A comparative overview of traffic flow modelling approaches for auralisation

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Summary

Auralisation of traffic flow noise has become an increasingly popular research area in recent years. Some algorithms that synthesise the noise emitted from a single vehicle pass-by as well as background traffic noise have been proposed, which could potentially be used to develop auralisations of traffic flow scenes. The process of auralisation is desirable as an alternative to established traffic noise monitoring and modelling techniques, which often take the form of long term, average A-weighted sound pressure levels. Whilst these techniques are of use for gathering objective parameters, they are not sufficient for describing the subjective experience of sound. Auralisation therefore offers an alternative approach to environmental sound evaluation providing an immediate aural understanding of an acoustic scene. As there are no standardized methods for traffic noise auralisation, the resultant modelled scenes can vary significantly, depending on the methods and algorithms utilized. This paper gives a comparative overview of the recently published traffic flow auralisation models, specifically focusing on the level of detail required for running these models. Based on the overview, a specific traffic flow auralisation framework is introduced and implemented, and some preliminary investigation is conducted into the plausibility of the resultant auralisations, with a particular focus on issues arising from HRTF processing used to spatialise elements of the synthesised traffic noise.

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1. INTRODUCTION

Traffic noise is the combination of noise generated by a flow of one or more vehicles, especially when there is high traffic volume and different driving patterns. Several prediction methods based on noise level metrics have been developed and applied for prediction of noise levels for rather complex traffic scenarios, such asmultiple vehicle types accelerating and decelerating at road junctions[1], with some methods also considering the effect of surrounding buildings, vegetation, road surface type, and climate[2], etc. However, these prediction values are often expressed in A-weigted sound pressure levels denoted by dB(A) which cannot fully describe road traffic noise. For example, studies on traffic noise annoyance showed that there can be a significant difference in annoyance judgment for different traffic structures with the same L_{Aeq} (the equivalent A-weighted noise level within a period) value[3, 4]. In addition to exploring novel time-varying indicators such as in [5], auralisation can be potentially used as an alternative to predict and evaluate traffic flow noise. Timbral changes, impulsive noises, and strong low frequency elements can be made audible with specific auralisation techniques.

As there are no standardized methods for traffic noise auralisation, the perceived results from different methods may vary significantly, depending on the models and algorithms used. According to the concept of auralisation in [6], there are three fundamental elements to be considered: source generation model, sound propagation model, and sound reproduction system. Different types of source generation and sound propagation models for traffic flow noise can be found extensively in the literature. Although most of these models have not been explicitly designed for the purpose of auralisation, some of them have been successfully used in that context, and can be potentially utilized to generate plausible sound scenes. According to the level of detail required to simulate traffic flow scenes, the present paper divides the source generation models into three categories, which are micro-scope models, meso-scope models, and macro-scope models, respectively. More detail about the categorization is presented in Section 2, in addition to a comparative overview of some typical source generation models in different categories. Regarding sound reproduction for traffic flow auralisation, binaural audio techniques such as Head Related Transfer Functions (HRTFs) are widely used for research purposes in literature. When using HRTFs, it is necessary to ensure the plausibility of the synthetic traffic flow noise does not change significantly when convolved with Head-Related Impulse Responses (HRIRs). This is because colouration caused by non-individual HRTFs without appropriate tuning can be significant and reduce the reproduction quality[7].

The structure of this paper is as follows: in Section 2 some recently published source generation models for traffic flow auralisation are presented for a comparative overview, and categorized by the level of detail required for implementation. In Section 3, the traffic flow auralisation framework used in this paper is described, and is accompanied by some preliminary analysis of the plausibility of the results.

2. OVERVIEW OF TRAFFIC FLOW SOURCE MODELS FOR AURALISATION

This section gives an overview of some recently published source generation models used for traffic flow auralisation. According to the level of detail required to simulate traffic flow scenes, these models are divided into three categories in this paper, which are micro-scope models, meso-scope models, and macro-scope models, respectively. Table I demonstrates some typical models with different levels of details/parameters required for traffic flow auralisation within each category.

2.1. Micro-scope models

Micro-scope models focus on the sound emitted from each vehicle from a low-level perspective. Flow noise is simulated by calculating the emission from each vehicle within small time blocks, and these sounds are summed together according to the distribution of vehicles during a specific period of time. The low-level perspective here means: for each vehicle, the rolling noise and the propulsion noise are calculated separately, and each noise is determined by multiple parameters such as gear setting, engine order, engine speed, tyre structure, and mechanical impedance of road surface[8, 9, 10]. Some low-level parameters, e.g. the engine load, can be calculated or measured based on data provided by the car manufacturers, such as the driving resistance, the gear ratio, etc. As a result, it often requires very detailed information (consisting of dozens or hundreds of time-varying parameters) to run a micro-scope model.

An advantage of micro-scope models is that it is possible to give full control of the signal characteristics. However, it is usually very computationally demanding and time-consuming to run a micro-scope model, limiting its suitability for real-time applications. Moreover, it may be troublesome to get access to the full range of parameters required to run a micro-scope model. Some typical micro-scope models for rolling/propulsion noise can be found in [8, 9, 10].

2.2. Meso-scope models

Meso-scope models focus on the sound emitted from each vehicle from a high-level perspective. As with micro-scope models, noise of a traffic flow scenario is simulated by summing sounds emitted from single vehicles. However, the status of each single vehicle is not determined by such a large number of low-level parameters. Instead, some empirical equations are proposed in meso-scope models. These empirical equations are derived from large measurement dataset with statistical analysis, an make use of high-level parameters (e.g. vehicle category, vehicle speed). The output sounds generated by meso-scope models do not exactly correspond to a specific vehicle sound, but provide the similarity in sound power levels and perceived plausibility. Some factors that influence the source timbre, such as acceleration/deceleration, driving patterns, road type, and road surface conditions, can be partly compensated or corrected by involving additional empirical equations. For example, in the Harmonoise[11] model, an empirical equation for correction of the constant speed condition is presented, but works only for the vehicle acceleration/deceleration status within $\pm 2\mathrm{m/s}^2$.

Compared with micro-scope models, meso-scope models have limited flexibility, relying on the effectiveness of derived empirical equations and measurement datasets. However, these models are less computationally demanding, and are less time-consuming to generate, which opens up the possibility of real-time applications with fewer parