 and 550 metres from the noise barrier, respectively.

Figure 7.2 shows the predicted measured values. The largest difference was 0.6 dB(A) and the average difference (predicted – measured) was -0.20 dB(A).
It can be concluded that the engineering model can give reasonably accurate predictions for the situations examined. Further validation is required for more complex situations for example in urban situations where noise mapping will be of greatest relevance.

Figure 7.2: Comparison between predicted and measured $L_{den}$ at Uonna
8 IMAGINE

A follow up project called IMAGINE (Improved Methods for the Assessment of the Generic Impact of Noise in the Environment) will build on the progress made in Harmonoise. The project started in December 2003 and was funded under the 6th EC Framework Program (CT-2003-5033549). This will enable more data to be collected and added in order to refine the prediction methods developed in Harmonoise. It will also enable methods for data collection to be defined and advice on the production of noise maps. The production of Action Plans will also be addressed and the link between traffic flow and noise models will be investigated. The prediction method will also be extended to industrial sources and aircraft so comprehensive mapping of noise sources will be possible. Details of IMAGINE can be obtained at www.imagine-project.org.

The work is divided into the work packages listed below.

- WP1: Mapping Specifications and GIS
- WP2: Demand and traffic flow modelling
- WP3: Monitoring and Measurement methods
- WP4: Aircraft Noise Sources
- WP5: Road noise sources
- WP6: Rail Noise Sources
- WP7: Industrial noise
- WP8: Dissemination
- WP9: Project Management
- WP10: Scientific Co-ordination

WP5 and WP2 are the areas of work most relevant to the development of traffic noise impact assessment. The Harmonoise engineering model is taken as a starting point for the work of WP5. The main goal of this work package will be to refine and add to the databases both for propulsion and rolling noise. Vehicle source data will also be collected for powered two wheelers (PTW). Within Harmonoise the focus was on obtaining results for larger vehicles so that information on PTWs is currently lacking. It will also be important to gather further data of the propulsion and rolling noise of trucks under different operating conditions and across a greater range of vehicle types. Statistics from member countries will also establish whether adjustments will be needed to take account of any differences in the vehicles fleet which could affect prediction accuracy. For example passenger cars might be on average heavier in northern Europe than in southern Europe and this may result in higher levels of rolling noise and perhaps propulsion noise in northern countries.

The results of a re-examination of existing data and some new measurement will enable the model coefficients and adjustments to be made with greater precision and across a wider range of vehicle types.

A close relation with WP2 on demand and traffic flow management will then link the noise power levels of each vehicle class to the noise emission of road traffic flows at specific locations on the network including junctions of various types.
9 Summary and conclusions

The Harmonoise project was designed to fulfil the need for a new prediction method that would fulfil the requirements of the European Directive for the Assessment and Management of Environmental Noise. This directive noted the lack of a harmonised and reliable method for noise prediction that could be adopted across Member States for the purposes of noise mapping.

The following conclusions can be drawn from this review of the Harmonoise project:

- The Harmonoise reference propagation model is based on state of the art prediction methods and has been used to validate the engineering model. The reference model is a toolkit of methods that can be used singularly or in combination. In many situations a hybrid model approach can be used. For example in the road cross-section the boundary element method can be used while in the far field a parabolic equation method can be used to take account of atmospheric effects.

- The engineering model uses a state-of-the art source model combined with a simplified propagation model which utilises a ray model approach although atmospheric effects are taken into account. The engineering model is expected to be used in the production of noise maps in 2012 and beyond.

- The engineering model has been validated against measured results at two road locations where the roads ran on embankments above essentially flat terrain. The differences between predicted and calculated values of $L_{den}$ were never greater than 1.5 dB(A) even at a distance greater than 1 km from the road. On average, the difference (predicted – measured) varied from 0.02 dB(A) to -0.2 dB(A) However, further validation is required for example in the more complex situations typically found in urban areas.

- In the follow on project IMAGINE further refinement of the source model will take place and the method will be extended to include aircraft and industrial noise sources.
Acknowledgements
The work described in this report was carried out in the Environment Group of TRL Limited.

References


Appendix A. Array and subtraction methods for measuring power train noise

A.1 Introduction

TRL are required to develop a test method for power train noise (propulsion noise). Such a method should enable the point source description of power train noise and if relevant aerodynamic noise. The description will involve the determination of effective source heights and powers and if necessary directivity.

A correct description of source height is necessary since it has a direct effect on the screening potential of roadside barriers and natural terrain features and to some extent on the ground effect, as the boundaries of the Fresnel zone will be dependent on source height. For example, if the source height is set too high then noise barrier heights will need to be correspondingly taller, increasing mitigation costs unnecessarily.

This report describes test methods that have been compared on the TRL test track during June 2002. The methods compared were:

A subtraction technique based on the measurement of SEL under cruise by (engine on) and coast by (engine off) conditions.

A T-array (Acoustic Camera) technique which allows a 2-D picture of the sources and their relative power to be established

A linear array technique which enable source heights to be established but not their horizontal distribution.

The subtraction technique was carried out by TRL and the array techniques by TNO.

A.2 Review of test methods

A.2.1 Array methods

Toorn et al. (Toorn et. al., 1996) describe a study designed to determine the main sources strengths and height distributions on a French TGV as a function of speed. The array (Syntacan) was 10m in height and mounted vertically and consists of 20 microphones. The useful frequency range was 125Hz to 2kHz in 1/12 octave frequency band. With a measurement distance of 25m the vertical resolution was less than 1m at frequencies around 1-2kHz but increased to 5m near 125Hz. The results were presented in terms of source height and source strengths in octave bands from 125Hz to 2kHz for train speeds in the range 200 to 300km/h.

More recently Toorn et al have extended the technique to measuring source heights and strengths of vehicles on a motorway (Toorn, 2001). Using the Syntacan array they were able to generate sufficient data to provide power levels and source heights for cars, lorries, buses and motorcycles. They found that two sources were sufficient to describe the vehicle emissions. The useful frequency range was from 63Hz octave to 8kHz octave. It was clear that for vehicles travelling on a motorway with a speed limit of 120km/h the dominant source at octave frequencies of 500Hz up to 8kHz was at ground level. At lower frequencies the source height increased so the dominant source height varied from 0.2m to 0.7m. They concluded that the lateral source distribution of a vehicle is not usually of importance for the calculation of the average noise level L_{Aeq} of traffic. The 1-D vertical array that was used integrated in the lateral direction and was therefore considered sufficient for characterising the vehicle sources.

A further development has been the T-array or Acoustic Camera which can be used to make images of both stationary and moving sound sources (Mast, undated). The equipment can also be used to provide sound exposure level (SEL) values during pass-bys enabling an evaluation of the source powers of vehicle sub-sources.
A.2.2 Subtraction method

This method described relies on examining the differences between the noise levels obtained during cruise-bys and coast-bys. Although the source height cannot be determined directly the difference in SEL levels under the two conditions would allow an estimate of the sound power of propulsion noise (engine, exhaust and transmission). Note that the calculated tyre/road noise component would in addition include contribution from any aerodynamic noise. Jonasson (Jonasson, 1999) describes tests carried out with a car at a speed of approximately 70km/h with microphones on the ground at distances of 1.65 to 5.65m from the middle of the vehicle. The differences were small (<2dB) at all frequencies. The largest difference occurs at 160, 250 and 500Hz. It was concluded that the lack of difference demonstrated the importance of tyre/road noise. The tests were repeated but closer to the vehicle 0.5 to 3m with 7 heights at the furthest distance. In this case larger differences were evident, with the engine on condition. Levels 8dB higher were recorded at the position 0.5m from the nearside wheel track. The maximum increase occurred in the 63Hz third-octave band. At a distance of 3m at a height of 4m the maximum increase was nearly 6dB and occurred at the higher frequency of 80Hz. Interestingly levels were higher in all third octave bands e.g. at 4KHz there was approximately a 4dB increase at each microphone position.

Jonasson (Jonasson, 1999) also reports on tests with vehicles with high exhausts but no conclusions can be drawn from the data presented. He also uses a simple model based on three source heights of 0.01, 0.15 and 0.30m to predict the difference between maximum pass-by level and SEL. These predictions are compared with measured values and generally show good agreement. However, it is not known if the agreement could be equalled or exceeded by using different combinations of source heights. Also the different sources could be given different source powers which would lead to a number of possible solutions some of which may improve the fit with measured data. However, due to its simplicity the method is worthy of further consideration.

TRL carried out some tests with a small car (Ford Escort), four-wheel drive vehicle (Vitara) and 2 axle truck (Ford Cargo) under coast by and cruise-by conditions (Watts, 2002). The microphone was positioned at a height of 1.2m placed 7.5m from the centre-line of the vehicle. The third octave spectra was captured at the maximum A-weighted level so that it was not possible to obtain SEL values for this later analysis. However, the data can supplement the SEL data referred to above. It was clear that differences in levels recorded under coast and cruise conditions increased with vehicle size and that the increases occurred at both low and high frequencies.

In the case of the Ford cargo a noticeable peak occurs during cruise-by at 80 to 100Hz which is of the order of 10dB higher than the corresponding values recorded for coast-by. In addition there are differences of 8dB at frequencies from 2-3kHz. For the small car the differences are less than 3dB at all frequencies and at some frequencies the levels were similar or the coast-by levels were higher than the cruise–by. For the large car more consistent increases under cruise by conditions can be observed. The differences are of the order of 2-3dB.

Although the contribution of engine noise under steady speed, idling and braking conditions can be examined in this way it would not be possible to estimate the effects under accelerating conditions. However, it is considered that the effects of engine load on noise output for many vehicle types may be relatively small. The size of the effect will need to be reviewed as part of this study.

For light vehicles it is probable that the differences between coast-by and cruise-by are too similar to allow an accurate estimate of the propulsion noise contribution. However, a large enough sample would yield guide values that could be used for noise prediction purposes. For heavier vehicles it is possible to estimate the contribution of power train noise with much more confidence.

A.2.3 Transfer function measurements

This method combines pass-by and in car measurements to separate the major sub-sources. In an early study Berge estimated power train noise by monitoring pressure in the intake manifold, to monitor engine load, and noise levels close to the vehicle (Berge, 1990). A microphone was mounted in the engine compartment and another adjacent to the exhaust outlet. These levels were then ‘calibrated’ to be equivalent to levels that would be measured at pass-by 7.5m from the vehicle.
and those recorded at a position 7.5m from the vehicle various engine and exhaust sources and a microphone placed at the side of the track. Research at General Motors and Purdue University have related the sound intensity levels measured near the contact patch of driven tyres on a passenger vehicle with pass by noise levels at the track side during coast and cruise conditions (Bolton et. al., 1995 and Donovan, 1993). Based on these measurements it was then possible to estimate the tyre noise contribution when the vehicle was accelerating. These data indicate that in some cases the contribution of the tyre/road noise produced under acceleration raised the A-weighted level by up to 9dB compared with cruise conditions.

In a recent study de Graaff (Graaff, 2003) extended the method to include tyre/road noise. For this purpose an additional microphone was placed 10 cm from tyre in addition to microphones mounted close to the engine and exhaust outlet. Engine speed and accelerator position were also recorded. All signals were recorded at 10 samples per second during actual driving in urban conditions.

Additional measurements were carried out at a proving ground. This involved driving past a trackside microphone at 7.5m conforming to the ISO 362 layout and also obtaining noise levels from a microphone that travelled with the vehicle car. This travelling microphone was mounted on a long pole 7.5m from the centre line of the vehicle.

Measurements were made under various operating conditions including:

- coast by to obtain the tyre noise component
- revving the stationary vehicle with the engine encapsulated to obtain mainly exhaust noise
- fast idling with the exhaust outlet extended to obtain mainly engine noise

By taking into account the partial correlations, attenuation between microphones and the cross-correlations (e.g. between signals from the microphones close to the tyres and exhaust) it was possible to estimate the contribution of the various sources at the 7.5m position during urban driving.

The method is sufficiently robust so as to exclude the effects of loud extraneous sounds during measurements in urban traffic e.g. the noise from a truck close to the microphone monitoring tyre noise when the test vehicle is stationary.

It is estimated that the accuracy of the A-weighted levels are of the order of ± 2 dB. The third octave levels have not been measured to the same accuracy and in some cases reach ± 50dB. It is considered that further work, including analysis of existing and new data, is required to refine the method to enable reliable prediction of third-octave levels to be obtained.

### A.2.4 Other methods

There are a number of further methods that have been used to investigate the contribution of power train noise to total noise. These have included:

- Sound intensity measurements of a vehicle on a dynamometer
- The use of lead cladding to cover parts of the vehicle
- Acoustic holography

### A.3 Options tested

The tests took place during the week beginning 10th June 2002. The weather was mainly dry with light winds and overcast sky. Building work was taking place near the perimeter of the track and it was prudent to take background noise measurements before each run in case an inspection of results indicated contamination. However, no such problems emerged during the analysis. To allow comparisons between an array technique (TNO method) and the single microphone method (TRL method) simultaneous measurements were taken for each pass-by. However, the two array techniques could not be used together due to lack of sufficient microphones so most runs were repeated so that comparable measurements were made with both the T-array and Syntacan.
On the first two days tests measurements were made on an ISO test surface. This surface is a fine graded surface that is used for vehicle noise emission tests. The surface conformed to the specification given in ISO 10844 (International Organisation for Standardisation, 1994). This surface was developed to test the noise emitted from the power unit related sources on the vehicle and therefore the contribution from tyre/road noise was minimised. This was achieved by specifying a small maximum chipping size of 8mm but with sufficient texture to reduce the noise associated with air pumping. A reflective low absorption surface was specified with a normal incidence sound absorption value $\alpha$ of less than 0.1.

On the third day a relatively high textured bituminous hot rolled asphalt surface with pre-coated chippings (HRA) was used for testing. This has been widely used on the trunk road and motorway network in the UK. On the fourth day a porous bituminous surface with maximum stone size of 6mm was employed (MARS6). The HRA produced relatively high levels of tyre/road noise while the MARS produced relatively low levels.

The vehicles tested on the ISO surface included:

- Peugeot 106 (diesel engine)
- Renault Espace (petrol engine)
- Ford cargo truck (4x2 flatbed with diesel engine manufactured 1990/91)
- Daf 95 (4x2 tractor unit with diesel engine manufactured 1987/88)

The Renault Espace and Ford cargo were tested on the HRA and MARS6 surfaces.

Additional tests were carried out on the HRA to check whether the subtraction method was sensitive enough to quantify aerodynamic noise. For these tests a short vertical board was attached to the roof of the Espace. The board was 0.5m high and spanned the full width of the roof. In addition, on the HRA and MARS6 surfaces a loudspeaker source was attached to the Espace and Ford cargo. The source emitted broad band noise and was positioned on the sides of the vehicles so that noise was radiated directly to the microphones. In the case of the Espace the source was placed in an open rear window at a height of 1.55m. For the Ford cargo the source was attached to a foot well close to the front wheel at a height of 0.83m.

### A.4 Subtraction method

To ensure that vehicle performance did not vary significantly during the tests the tyres and engine of each test vehicle was warmed up before testing by driving around parts of the test track. It was also important to ensure that for a particular comparison the speeds of pass-bys under coast and cruise conditions were very similar so that the subtraction would yield the true contribution of the power train sources. Generally this was ensured by carrying out 2 or more coast-by conditions first and recording the speeds achieved. Three cruise-bys were then carried out in order to match one of the speeds achieved in coast bys as closely as possible. A radar speed meter was used to indicate the speed as the vehicle passed the microphones. After each run the driver was given feedback on his performance in matching speeds. Often an identical pair of radar speed readings was obtained but occasionally this was not possible and a difference of 1km/h was accepted. During coast–bys the driver was instructed to cut the engine and disengage the transmission before reaching the entrance to the test section.

### A.4.1 Measurements

Both A-weighted SEL and maximum levels were recorded over a 30m length of the test surface. The measurement of SEL followed the method proposed by Jonasson (Jonasson, 2002). The positions of the microphones are shown in plan in Figure A1. Microphones were set up at heights of 0.2m, 1.2m and 3m at a distance of 7.5m from the middle of the test lane. Infra-red sensors were set up at the entrance and exit of the test area which was 30m long and the microphones were positioned opposite the midpoint position. Reflective strips were attached at the midpoint position on each vehicle tested.
Two B&K 2144 analysers were used to collect noise data from the three microphones and the pulses from the infra-red detectors at the entrance and exit to the test strip. The pulse generated as the vehicle entered the test strip started the sampling and the number of sample taken for analysis was determined from the time interval \( T \) between entry and the exit pulses. Samples were taken every 30ms and the averaging was set at “fast” (1/4 s) exponential. The frequencies analysed ranged from 20Hz to 10kHz. The \( L_{Aeq} \) was obtained by averaging the samples over period \( T \) and the SEL was derived from:

\[
\text{SEL} = L_{Aeq} + 10 \log T
\]

The maximum level \( L_{Amax} \) was obtained by finding the maximum value of the samples taken within the time interval \( T \). Calibration of the noise measurement system was made prior to and periodically (i.e. at least every 2 hours) throughout the measurement period using a B&K 4231 acoustic calibrator. Changes in consecutive calibrations were never more than 0.5dB. The air temperature ranged from 14 to 18°C and the track surface temperature from 20 to 33°C. Background noise levels were never more than 58dB(A) and the average was close to 50dB(A).

\[\text{Figure A1: Location of microphones at the test site}\]

\[\text{A.4.2 Results}\]

Much data was collected during the four days of testing and only the more important results are presented below. The results of measurements on the ISO surface are described first followed by an examination of the contribution of aerodynamic noise using the Espace and a comparison of the results from the Ford Cargo on the HRA and MARS6 surfaces. Finally the power train contributions obtained from array and subtraction methods are compared. All results presented for the subtraction method were obtained for the 1.2m high microphone and are given in terms of SEL calculated over the 30m test surface. It is expected that the results for the contribution of the power train noise will not differ greatly for the different microphone heights but this will need to be checked during subsequent analyses. Tables A1 to A4 in the Appendix A8 list SEL values for each test condition and the data is illustrated in graphical form in the sections below.

\[\text{A.4.2.1 Comparisons on the ISO surface}\]

The SEL third octave band levels for closely matched coast-by and cruise-by speeds are given in Figure A2a and A2b for the Peugeot 106 at speeds of 49-50km/h and 92km/h. The contribution of the power train noise is obtained by subtraction. In some third octave bands it was not possible to compute the power train level because the level recorded during coast-by were very similar or slightly higher than during cruise by. In these cases the errors involved in calculating the power train component is large compared with the small size of the component being measured. For these reasons the band levels are not plotted in the following graphs although the expected levels in these bands is indicated by joining the plotted points either side of these missing values where this is possible. All missing values are listed in the figure legends.
At the 50km/h speed the main contribution of power train noise to total noise occurs in the 50Hz band where the peak is about 10dB higher than during coasting. However there are also significant contributions at around 125Hz and above 2kHz.

At the higher speed of 92km/h the only significant contribution is around 80Hz where the peak is still approximately 10dB higher than during cruising. The shift to higher frequencies is due to the increase in rotational speed of the engine.

(a) **49-50km/h** (missing values at 20, 25 and 63Hz)

![Graph](image1)

(b) **92km/h** (missing values at 20, 50, 125 and 1600 Hz)

![Graph](image2)

**Figure A2: A-weighted SEL third octave band levels for Peugeot 106 on ISO surface**

In the case of the Renault Espace the power train noise is more prominent at the lower speeds than for the Peugeot 106 with power train noise exceeding rolling noise below 400Hz. There is a very prominent peak at 50Hz which is 15dB above the rolling noise. At higher frequencies its contribution is small except at the three highest frequencies.

Unlike the Peugeot 106 at the higher speed the peak below 100Hz is not obvious and in general it is only at some bands below 100Hz that power train noise exceeds rolling noise. Even at these low frequencies the exceedances are not large.
For the heavier vehicles the power train noise is much more prominent than is the case for the two cars tested as can be readily seen in Figure A4. Generally, at the lowest speed of 36km/h power train levels are well above rolling levels with a peak at 80Hz which is 20dB above the rolling level. At mid frequencies (800-1000Hz) levels are nearly 10dB higher.

At 72km/h power train noise is much less significant and only exceeds rolling noise in the 50 to 125Hz band. The peak is approximately 15dB higher than rolling noise at 63Hz.
For the Daf tractor unit the power train noise is even more dominant. It can be seen in Figure A5 that again there is a substantial peak at low frequencies (63Hz band) that at the lowest speed is 15dB above rolling noise. However at the lowest speed, the important difference from the other vehicles tested is the very large increases measured in all bands except the very lowest and 80Hz. In fact as frequency increases this difference generally increases so that the largest difference of 20dB is observed at the highest frequency.

At the higher speed of 71-72km/h this pattern is repeated except that increases are lower. For example at the highest frequencies the power train noise is approximately 10dB above rolling noise and the peak in the 63Hz band is just over 10dB.
A.4.2.2 Evaluation of the contribution of other sub-sources

It was important to determine if the subtraction and array methods were sensitive enough to quantify sub-sources other than power train noise. Two additional tests were therefore included. The first involved generating additional aerodynamic noise by placing a vertical board on the roof of the Espace and the second involved placing a loudspeaker noise source on the side of the vehicle as detailed in the description above. Results for the Espace are presented in Figure A6 below.

The effects of the board in producing an additional noise source are very slight and this agrees with the subjective impression standing close to the test site. Levels due to this additional source are generally 5 to 10dB lower than rolling noise without the source present. It is only at the very low frequencies around 30Hz that its contribution is higher than the rolling noise without the board present. Note that the test nicely illustrates the sensitive of the subtraction method in quantifying small additional sources across a very wide range of frequencies.

Figure A5: A-weighted SEL third octave band levels for Daf tractor unit on ISO surface
(a) 95 km/h on HRA with/without additional aerodynamic source (missing values at 20, 25, 100 and 500Hz)

(b) 52-53km/h on MARS6 with/without loudspeaker source (missing values at 20, 25, 31.5 and 50Hz)

Figure A6: A-weighted SEL third octave band levels for Renault Espace with/without additional sources

In the case of the broad band source this produced significant noise at all frequencies above 80Hz. Levels were 20-30dB higher above 2000Hz. This agreed with the subjective impression during pass-by. Again it is evident that the subtraction method is suitable for demonstrating the effects of broad band sub-sources especially where they are likely to be significant to the listener.

A.4.2.3 Quantifying power train noise on different surfaces

The ability of the subtraction method to resolve power train noise on widely different surfaces was tested by comparing the results from operating a test vehicle (Ford Cargo) at approximately the same pass-by speed on the ISO, HRA and MARS6 surfaces. The results are given below in Figure A7.
(a) 72km/h on ISO surface (missing values at 20, 25, 31.5, 160, 200, 400, 6300 Hz)

(b) 70km/h on HRA (missing values at 20 and 25Hz)

(c) 72km/h on MARS6 (missing values at 20Hz)

Figure A7: A-weighted SEL third octave band levels for Ford Cargo on different surfaces
It can be seen that the smoothest power train spectra was obtained for the MARS6 surface and under this condition there was only a single missing value (20Hz). Since rolling noise is the lowest on this surface and consequently the difference between coast and cruise would be greatest, it would be expected that the contribution of the power train noise would be more accurately determined. However, power train noise may be underestimated if noise reflected from the porous surface near the vehicle makes a significant contribution to the total.

In the Figure A8 below the power train spectra are compared on a single graph. The results for the MARS6 is generally a little below that for the HRA at most frequencies probably as a result of the absorption of some reflected noise. However, it demonstrates that the power train noise component calculated on two very different surfaces, a rough reflective surface, HRA, and a smooth absorptive surface, MARS6, give very similar results i.e. within -2.5 and +3.7 dB from 40 to 10000Hz.

The results for the ISO are more erratic but generally following the trend. Several of the band levels were missing from the results for this surface which suggests measurements conditions were not ideal.

![Figure A8: A-weighted SEL third octave band levels for power train noise of the Ford Cargo travelling between 70-72km/h on different surfaces](image)

**A.5 Array methods**

**A.5.1 SEL measurements**

The details of the measurement method with the T-array (Acoustic Camera) and Syntacan are detailed in a TNO report (Mast. et. al., 2003). Views of the T-array and Syntacan on the TRL test track are shown in Figure A9. The options tested follow precisely those outlined above and a comparison of the SEL results for array and subtraction methods are presented where possible. The pass-bys selected for analysis for the T-array and subtraction methods were identical but tests with the Syntacan were taken on the following day and it was not always possible to match speeds exactly. However, the speed differences between runs were of the order of 1 or 2km/h and it is unlikely this variation would make a substantial difference to the calculations of the power train contribution.

The array methods are limited in frequency range from 200 to 2.5 KHz and for this reason it is only possible to compare the results from the subtraction method in this range. The TNO analysis has concentrated on measurements taken on the ISO surface and these will be presented in this report. Figure A10 compares the power train noise calculated for the Peugeot 106 at the two speeds of 49-50km/h and 90-92km/h. It is clear that over the frequency range from 200 to 2,500Hz the methods show similar trends of increasing power with frequency.
Differences are generally less than 5dB except in the case of the T-array at 90km/h where there is no clear trend. In the latter case it is likely that measurement error has resulted in the large fluctuations.
(a) **49-50km/h** (missing values: T-array none; Syntacan at 200Hz; Subtraction at 20, 25, and 63Hz)

![Graph showing A-weighted SEL third octave band levels for power train noise of the Peugeot 106 on the ISO surface calculated by array and subtraction methods](image)

(b) **90-92km/h** (missing values: T-array none; Syntacan none; Subtraction at 20, 50, 125, and 1600Hz)

![Graph showing A-weighted SEL third octave band levels for power train noise of the Peugeot 106 on the ISO surface calculated by array and subtraction methods](image)

**Figure A10: A-weighted SEL third octave band levels for power train noise of the Peugeot 106 on the ISO surface calculated by array and subtraction methods**

Figure A11 compares the results for power train noise for the Renault Espace. The general trends are similar with fairly good agreement between the array and subtraction methods i.e. within 10dB. The differences are smaller at the higher speed and less than approximately 5dB. However, at this higher speed it should be noted that there were only 2 valid results using the Syntacan array.
(a) **50-51km/h** (missing values: T-array at 400Hz; Syntacan at 200,500,630,800,1250,1600Hz; Subtraction none)

![Graph A11](image1)

(b) **84-90km/h** (missing values: T-array at 200,315,800Hz; Syntacan at 200-630Hz,1000,1250,2000,2500Hz; Subtraction none)

![Graph A11](image2)

**Figure A11: A-weighted SEL third octave band levels for power train noise of the Renault Espace on the ISO surface calculated by array and subtraction methods**

The results for the Ford Cargo are presented in Figure A12. At the lower speed the general trends are very similar with differences less than approximately 5 dB. At the higher speed agreement remains good except at the two lowest frequencies where comparisons are possible. It is likely that the subtraction method gives results on this surface that are too low. This has been noted above when results of the subtraction method were compared on different surfaces (see Figure A8). It is likely that measurement error was particularly large in this case.
(a) **35-36 km/h** (missing values: T-array none; Syntacan none; Subtraction at 4000-10000Hz)

(b) **70-72 km/h** (missing values: T-array at 200Hz; Syntacan none; Subtraction at 20, 25, 31.5, 160, 200, 400, 6300Hz)

Figure A12: A-weighted SEL third octave band levels for power train noise of the Ford Cargo on the ISO surface calculated by array and subtraction methods

Figure A13 gives the results for the Daf tractor. The general trends for the methods are very similar especially at the lower speed where differences were less than approximately 3dB. At the higher speed agreement was However, again the array results lay approximately 5-6dB above those for the subtraction method. At the higher speed differences were large but did not exceed 10dB. There were very few missing values and it is likely that the large power train contribution to the total power output was responsible for ensuring good measurement accuracy.
(a) **34-35 km/h** (missing values: T-array none; Syntacan none; Subtraction at 20-40Hz)

![Graph showing A-weighted SEL third octave band levels for power train noise of the Daf tractor on the ISO surface calculated by array and subtraction methods at 34-35 km/h.]

(b) **70-72 km/h** (missing values: T-array none; Syntacan none; Subtraction none)

![Graph showing A-weighted SEL third octave band levels for power train noise of the Daf tractor on the ISO surface calculated by array and subtraction methods at 70-72 km/h.]

Figure A13 A-weighted SEL third octave band levels for power train noise of the Daf tractor on the ISO surface calculated by array and subtraction methods

**A.5.2 Source localisation**

The T-shape array was used to obtain contour plots of the sound exposure level during pass-by that could be superimposed on a picture of the vehicle. These ‘acoustic pictures’ were taken during both cruise and pass-by so that it was possible by subtraction to identify the location of the power train sub-sources. Figure A14 shows examples of these contour plots for the Peugeot 106.

It can be seen that the effective source position of power train noise lies between the vehicle body and the track surface and is concentrated behind the front wheel. There is a smaller contribution from the exhaust pipe outlet behind the rear wheels. Similar source positions were found for the other vehicles tested.
Figure A14: SEL plots at 2kHz for the Peugeot 106 travelling at 50km/h (Mast et. al., 2003)

A.6 Conclusions

Using the subtraction method and based on measurements at a height of 1.2m and 7.5m from the middle of the vehicle track, it was possible to estimate power train noise levels in terms of SEL over a wide frequency range from 20 to 10000Hz. From these results it will be possible to calculate the sound power level using an appropriate propagation model (Jonasson H G (1999). Under good measurement conditions it appears that the results are insensitive to the road surface over which the tests are conducted since very similar results were obtained from relatively quiet and noisy road surfaces (HRA and MARS6). Errors will be largest where the contributions are relatively small.
although it has been demonstrated that the method is sufficiently accurate to detect a weak aerodynamic noise source. It is considered especially important to closely match speeds when comparing results from coasting and cruising runs so that the tyre/road noise is very similar under the two conditions.

Generally, the results from the subtraction method results agree well with the trends obtained with arrays methods with maximum differences confined to 10dB in most cases. The array methods were restricted to a frequency range of 200 to 2500Hz so it has not been possible to make comparisons at low (20 to 160Hz) and high (3150 to 10000Hz) frequencies.

The results indicate that the fundamental engine firing frequency below 100Hz is readily detected in all vehicles under all conditions tested except that it was found to be insignificant in the petrol engine car (Renault Espace) at a relatively high speed (84km/h). For the trucks tested at low speed (35km/h) the power train noise was dominant at most frequencies and at the higher speed of 70km/h it was still dominant in one vehicle (Daf tractor) but only below 100Hz in the other vehicle (Ford Dodge). The Daf tractor was manufactured in 1988/89 and it is likely that more recent vehicles of this type have a significant quieter power train contribution due to advancements in noise control engineering.

It is concluded that the subtraction method based on the Nortest procedures for obtaining SEL is sufficiently accurate to enable power train contributions to be determined over a wide range of frequencies (20-10000Hz). The array methods should also be able to supply this information in the range 200 to 2500Hz and these techniques will also enable sub-source heights to be determined within this frequency range.

A.7 References


### A.8 Tables of results

#### Table A1: A-weighted SEL third octave band levels for Renault Espace with and without additional sources

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Surface</th>
<th>Condition</th>
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<th>45</th>
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#### Table A2: A-weighted SEL third octave band levels for Ford Cargo on different surfaces

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Table A3: A-weighted SEL third octave band levels for power train noise on the ISO surface calculated for array and subtraction methods

| Speed/Level | Vehicle | Measurement Method | Max SEL (dB) | 36 | 24 | 180 | 108 | 63 | 36 | 20 | 12 | 10 | 8 | 6.3 | 5 | 4.1 | 3.6 | 3.1 | 2.5 | 2.2 | 2.0 | 1.5 |
|-------------|---------|-------------------|-------------|----|----|-----|-----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 200          | Sedan    | Array             | 86.8         | 57.4| 57.0| 55.8| 55.4| 54.3| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.2| 48.3| 47.3| 46.3| 45.3|
| 200          | Sedan    | Subtraction       | 87.1         | 57.7| 57.3| 56.2| 55.8| 54.7| 54.2| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.3| 48.3| 47.3| 46.3|
| 200          | Sedan    | Total             | 87.5         | 57.7| 57.3| 56.2| 55.8| 54.7| 54.2| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.3| 48.3| 47.3| 46.3|
| 200          | SUV      | Array             | 87.5         | 57.7| 57.3| 56.2| 55.8| 54.7| 54.2| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.3| 48.3| 47.3| 46.3|
| 200          | SUV      | Subtraction       | 87.5         | 57.7| 57.3| 56.2| 55.8| 54.7| 54.2| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.3| 48.3| 47.3| 46.3|
| 200          | SUV      | Total             | 87.5         | 57.7| 57.3| 56.2| 55.8| 54.7| 54.2| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.3| 48.3| 47.3| 46.3|
| 200          | MPV      | Array             | 87.5         | 57.7| 57.3| 56.2| 55.8| 54.7| 54.2| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.3| 48.3| 47.3| 46.3|
| 200          | MPV      | Subtraction       | 87.5         | 57.7| 57.3| 56.2| 55.8| 54.7| 54.2| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.3| 48.3| 47.3| 46.3|
| 200          | MPV      | Total             | 87.5         | 57.7| 57.3| 56.2| 55.8| 54.7| 54.2| 53.8| 53.3| 52.8| 52.3| 51.7| 51.2| 50.6| 49.9| 49.3| 48.3| 47.3| 46.3|

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Appendix B. State of the art modelling – description of TRL models including barrier crowning

B.1 General description of the models

B.1.1 Introduction
TRL have developed in conjunction with Brunel and Bradford Universities a range of Boundary Element Method (BEM) programs that can be used to examine the effects of novel shaped barriers. The BEM is effective for obtaining accurate solutions to the standard Helmholtz wave equation governing the propagation, reflection and scattering of acoustic waves in a homogeneous atmosphere. The method is well developed with a large amount of literature describing the solution to problems mainly concerning outdoor propagation and in particular to the solution of noise screening of barriers of complex designs on flat ground where no analytic solutions are available. BEM methods have recently been extended to consider the effects of propagation from depressed and elevated roads and for long range problems involving propagation over variable impedance ground and ground of varying height. Although BEM models were developed initially to solve strictly 2-D problems, e.g. the propagation from an infinitely long road where the sources were assumed to be coherent line sources, it has recently been possible to model incoherent line sources. This is closer to the real situation since the traffic stream is composed of a large number of independent sources. This advance has been possible due to the demonstration that a solution to the incoherent line source problem is equivalent to a sequence of 2-D problems by a partial Fourier transformation (Duhamel, 1996). Note that the incoherent line source models that have been developed do not allow variations in geometry or impedance along the length of the road; in this respect they are not truly 3-D models. Commercially available fully 3-D models have been developed, e.g. SYSNOISE, but because of the degree of computation required to solve even modest problems of barriers a few metres in length they are not a practical tool at the present time.

In early studies at TRL flat ground problems were examined using a coherent line source and a simple empirical impedance model (Delany and Bazley, 1970). The aim was to develop more efficient noise screens by calculating the screening performance of a wide variety of barrier profiles (referred to as “crowns” in subsequent sections). Predictions were compared with scale models or full-scale tests at TRL’s Noise Barrier Test Facility (NBTF). Subsequently the BEM program was modified so that solutions could be made for more difficult ground geometries such as depressed roads (program ILV10CM) and elevated roads (ILV10CME). The effects of combining noise barriers with porous asphalt surfacing was also examined by implementing the Attenborough 4 parameter impedance model (Attenborough and Howarth, 1992) as an alternative to the Delany and Bazley model in these programs. An incoherent line source version of the ILV10CME program was also implemented (program FULLE) and a further modification allowed vertical louvred barriers to be examined (ILV10CMT). Very recent developments have allowed the discretisation out to over several hundred metres for the case of a gently varying ground profile (NOISEPROP). This means that changes of impedance and changes in height can be modelled, although as yet it is not possible to model sharp discontinuities or edges so that noise barriers cannot be modelled successfully with this program.

B.1.2 Basic assumptions
It is assumed in ILV10CM that the traffic stream can be represented by a coherent line source i.e. that the problem is essentially 2-D. In program ILV10CME there is the option of running with an incoherent line source. It is also assumed in ILV10CM and ILV10CME that the ground plane is perfectly flat outside the road cross-section that includes the sides of the cutting and embankments. It is also assumed that there is no back-scatter of sound from the ground outside the road cross-section so that the problem can be solved in two stages removing the necessity to discretise the whole problem. A further assumption is that the impedance model, either Attenborough’s impedance model or Delany and Bazley, is an adequate description of surface impedance. In particular when using Delany and
Bazley the assumption is made that the ground is locally reacting so that the characteristic surface impedance does not depend on angle of incidence. It is assumed in IL10CM and ILV10CME that the atmosphere is still and homogeneous so that there is no refraction of the propagating sound waves. In the case of NOISEPROP it is assumed that the gradient varies smoothly without surface discontinuities and that the maximum slope is not greater than 1 in 2. Ranges of up to 500m have been examined. Run times beyond 2,500 Hz however take over 3 days to complete. In combination with Atm_Effect the program can be used to model a still atmosphere where the sound speed increases or decreases with height exponentially.

B.1.3 Equations

In principle, the mathematical formulation of the boundary element method is as follows (for a more detailed description, see (Hothersall et. al., 1991), (Chandler-Wilde, 1997), (Watts et. al., 1999)).

Consider the cross-section shown in Figure B1. A coherent monofrequency line source of sound is situated in a homogeneous medium above a locally reacting plane of homogeneous normalised surface admittance \( \gamma \). A noise barrier of infinite length lies on the plane, and it is assumed that the cross-sectional shape and the acoustical properties of the noise barrier do not vary along its length, and also that the line source and axis of the barrier are parallel, and parallel to the plane. The problem is two-dimensional: let us assume a Cartesian co-ordinate system \( Oxyz \), defining the \( z \)-axis as being parallel to the line source. The geometrical and acoustical variables are therefore constant in the \( z \)-direction. The datum \( y = 0 \) lies at or below the ground surfaces.

![Figure B1: The basic 2-D situation for acoustic propagation](image)

Denoting the source and receiver positions as \( r_0 = (x_0, y_0) \) and \( r = (x, y) \) respectively, the surface of the barrier as \( \gamma \) and the sound pressure at the receiver due to the acoustic radiation of the source as \( p(r, r_0) \), then \( p(r, r_0) \) satisfies the Helmholtz equation

\[
\nabla^2 p(r, r_0) + k^2 p(r, r_0) = \delta(r - r_0)
\]

On the ground and noise barrier surfaces, \( p(r, r_0) \) satisfies the impedance boundary condition

\[
\frac{\partial p}{\partial n} = ik\beta p
\]

In addition, \( p(r, r_0) \) also satisfies the Sommerfeld radiation conditions.

To use the boundary element method, we reformulate the problem as a boundary integral equation using a suitable Green's function, defined for the upper half-plane \( y \geq 0 \). Let \( G_{bc}(r, r_0) \) denote this Green's function which is given by
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\[ G_{\text{fc}}(\mathbf{r}, \mathbf{r}_0) = \frac{i}{4} H_0^{(1)}(k R) - \frac{i}{4} H_0^{(1)}(k R') + P_{\text{fc}}(\mathbf{r}, \mathbf{r}_0) \]  

(B.3)

where the first and second terms are the direct and reflected wave contributions respectively, where \( R \) and \( R' \) are the distances from receiver to source and from receiver to image source, and \( P_{\text{fc}}(\mathbf{r}, \mathbf{r}_0) \) is the correction factor which is required if the boundary is non-rigid, i.e. \( P_{\text{fc}}(\mathbf{r}, \mathbf{r}_0) = 0 \) for rigid ground.

From Green’s second theorem it can be shown that if \( p(\mathbf{r}, \mathbf{r}_0) \) satisfies the above boundary value problem (B.1) and (B.2), then \( p \) also satisfies the boundary integral equation

\[ \varepsilon(\mathbf{r}) p(\mathbf{r}, \mathbf{r}_0) = G_{\text{fc}}(\mathbf{r}, \mathbf{r}_0) + \int_{\gamma} \left( \frac{\partial G_{\text{fc}}(\mathbf{r}, \mathbf{r})}{\partial n(\mathbf{r})} - ik\beta \sigma G_{\text{fc}}(\mathbf{r}, \mathbf{r}_0) \right) p(\mathbf{r}, \mathbf{r}_0) \, ds(\mathbf{r}) \]  

(B.4)

where \( \varepsilon(\mathbf{r}) = 1 \) for \( \mathbf{r} \in \partial \gamma \), \( \varepsilon(\mathbf{r}) = 0.5 \) for \( \mathbf{r} \in \gamma \). To solve this integral equation, the following method is used:

First \( \gamma \) is approximated as a polygonal arc consisting of \( N \) straight line segments. Denoting the midpoint an length of each boundary element as \( \mathbf{r}_n = (x_n, y_n) \), the integral equation can be approximated by

\[ \varepsilon(\mathbf{r}) p_N(\mathbf{r}) = G_{\text{fc}}(\mathbf{r}, \mathbf{r}_0) + \sum_{n=1}^{N} \left( b(\mathbf{r}, \gamma_n) - ik\beta(\mathbf{r}_n) c(\mathbf{r}, \gamma_n) \right) p(\mathbf{r}_n, \mathbf{r}_0) \]  

(B.5)

where \( b(\mathbf{r}, \gamma_n) \) and \( c(\mathbf{r}, \gamma_n) \) are approximations to the integrals of \( \partial G_{\text{fc}}(\mathbf{r}, \mathbf{r}_0)/\partial n \) and \( G_{\text{fc}}(\mathbf{r}, \mathbf{r}_0) \) respectively in (B.4). Note that this equation expresses \( p_N(\mathbf{r}) \) at the point \( \mathbf{r} \) in terms of the values of \( p_N(\mathbf{r}_n) \), \( n = 1, 2, \ldots, N \), i.e.

\[ \sum_{n=1}^{N} a_{mn} p_N(\mathbf{r}_n, \mathbf{r}_0) = G_{\text{fc}}(\mathbf{r}_0, \mathbf{r}_m), \quad m = 1, 2, \ldots, N \]  

(B.6)

where

\[ a_{mn} = \frac{1}{2} \delta_{mn} - b(\mathbf{r}_m, \gamma_n) + ik\beta(\mathbf{r}_n) c(\mathbf{r}_m, \gamma_n), \quad m, n = 1, 2, \ldots, N \]  

(B.7)

Following this (B.5) can then be used to calculate \( p \) at any other point on or off the boundary.

By calculating the attenuation for 3 different cases, namely in free-field, due to the presence of the ground only, and due to the combined presence of the ground and barrier, and applying these results to a source spectrum which is characteristic of road traffic, broad band sound pressure levels (SPL) and insertion losses (IL) can be determined. Insertion loss is defined as the reduction in SPL following the introduction of the barrier, i.e. at the particular frequency corresponding to the wave number \( k \),

\[ IL = -20 \times \log_{10} \left| \frac{p(\mathbf{r}, \mathbf{r}_0)}{G_{\text{fc}}(\mathbf{r}, \mathbf{r}_0)} \right| \text{ dB} \]  

(B.8)

For very large \( N \), the computational cost is dominated by the solution of the linear equations (B.6) (approximately \( N^2/3 \) multiplications are required). For values of \( N \approx 1000 \), the cost of setting up the matrix \( [a_{mn}] \) is important, especially if \( \beta_c \neq 0 \). When \( \beta_c \neq 0 \) the cost is dominated by the evaluation of \( P_{\text{fc}}(\mathbf{r}_m, \mathbf{r}_n) \) for \( m = 1, 2, \ldots, n \).

It should be noted that the above description is somewhat simplified. In particular, in the current versions of ILV10CM, ILV10CME, and FULLE, equations (B.5) and (B.6) are modified by using, in place of (B.4), a combined integral equation formulation, proposed originally by Burton and Miller, and used in the context of outdoor propagation by Duhamel (Duhamel, 1996). These modifications are necessary to avoid problems with irregular frequencies. In the program NOISEPROP equation (B.4) is solved but with the impedance Green’s function replaced by the simpler free field Green’s function. This removes the irregular frequency problem but at the cost of discretising the whole boundary. But
discretising the whole boundary is, in any case, required if the whole boundary is undulating, and NOISEPROP is designed for this situation. Equations (B.5) and (B.6) do not precisely apply to NOISEPROP. The integral equation is discretised in NOISEPROP by approximating the unknown pressure field and the smooth parts of the Green’s function by high degree trigonometric polynomials, which gives a rapidly converging numerical scheme in the limit as $N$ increases. This discretisation scheme is described in (Meier et. al., 2000) and (Meier, 2001).

An important computational point is the evaluation of the impedance Green’s function which must be done efficiently and accurately. This is carried out using the method of (Chandler-Wilde and Hothersall, 1995)

**B.1.4 Input and output**

The input specification is given via two input files which have a common format across programs. The first of these, TINPUT, specifies geometry and surface properties. An example file for a louvred partial cover overhanging the road (as shown in Figure B2) is given in Figure B3 below.

**Figure B2: Louvred partial cover overhanging road (0.5 m long absorptive louvres at 45°)**
Figure B3: Sample input file TINPUT for an absorptive louvred partial cover

The first part details the Cartesian co-ordinates of the road cross-section including the barrier (for brevity only one louvre is specified in Figure B3) and simulated light vehicle shape. Figure B4 shows the cross-section used to represent a typical light vehicle with its two source positions. The second part lists the impedance of all surfaces that are to be discretised in terms of four Attenborough parameters (flow resistivity, layer depth, tortuosity and the major angle of incidence). The third section details the
parameters needed to define the impedance of the ground followed by the source positions (See “Ground stage 1” and “Ground stage 2”). For simplicity it has been assumed that the predominant vehicle noise is tyre/road surface noise. For light vehicles, sources were located on the nearside and offside of the vehicle at a height of 0.05m above the road surface. In the case of heavy vehicles the effective source height was higher at 0.1m. Finally the location of the receivers beyond the barrier for which SPLs are required are given in Cartesian co-ordinates.

![Figure B4: Cross-section and source positions representative of a typical light vehicle](image)

The source is characterised in the separate file TINPUTSP, an example of which is presented in Figure B5. The first column lists the one-third octave centre frequencies from 100Hz to 5kHz. In the second column the fineness of discretisation is given. The values given are the length of the boundary elements in terms of the fraction of the wavelength at that frequency. Apart from the highest frequency the fraction is λ/5 or lower. In the third column the sound pressure levels (SPLs) at each one-third octave band centre frequency are given. In the final column the corresponding A-weighted levels are listed. The SPLs were inferred from road side statistical pass-by measurements (SPBs) on a hot rolled asphalt surface for light vehicles normalised to a speed of 110km/h. Similar measurements were also carried out for heavy vehicles (greater than approximately 1.5t) on the same surface but normalised to 95km/h. (Watts et al., 1999) give further details of the method of calculating the source levels from SPB measurements.

There are two main outputs and Figure B6 shows a section of the most comprehensive. This gives results for the 100Hz one-third octave centre frequency for each receiver position defined by Cartesian co-ordinates. Tabulated are the un-weighted SPLs, insertion losses and excess attenuations. The final portion of the output gives linear and A-weighted levels. Also given in this file is a summary of the information in the input file (TINPUT). The less comprehensive file does not contain this summary and there is generally less description of the quantities.

In the case of the Matlab program NOISEPROP the four parameter Attenborough model is used. In the input statement an effective flow resistivity, a reduced porosity and an effective layer depth are given and tortuosity is not required as a separate quantity. The horizontal co-ordinates of any changes in impedance are also given and the impedance values of the different ground covers are specified in the same manner.
18.2 % LCAL3E TINPUTSP file (28/5/97)
100.000 0.0300  76.0  56.9  % This file contains two 1/3rd octave
125.893 0.0350  72.4  56.3  % light vehicle spectra, adjusted from
158.489 0.0400  70.9  57.5  % the LGT3E file to fit measured
199.526 0.0450  73.0  62.1  % results for HRA roads.
251.189 0.0500  71.9  63.3  % 1: Linear spectrum.
316.228 0.0600  72.6  66.0  % 2: A-weighted spectrum.
398.107 0.0700  72.8  68.0
501.187 0.0800  74.2  71.0
630.957 0.0900  77.7  75.8
794.328 0.1000  80.9  80.1
1000.000 0.1250  83.9  83.9
1258.925 0.1250  80.2  80.8
1584.893 0.1250  77.3  78.3
1995.262 0.1250  74.0  75.2
2511.886 0.1250  71.8  73.1
3162.278 0.1600  68.5  69.7
3981.072 0.2000  64.8  65.8
5011.872 0.2500  61.4  61.9

Figure B5: Sample File TINPUTSP used for specifying one-third octave band spectrum at 1m (100Hz to 5kHz)

SOURCE SPECTRUM NUMBER 1
-------------------------
THIS SPECTRUM IS THE SINGLE FREQUENCY  100 HZ.

RECEIVER  X-COORD. OF  Y-COORD. OF
NUMBER  RECEIVER/M  RECEIVER/M  SPL/DB  EA/DB  IL/DB
--------  -----------  -----------  ------  -----  -----  ------
1   -5.00        4.50      68.38     2.20    7.42
2   -10.00       4.50      62.78     6.51   11.72
3   -20.00       4.50      63.37     4.09    9.20
4   -40.00       4.50      51.80    13.36   18.25
5   -80.00       4.50      57.02     5.54   10.07
6   -160.00      4.50      55.15     4.61    8.58
7   -320.00      4.50      51.58     5.27    8.35
8   -640.00      4.50      46.98     6.92    8.42
9   -1280.00     4.50      40.97     9.95    8.56
10  -5.00        1.50      62.35     8.43   13.88
11  -10.00       1.50      50.29    19.11   24.52
12  -20.00       1.50      61.30     6.21   11.54
13  -40.00       1.50      61.60     3.58    8.78
14  -80.00       1.50      59.40     3.16    8.14
15  -160.00      1.50      56.25     3.51    8.09
16  -320.00      1.50      52.47     4.39    8.21
17  -640.00      1.50      47.89     6.01    8.38
18  -1280.00     1.50      41.97     8.95    8.55
19  10.00       10.00     65.31     3.56    8.60
20  -10.00      20.00     72.48    -4.76   -0.13
21  -10.00     -20.00     72.20    -6.59   -2.35

THE MEAN INSERTION LOSS OVER THE FIRST 6 RECEIVER POSITIONS IS 10.87 DB.

Figure B6: File TOUTPT showing levels for 100Hz
B.1.5 Ground

The programs (except NOISEPROP) have the facility to use either the Delany and Bazley or Attenborough models. A value of either 0 (Delany and Bazley) or 1 (Attenborough) is set in the TINPUT file. In Figure B3 it can be seen that the Attenborough model has been selected. Whichever model is used, the assumption is made that the surface consists of a layer of finite or infinite thickness of homogeneous porous material, with a rigid backing. For each discretised surface in the road cross-section, 4 parameters are given as described in section B1.4 above. The 5th parameter gives the dominant angle of incidence on that segment. In the case of the road surfaces and ground outside the road cross-section the dominant angle will be close to 90 degrees as the wave direction is approximately parallel to those surfaces. For other surfaces that are discretised a value of –1 is usually set. This instructs the program to automatically calculate the dominant angle of incident from the mean source position to each boundary element.

Undulating terrain is handled in NOISEPROP. The facility to specify a dominant angle of incidence is not currently available and the ground is assumed locally reacting.

B.2 Screening

B.2.1 Barriers

There is no restriction on the shapes of barriers that can be modelled including complicated interference type barriers (Watts and Morgan, 1996). Figure B7 shows an example of a commercial product Calmzone. This was constructed from a stack of pipes of various lengths but all with similar rectangular cross-sections. The simulation is not perfect however as the pipes can only be modelled in 2-D so that the side walls of the pipes are missing. Nevertheless there was good agreement between measured and predicted values of insertion loss (see section B3 below).

![Figure B7: "Calmzone" profile fitted to a 2m high barrier](image)

There have been a number of studies carried out by TRL for the UK Highways Agency that have examined a wide range of barrier crowns for controlling traffic noise alongside major routes. Early studies were concerned with developing simple crowns that would improve screening performance without adding height to the barrier. This would have advantages for new roads where there was concern that residents would be concerned about the loss of view if conventional tall barriers were installed. For existing roads there was a possibility of retro-fitting existing barriers in situations where better screening was required due for example the growth of traffic or widening of the road. As a result of this work multiple edge barrier designs were developed and patented (Watts et. al., 1994), (Crombie et. al., 1995) and a trial installation was erected at three locations alongside the M25 around London (Watts, 1996). Figure B8 shows some of the designs developed for this work. BEM studies have also
been undertaken to optimise the efficiency of such a multiple-edge design by changing the inclination and acoustic treatment of the additional panels (Morgan, 2000).

![Figure B8: Multiple edge designs](image)

Studies have also been performed investigating the effects of different barrier profiles, including the curved designs shown in Figure B9, on the attenuation of railway noise when installed at the trackside. This was performed using a version of the boundary element model which had been adapted to model sources with dipole radiation characteristics (Morgan, 2000).

The barrier surfaces can take any specified impedance values by setting the correct impedance parameters in the TINPUT file. In later work the effectiveness of various shaped earth mounds with and without novel barriers was also examined (Watts, 1999). It was recognised that because of the rounded shape these structures were potentially inefficient in controlling the spread of noise. It was shown that multiple barriers with a height of only 0.5m could significantly improve screening performance. In further work the effects of vertically louvred barriers was examined with the aim of providing a view of the surrounding countryside for drivers without significantly reducing screening performance (Watts, 2001). This required the development of a further Fortran Program ILV10CMT where the 2-D available in the program was transformed from the vertical cross-section to the horizontal.
B.2.2 Elevated and depressed roads

The program ILV10CM was developed to cope with depressed roads or cuttings.

An intrinsic requirement of the mathematical formulation is that all of the ground surfaces should be above some fixed horizontal datum. In the numerical method any part of the boundary above this datum must be discretized into boundary elements so that complex cross-sections with a large cross-section above this datum cannot be efficiently modelled.

By carrying out the calculations in two stages it is possible using ILV10CM to increase efficiency substantially.

Consider the simple case of a cutting with a horizontal floor (of admittance $c_1$) flanked by two embankments as shown in Figure B10.

The sound source is supposed situated inside the cutting. Outside the cross-section $ABCDEFGHIJKL$ the ground surface is assumed to coincide with the $x$-axis and to have admittance $c_2$. However, it is reasonable to assume that, if the points $A$ and $L$ are sufficiently far from the source, the geometry beyond these points has negligible effect on the sound pressure at some arbitrary point within the cutting. This allows the implementation of a two-stage approach.

The cross-section is first translated to bring the geometry into the half plane $y \geq 0$ and modified to produce that shown in Figure B11. By setting the admittance of the line $y = 0$ to the left of $S1$ and the right of $S2$ to that of the cutting floor, i.e. $c_1$, the integral in (B.4) only extends over the two raised
surfaces $S_1ABCDEF$ and $GHIKLS_2$. Once the pressures on these surfaces have been evaluated, the integral equation can be used to calculate the pressure and its normal derivative at a series of receiver points which lie on the line $EH$ between two points on the cutting sides (the dotted line in the Figure). This line must lie below the top of the cutting and at or above the original ground level outside the cutting and is used in Stage 2 as a barrier surface.

![Figure B11: Cross-section for Stage 1](image)

At Stage 2 of the calculation the sides $S_1AB, EF, HG$, and $KLS_2$ are discarded and the axes shifted to obtain the revised cross-section of Figure B12.

![Figure B12: Cross-section for Stage 2](image)

The situation is now the same as that in Figure B10 except that values of $p$ and $\partial p/\partial n$ on $EH$ have now been calculated, from which we can obtain the admittance $\beta$ on $EH$ by $\beta = (\partial p/\partial n)/(ikp)$. The integral equation (4) can now be used to calculate $p$ at points outside the cutting, the integral extending only over the reduced cross-section $BCDEHIJK$.

The model significantly reduces the computation time required for modelling such arrangements. Results obtained using the model show very good agreement with those from an original single-stage model for comparable cross-sections, for both rigid and non-rigid cases.

B.3 Validation

Throughout the various stages of the development of the BEM models there have been checks made on the prediction accuracy. Early studies at Bradford University involved validation against analytic solutions for a 2-D problem which could be solved exactly (Hothersall, 1991). As an example the
solution was obtained for the sound field around a semi-circular section on a hard surface boundary. Since the flat boundary is perfectly reflecting the problem is equivalent to that of the scattering of sound, emitted by the original source and the source located at the image point, by the circular obstacle and its image in the boundary. A solution in the form of a convergent series of Bessel functions of integer order can be derived for this problem. An insertion loss spectrum was calculated for a range of receivers and compared with the numerical solutions at one-third octave band centre frequencies form 63Hz to 4kHz. At frequencies ≤ 2kHz the differences between the two methods was less than 0.5dB. At higher frequencies larger differences occurred due to third octave frequencies being close to the eigenfrequencies of the boundary value problem. These eigenfrequencies depend upon the shape and area of the cross-section but increase in density with increasing frequency. In later developments of the model the eigenfrequency problem was overcome by employing, as in Duhamel (Duhamel, 1996), a combined integral equation approach.

Predictions were also made with experimental results of measurements made outdoors on a square barrier. Good agreement was obtained at all frequencies up to 4kHz (<2dB). It was concluded that using the 2-D model gives a good indication of excess attenuation or insertion loss values that would be obtained using a point source. Also predictions at one-third octave band centre frequencies provide a good indication of experimentally measured excess attenuations over the one-third octave bands.

Extensive checks were also made on the program developed for vertical louvres ILV10CMT. Scale model tests were carried out in an anechoic chamber with hard reflective floor using an air jet source and 1/20 scale model louvred and solid barriers (Watts et. al., 2001). There was generally good agreement between the measured and predicted A-weighted insertion losses for the different designs of barrier at various angles to the barrier normal. This gave confidence in the model results for other designs of louvred barrier.

Later predictions were compared with the results obtained from full-scale experiments using the noise barrier test facility (NBTF) at TRL (Watts et. al., 1994). The facility consisted of a 20m long test barrier on an asphalt surface with a flat grass field beyond. The noise source consisted of an 800W speaker which was capable of delivering sufficient acoustical power so that background levels did not add significantly to the noise levels measured in the shadow zone of the test barrier. A reference microphone positioned 1m from the speaker enabled adjustments to be made for any variation in source strength. Random noise recorded on a digital tape recorder was used as the source signal. Microphones were placed at 20m, 40m and 80m from the barrier and at heights of 1.5m and 4.5m. Separate measurements were carried out with the source at 5.5m and 7.8m form the barrier. Measured levels were adjusted to zero wind speed and averaged to obtain an overall indication of the noise level in the screened area. Novel profiles such as multiple edge and T-shape barriers were tested and the results compared with those from the numerical BEM model (Watts et. al., 1994) and later other profiles were tested e.g. an interference type barrier (Watts and Morgan, 1996). The agreement between the improvements over a simple barrier of identical height in the measured and predicted A-weighted levels based on a standard traffic noise spectrum were reasonably close and are plotted in Figure B13.
To extend predictions to traffic situations it is strictly necessary to model the line source not as coherent but as incoherent. Unfortunately this possibility was not available in the early studies. However, it can be argued that the relative performance of noise barriers are similar for the two line sources based on scale model work (Kotasu and Yamashita, 1973).

In order to obtain a validation under real life conditions a design of multiple edge barrier similar to that shown in Figure B8(a) was tested at 3 motorway sites (Watts, 1996). The barriers at all sites were located on earth embankments that varied in height from 1.7m to 5.2m. The profile was added so that the overall height did not increase. Before and after noise measurements were taken under different wind conditions and normalised to zero wind speed so that comparisons could be made. It was shown that depending on originally screening performance the improvements as a result of fitting the profile varied from zero to over 3dB(A). At the site with the lowest embankment the performance of the profile (average reduction in noise level of 2.5dB(A) was similar to that predicted for a barrier of the same height at a flat site using the 2-D model i.e. 2.4dB(A).

Program ILV10CME which was used to predict the spread of noise from traffic running on an embankment was used to predict one-third octave band levels at various distances up to 500m form a 3m high embankment.

### B.4 Operational versions

Currently we have Fortran Programs ILV10CM, ILV10CME, FULLE and IL10CMT and Matlab program NOISEPROP operational. The features of these models are summarised in table B1 below:

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Source</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fortran</td>
<td>ILV10CM</td>
<td>Coherent</td>
<td>Flat ground and depressed roads</td>
</tr>
<tr>
<td></td>
<td>ILVCME</td>
<td>Coherent</td>
<td>Elevated roads</td>
</tr>
<tr>
<td></td>
<td>FULLE</td>
<td>Incoherent</td>
<td>Elevated roads</td>
</tr>
<tr>
<td></td>
<td>ILV10CMT</td>
<td>Coherent</td>
<td>Vertical louvres</td>
</tr>
<tr>
<td>Matlab</td>
<td>NOISEPROP</td>
<td>Coherent</td>
<td>Undulating ground with changes of impedance</td>
</tr>
</tbody>
</table>

![Graph](image-url)
Generally runs are carried out at on-third octave centre frequencies from 100Hz to 5kHz with
discretisation no greater than $\lambda/5$. The maximum number of elements is determined by memory size in
the Fortran programs and several thousand elements are possible on current PCs with memories of
several hundred MBs. Run times using a PII processor to complete solutions at all one-third octave
frequencies are approximately of the order of 1 day using the coherent source at two positions in
nearside and far side carriageways. With the incoherent source there is an order of magnitude increase
in runtime which makes routine problem solving impractical. The NOISEPROP program takes 3 days
to complete for problems with a range of 500m for frequencies from 100Hz to 2.5kHz. To complete
frequencies up to 4kHz would require 9 days.

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Appendix C. Barriers – Quantification of barrier top performance in non-neutral atmospheres

C.1 Introduction

It is known that the insertion loss of plane barriers can be significantly reduced by adverse wind vectors but it is not known how the performance of novel barrier caps will change. It is likely that the sound scattering due to turbulence and degree of refraction due to wind gradients will vary with the design of the barrier cap and it is for this reason that a method is required to quantify performance under different wind vectors. Such a method would allow the effect to be taken into account in a suitable prediction method.

C.2 Barrier efficiency in non-neutral atmospheres

The aim is to specify a method that allows the insertion loss of a barrier to be calculated based on results for a neutral atmosphere. Unfortunately there is no validated method for predicting the acoustical effects of turbulence around a complex barrier shapes although it is hoped to develop methods as part of a research programmes being considered for funding by the UK Engineering and Physical Science Research Council (EPSRC). The DWW of the Netherlands is also interested in exploring this problem as part of the Innovations Programme (IPG). It is expected that these studies will allow results to be obtained for some generic shapes e.g. plane barriers cylinders, T-shapes and multiple edges. If the results are not too sensitive to shape it may be possible to make predictions for a range of atmospheric conditions which can then be used to obtain predictions for any given receiver position.

Preliminary experimental results of an investigation carried out by TRL demonstrate that wind induced turbulence effects are important and vary according to detailed design. Further these effects are measurable close to the barrier (i.e. at 1m) and may therefore have significant effects on diffraction efficiency at greater distances. Figure C1 shows the results of insertion loss measurements taken close to a T-shaped profile using the maximum length sequence method (MLS).

![Figure C1: Insertion loss spectra for absorptive T-profile barrier with receiver level with profile top (a) for source at 0.11 m below top of barrier and (b) for source at 0.36 m below top of barrier. (○) wind speed = 0 m/s, (Δ) wind speed = 4 m/s](image)
It can be seen that above 1.6 kHz noticeable effects of wind on insertion loss are apparent at a wind speed of 4 m/s in the direction source to receiver (component measured perpendicular to the barrier).

C.3 Suggested implementation

Two approaches are suggested one numerical and one experimental.

C.3.1 Numerical methods

An exploratory approach to the problem has involved the use of computer modelling (CFD) methods to compute the time averaged flow vectors around a series of complex barrier including both Y shaped and perforated barriers (Heimann and Blumrich, 2002). Figure C2 shows this averaged flow for a slotted barrier shape.

![Average wind flow around a plane and slotted barrier shape](image)

Figure C2: Average wind flow around a plane and slotted barrier shape (Heimann and Blumrich, 2002).

Results were obtained for a series of infinitely long barrier shapes with the wind direction perpendicular to the line of the barriers. This allowed 2D solutions to be obtained. The grid size used in these computations was 25 cm. It should be noted that predictions are for mean time averaged flow vectors. This implies that short term fluctuations due to turbulence, for example close to the diffracting edges, are not included. It remains to be demonstrated whether this omission has any effect on the average level of $L_{Aeq}$.

With the average flow determined it is then possible to use the Linearized Euler (LE) sound propagation model with a grid size of 5 cm to determine the sound field around the barrier. Figure C3 illustrate the advantages of different shapes in an undisturbed flow speed of 5 m/s at a height of 10 m.

A disadvantage of this approach is the computer processing time involved in prediction. If the wind is blowing obliquely across the barrier or the wind speed varies then further computations are required. However, as a reference method it is promising.
Figure C3: Predicted change in insertion loss based on linear levels (100 to 1000Hz) at 5m height due to wind at 5m/s for a range of novel barrier designs where barrier F is the slotted design shown in Figure C2 (Heimann and Blumrich, 2002). Positive values indicate a worse situation (higher noise levels).

C.3.2 Experimental

An experimental approach is also suggested based on considerable experience testing under different wind conditions at TRL’s full-scale noise barrier test facility (NBTF) (Watts et. al., 1994), (Watts, 1996), (Watts, 1996).

Figure C4 shows a view of the facility that has been used to measure insertion loss out to 80m. This consists of a portable sound source, a level section of flat asphalt surface representing the road, a 20m long section of test barrier and a flat grassland area beyond. The noise source consisted of a dual cone loudspeaker system rated at 800W which was capable of delivering random noise at a level of 110dB at 1m from the speaker in the frequency range from 100Hz to 3.5kHz. The loudspeaker was mounted on a trolley that could be adjusted for height and inclination so that it can be easily transported to various positions in front of the speaker. Microphones were placed at various positions behind the barrier. During each of the measurement periods of 16 seconds, wind speed and direction were logged at one second intervals. Repeat measurements were taken under different wind conditions on different days so it was possible to examine the effects of wind on different barrier crowns. As an example the A-weighted level plotted against the normal component of wind speed for a plane 2m reflective barrier and a multiple edge barrier of the same overall height are given in Figure C5.

The slope of the sound pressure level against component of wind speed can be used to compare different barrier options. In the examples given in Figure C5 the correlation coefficient is relatively high at 0.89 and the slope is 0.96 i.e. nearly a 1dB increase in SPL for each increment of 1m/s in wind speed component (measured positive from source to receiver). For the multiple edge profile the slope is higher at 1.28 and the correlation coefficient is 0.95.
The proposed approach would be to measure under different wind conditions the improvement in insertion loss of the novel crown over a plane barrier of identical overall height across a broad frequency range at different positions (heights and distances) behind the barrier. Tests would be repeated with the source in at least two locations in front of the barrier to represent typical positions of the traffic stream. Measurements would be repeated for 2m, 3m and 4m high barriers (although results from a 3m barrier may be sufficient in many cases). Measurements would be made for normal and oblique propagation across the barrier. Flat grassland beyond the barrier would be required although an acoustically hard surface could also be tested if considered appropriate. The measured differences, $MD_i$, due to the novel crown compared with the situation with a plane barrier of identical height at the $i^{th}$ third octave frequency band would then be used to populate a table that can be used to predict the
change in performance at receivers at intermediate heights and distances. A simple linear relationship with normal component of wind speed $\omega$ in free field is proposed:

$$MD_{i,r} = A_{i,r} \omega + C_{i,r}$$

There would obviously be risks in extrapolating the results beyond the distance and heights where these measurements would have been taken so it would be important to make measurements over a greater range as possible to encompass a wide range of possible receiver positions. It would be necessary to standardise the position of the anemometer such that readings were not influenced by the barrier. A position along the line of the barrier but above the barrier crown (say 10m above the ground plane) could be chosen as a reference position. Practical measurement considerations may limit the range of measurements to <100m e.g. background noise levels may be too high. However, in many cases it is the improvement close behind the barrier that is required since effectiveness of the barrier decreases with distance.

The hybrid model (BEM + PE) would be employed to calculate the predicted differences $PD_{i,r}$ for all the measured situations. The correction factor $\Delta_{i,r}$ to adjust predictions and thereby calibrate the prediction model is given by:

$$\Delta_{i,r} = MD_{i,r} - PD_{i,r}$$

If $\Delta_{i,r}$ is not significantly different from zero due to the confidence limits of the experimental data then it will be sufficient to use the results of hybrid model for prediction purposes. In cases where the correction factor is non-zero the results of the hybrid model can be calibrated by applying the factor. For new situations interpolation and possibly extrapolation (with caution) of the correction factors may be used.

Note that the approach can also be applied in the case of the engineering model. For this application predictions would be made using the appropriate ray acoustic model.

C.4 References


Appendix D. Noise emission from road traffic

D.1 Introduction

Variations in speed are known to effect the overall pass-by level but the effect of the statistical variation about a mean value on the long term average noise level are not well understood. Consequently there is a need to examine the extent of the effect requires analysis since for example to what extent to the additional noise produced by relatively fast moving traffic cancel out the benefits of lower speed vehicles. There is also the variation of speed along a section of road where there is a junction, pedestrian crossing or traffic calming device. A similar situation arises where it is possible that the extra noise arising from accelerating vehicles leaving the junction or traffic calming device is compensated by the lower noise of approaching vehicles required to decelerate.

D.2 Source model

The Harmonoise source model (Jonasson et al, 2004) consists of two sources i.e.

- a source placed 0.01m above the road surface which in terms of sound power is 80% rolling noise and 20% propulsion noise and
- a source at 0.3m above the road surface for light vehicles and 0.75m for heavy vehicles which consists of 80% propulsion noise and the remainder rolling noise.

The sound power of the rolling noise is given by the well known relationship:

\[
L_{WR}(f) = a_{p}(f) + b_{p}(f) \log \left( \frac{V}{V_{ref}} \right)
\]  
(D.1)

The sound power of propulsion noise is given by:

\[
L_{WP}(f) = a_{p}(f) + b_{p}(f) \log \left( \frac{V - V_{ref}}{V_{ref}} \right)
\]  
(D.2)

A different set of coefficients in the above expressions are given for different categories of vehicles. Corrections are made for the different number of axles, road surface, temperature, acceleration/gradient etc. There is also a directivity correction which is ignored in the treatment outlined below (see section 4.3.3).

In order to predict the equivalent continuous sound level \(L_{eq}\) at the roadside for different speed distributions on a long straight road it is necessary to calculate the sound exposure level (\(SEL\)) from the sound power level \(L_{w}\) of the different category of vehicles.

It can be shown that in a given frequency band:

\[
SEL = L_{w} - 10 \log \nu + 10 \log(d) + 10 \log \alpha - 10 \log[4\pi(d^2 + (h_r - h_s)^2)] - \Delta L
\]  
(D.3)

Where \(\nu\) is the vehicle speed in m/s, \(d\) is the distance of the microphone from the source, \(\alpha\) is the angle subtended during the integration (assumed to be \(\pi\) radians) and \(h_r\) and \(h_s\) are the heights above ground level of the receiver and source respectively. \(\Delta L\) is a term included to account for reflections effects.

For a highly reflective road surface and the low source this is close to 6dB.

If the hourly flow on the road is \(n_c\) vehicles of category \(c\) then the \(L_{eq}\) over one hour is given by:
For simplicity in the calculations below it is assumed that all vehicles pass the microphone at the same distance $d$ from the receiver and that the broad band A-weighted level $L_{Aeq}$ is employed.

**D.3 Freely moving traffic on high speed roads**

Where vehicles are not impeded or freely moving it has been found that the speed distribution approximates to a normal or Gaussian distribution. Early work suggests that the standard deviation of the speed distribution of traffic (all types included) $\sigma$ is approximate one-fifth of the mean (RRL, 1965) over wide range of road types.

The UK Department for Transport publishes annual speed data based on measurements of many thousands of vehicles. This is in the form of the average speed and the percentages $P_1$ exceeding various speeds $S_i$ at and above the posted speed limit (Department for Transport, 2003).

Assuming a normal distribution of vehicle speeds as shown in Figure D1, for a given probability the standard deviation can be estimated if the average value $S_0$ is known.

![Figure D1: Normal distribution assumed for analysis of speed effects](image)

The standard deviation $\sigma$ can be obtained from:

$$S_i - S_0 = F \sigma$$  \hspace{1cm} (D.5)

where $F$ is the fraction of a standard deviation which leads to the observed percentage at speed $S_i$. The value of $F$ was obtained from statistical tables by entering the percentage expressed as a probability $P_i$. For each vehicle type shown in Table D1 the value of $\sigma$ was estimated at two speeds and then averaged.
Table D1: Vehicle speeds on UK motorways subject to 113km/h (70mile/h) speed limit (based on 27 sites)

<table>
<thead>
<tr>
<th>Vehicle class</th>
<th>Number observed (thousands)</th>
<th>Average speed (m) (km/h)</th>
<th>Estimated standard deviation (σ)</th>
<th>σ/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles</td>
<td>2,468</td>
<td>114.3</td>
<td>27.97</td>
<td>0.245</td>
</tr>
<tr>
<td>Cars</td>
<td>409,120</td>
<td>112.7</td>
<td>18.56</td>
<td>0.165</td>
</tr>
<tr>
<td>Light goods</td>
<td>45,846</td>
<td>111.0</td>
<td>18.19</td>
<td>0.164</td>
</tr>
<tr>
<td>Buses and coaches</td>
<td>3,388</td>
<td>96.6</td>
<td>8.75</td>
<td>0.091</td>
</tr>
<tr>
<td>2 axle trucks*</td>
<td>23,556</td>
<td>96.6</td>
<td>15.44</td>
<td>0.160</td>
</tr>
<tr>
<td>&gt;2 axle trucks*</td>
<td>47,316</td>
<td>86.5</td>
<td>5.88</td>
<td>0.068</td>
</tr>
</tbody>
</table>

*Over 3.5 tonne gross weight

It can be seen that generally the heavier the vehicle the smaller is the σ/m ratio. In the UK the speed limit for heaviest trucks is 96km/h (60 mile/h) and in practice many trucks are driven close to this speed resulting in the relatively small ratio. In contrast car drivers and especially motorcycle riders are often driving in excess of the posted speed limit and the speed variation is consequently significantly wider.

Equations (D.1), (D.2) and (D.3) were used in the assessment of the importance of speed distribution rather than average speed for determine LAeq levels. As an illustration three vehicle categories were examined i.e. cars, 2-axle trucks (with weights over 3.5 tonne) and heavy trucks with more than 2-axles. The parameter values for the equations were obtained from the source model report of WP1.1 (Jonasson, 2004). The values of m and σ were obtained from Table D1. The hourly flow was assumed to be 3600 vehicles. The percentages of vehicles falling in bands of width 0.5 b in the range ± 3.25 b were calculated from normal statistics.

Table D2: Hourly LAeq based on speed distribution and on the average speed

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>LAeq [dB(A)]</th>
<th>Increase in speed to achieve equality (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Based on average</td>
<td>Based on distn</td>
</tr>
<tr>
<td>Cars</td>
<td>82.25</td>
<td>82.45</td>
</tr>
<tr>
<td>2-axle trucks</td>
<td>84.62</td>
<td>84.90</td>
</tr>
<tr>
<td>&gt;2-axle trucks</td>
<td>87.78</td>
<td>87.83</td>
</tr>
</tbody>
</table>

It can be seen that there is a small increase in LAeq if the speed distribution is used in the calculation rather than the average speed. The right-hand column lists the increase in average speed that would be needed to obtain the same result as the value based on the speed distribution.

D.4 Traffic in urban areas

Traffic in urban areas is often not freely moving however at certain off-peak hours especially at night the speed variation is likely to approach the Gaussian distribution. UK Department for transport statistics were used to compile the data in Table D3 using the approach adopted in the previous section.
Table D3: Roads subject to a 52km/h (30mile/h) speed limit (based on 30 sites)

<table>
<thead>
<tr>
<th>Vehicle class</th>
<th>Number observed (thousands)</th>
<th>Average speed ((m)) (km/h)</th>
<th>Estimated standard deviation ((\sigma))</th>
<th>(\sigma/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motorcycles</td>
<td>741</td>
<td>46.7</td>
<td>14.39</td>
<td>0.308</td>
</tr>
<tr>
<td>Cars</td>
<td>54,117</td>
<td>49.9</td>
<td>9.70</td>
<td>0.195</td>
</tr>
<tr>
<td>Light goods</td>
<td>4,337</td>
<td>51.5</td>
<td>8.37</td>
<td>0.163</td>
</tr>
<tr>
<td>Buses and coaches</td>
<td>505</td>
<td>45.1</td>
<td>8.91</td>
<td>0.198</td>
</tr>
<tr>
<td>2 axle trucks*</td>
<td>1,319</td>
<td>49.9</td>
<td>9.25</td>
<td>0.185</td>
</tr>
<tr>
<td>&gt;2 axle trucks*</td>
<td>462</td>
<td>49.1</td>
<td>7.71</td>
<td>0.157</td>
</tr>
</tbody>
</table>

*Over 3.5 tonnes gross weight

It can be seen that the \(\sigma/m\) is generally significantly larger than is the case for motorway traffic indicating a greater relative variation in speed. It is also noticeably that the average speeds and standard deviations do not differ so widely between vehicle classes as is the case for motorway traffic. This is because individual vehicles are constrained to travel at relatively low speeds by the low speed limit, congested traffic and frequent junctions. The exception is motorcycles which is not surprising since they are more able to weave between stationary or slow moving traffic. It is likely that the assumptions concerning a normal distribution are not so robust in such cases due to periods of congested traffic so that the estimates of standard deviation could be misleading. Information concerning detailed speed profiles of traffic on an hourly basis is difficult to find but useful information was provided by the traffic authorities of one European capital city.

Figure D2 gives the counts of vehicles falling in the following speed bands for selected hours throughout the day and night: 0-10, 10-15, 15-20, 20-25, 30-35, 35-40, 40-45, 50-55, 55-100 and >100 km/h.

**Figure D2: Speed distributions at selected hours during the day and night**
It can be seen that the speed distribution changes from a normal distribution during low flow conditions to flat-topped, skew and bi-polar distributions during congested periods.

The data was not detailed enough to allow individual vehicle speeds to be logged so for the purposes of this analysis it was assumed that two types of vehicle were present i.e. cars and two-axle delivery trucks. The heavier vehicles making up 15% of the total count in any one hour. It was also assumed that the speed distributions of the two vehicle classes were similar. Using the analysis outlined in the previous section the $L_{Aeq}$ in each hour was computed based on the average speed and the distribution. An additional distribution used was the theoretical normal distribution based on average speed and the standard deviation. Table D4 summarises the results:

Table D4: Hourly $L_{Aeq}$ based on speed distribution and on the average speed

<table>
<thead>
<tr>
<th>Speed distribution</th>
<th>$L_{Aeq}$ [dB(A)]</th>
<th>Difference</th>
<th>Increase in speed to achieve equality [km/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal (theoretical)</td>
<td>64.19</td>
<td>0.24</td>
<td>2.20</td>
</tr>
<tr>
<td>Normal (measured)</td>
<td>64.13</td>
<td>0.40</td>
<td>3.60</td>
</tr>
<tr>
<td>Flat-topped</td>
<td>65.57</td>
<td>0.61</td>
<td>9.66</td>
</tr>
<tr>
<td>Skew</td>
<td>64.93</td>
<td>0.78</td>
<td>11.02</td>
</tr>
<tr>
<td>Bi-polar</td>
<td>65.41</td>
<td>0.87</td>
<td>15.29</td>
</tr>
</tbody>
</table>

It can be seen that generally the greater the departure from a Gaussian distribution the larger is the difference between $L_{Aeq}$ based on the average speed and on the actual distribution. The largest difference is for the bi-modal distribution where the average speed was lowest (15.4 km/h). This probably results from a mixture of heavily congested and more freely moving conditions. Larger speed increases are required to achieve equality due to the fact that at relatively low speeds above 10km/h the SEL does not change very quickly with increasing speed. To illustrate this point Figure D3 shows the speed variation of SEL for category 1, 2 and 3 vehicles. Note the minimum near the average speed.

![Figure D3: Variation of SEL with vehicle speed](image)

<table>
<thead>
<tr>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
</tr>
</thead>
</table>

It can be seen that the speed distribution changes from a normal distribution during low flow conditions to flat-topped, skew and bi-polar distributions during congested periods.
**D.4.1 Effects of speed variation near a junction**

There has been little recent modelling work carried out into the effects of road junctions on overall average noise levels although early work examined the effect with a simple source model (Jones et al., 1979). In a recent Swedish study carried out by SP (Bredenfeldt and Nilsson, 2004) road side noise measurements were carried out close to roundabouts and junctions with traffic lights. As a reference a position with free flowing traffic 100 m in front of the roundabout/junction was used. The authors concluded that a roundabout, which is designed to slow down the traffic from 50 km/h to 30 km/h without significant levels of acceleration/deceleration reduced the $L_{Aeq}$ level to 2.9 dB(A) below that predicted from the Harmonoise model if a steady speed through the junction was assumed. For junctions with traffic lights the trend was similar but the spread in data was greater. It was found that the $L_{Aeq}$ was always lower close to the crossing than it was at a distance of 100m before the junction. There were some uncertainties associated with the study as it proved difficult to correct accurately for the influence of roads crossing the road under study. However it was quite clear that roundabouts and junctions with traffic lights decrease rather than increase the noise level in the vicinity of the junction. Note that the study sites had a small flow of heavy vehicles and so the results may need to be revised where the percentage is significant.

In order to further examine the likely size of the effect in the present study a simplification of the situation was carried out to the source model. First the variations in the horizontal and vertical direction (directivity) were ignored and secondly the propagation was assumed to be over hard ground. Directivity in the horizontal direction is not well defined (Jonasson et al., 2004) and is not thought to amount to a large effect. For the present simulation a single height of receiver at 1.2m was assumed so that vertical directivity is unimportant when making comparisons. In addition in many urban situations the hard ground assumption is not unrealistic.

**D.5 Junction simulated**

The junction simulated was a simple junction where all vehicles are required to stop. It was assumed that the effects of the traffic on one arm of the junction was relatively small (due to small traffic flow and screening effects of buildings) and could be neglected in determining the levels on the road considered. The effective vehicle source positions for vehicles approaching and leaving the junction were 5 m apart. Only light vehicles (category 1 vehicles) were simulated and the following approach speeds and deceleration/accelerations rates were chosen:

1. 50 km/h approach speed with deceleration/acceleration rate of 2 m s$^{-2}$.
2. 60 km/h approach speed with deceleration/acceleration rate of 2 m s$^{-2}$.
3. 40 km/h approach speed with deceleration/acceleration rate of 2 m s$^{-2}$.
4. 50 km/h approach speed with deceleration/acceleration rate of 1 m s$^{-2}$.

The speeds of 40 and 60 km/h were chosen to represent 1 standard deviation above and below the mean speed of 50km/h which was based on $\sigma/m = 0.195$ for cars (see Table D3). An acceleration/deceleration rate of 2m.s$^{-2}$ was chosen as it was considered a typical value based on test track experiments with a range of vehicles and had been selected in a previous study (Jones et al., 1981).

Thus for example in the first simulation the approach speed was set at 50 km/h with a constant deceleration of 2 m.s$^{-2}$ approaching the junction and 2 m.s$^{-2}$ acceleration when leaving the junction. Predictions were made on each side of one arm of the junction with receiver placed at a height of 1.2 m at distances of 7.5 m, 15m and 30 m from the nearest source line. The distance from the stop line was 0, 5, 10, 20, 40, 60 and 80 m. The line sources consisted of individual non-coherent sources placed 1m apart stretching back to 100m from the stop line and 110m beyond. At each individual source position the sound power was calculated using the speed profile based on the assumed acceleration and deceleration rates. With an approach speed of 50km/h the distance from the stop line where deceleration commenced was 48m. It was assumed that vehicles stopped for 10 s at the junction before accelerating away in the same direction. The average level $L_{Aeq}$ was calculated based on a traffic volume of 500 vehicles per hour in each direction. The reference condition was a section of...
road without a junction where all vehicles travelled at a speed of 50 km/h without stopping. The difference in $L_{Aeq}$ with and without a junction present was calculated and a contour plotting routine was used to interpolate values.

**D.5.1 Results of junction simulation Junction simulated**

The contour plots for the differences in $L_{Aeq}$ (level with junction – level without junction) for the 4 situations simulated are given in Figures D4 to D7. Some general trends can be observed from these plots. As expected the noise exposure on the side of the junction where vehicles are accelerating is greater in all cases than on the side where they are decelerating.

In the case of an approach speed of 50 km/h with acceleration of +/- 2 m.s$^{-2}$ it is clear that noise exposure is always slightly greater than with a vehicle travelling at constant speed. The maximum occurs at the stop line where a maximum increase of 2.2 dB was predicted. At a distance of 60 m or greater from the stop line the level increase is less than 1 dB(A).

![Figure D4: Simulation 1, 50 km/h approach speed](image)

For the second simulation with an approach speed of 60 km/h the maximum increase is smaller at 1.3 dB with some decreases close to the decelerating vehicles. The largest decrease was -0.73 dB(A).

![Figure D5: Simulation 2, 60 km/h approach speed](image)
With vehicles approaching at 40 km/h the predicted increases in noise are more substantial with increases in noise reaching a maximum of 3.5 dB(A) at the stop line. However, as noted in previous cases the effect reduces with distance from the junction and at a distance of 40m and beyond the increase were less than 1 dB(A).

![Figure D6: Simulation 3, 40 km/h approach speed](image)

For vehicles travelling initially at 50 km/h but then decelerating at a low rate of 1 m.s\(^{-2}\) there are reductions in noise at almost all positions. The greatest reduction of 2.4 dB(A) was predicted at 20m from the stop line.

![Figure D7: Simulation 4, 50 km/h approach speed and with low acceleration and deceleration (1 m.s\(^{-2}\))](image)

Of course the balance of propulsion noise and rolling noise will depend on the road surface and different sizes of effects would be expected on quieter or noisier road surfaces. For the current simulations a 2 year old SMA 0/16 surface was selected as being fairly typical of surfaces in Northern Europe. In addition the presence of heavy vehicles would increase the influence of propulsion noise and would affect the predictions if they were present in a significant amount.

It is interesting to note that the site measurements reported above (Bredenfeldt and Nilsson, 2004) near a roundabout where deceleration rates were judged to be modest indicated nearly a 3 dB(A) reduction
of noise level near the junction compared with the situation where a steady speed through the junction was assumed. This is similar to the results of the final simulation presented above where a relatively low deceleration rate of 1 m.s\(^{-2}\) was assumed.

D.6 Summary

The following conclusions can be made for the calculation of \(L_{Aeq}\) based on the average speed.

- For freely moving traffic the speed distribution approximates to a normal or Gaussian distribution. Under these conditions the \(L_{Aeq}\) based on the average speed underestimates the \(L_{Aeq}\) based on a speed distribution from between 0.05 to 0.28 dB(A). The smallest difference occurs for the heaviest vehicles where the standard deviation is smallest.

- Data collected in urban areas suggests that speed variation expressed as a ratio of average speed is relatively large compared with the situation under free flow conditions on high speed roads.

- These urban data indicate a complex pattern of changes in speed variation over 24 hours. Under low flow conditions vehicles are freely moving and the speed variation approximates to a Gaussian distribution. Under more congested conditions the distribution becomes flat-topped or skewed. Finally, under heavily congested conditions a bi-modal distribution can be observed.

- For these urban conditions it was found that the \(L_{Aeq}\) based on average speed was up to 0.9 d(A) lower than that based on the distribution of speeds obtained from the local highway authority. Thus the effect may be small enough to be considered insignificant for noise mapping purposes.

- At road junctions the deceleration and acceleration of vehicles can change the roadside average noise levels compared with a situation without a junction where vehicles can travel at a steady speed. The simulation of a number of scenarios with light vehicles indicated that the effect is very variable depending on assumptions made. In some cases a decrease in average noise occurs especially with a low acceleration and deceleration rate and where the approach speed is high. The results of the low acceleration condition were similar to the results of a study conducted near a roundabout. Across the range of conditions examined the effects were generally not more than 3 dB(A) and were localised such that maximum levels generally occurred within 15 m of the junction and became much lower at greater distances from the junction. If accurate levels are required close to the junction a full simulation may be required and account should be taken of heavy vehicles if their numbers are significant. However, for many situations the average level may not depart significantly from the level assumed for a steady speed across the junction.

D.7 References


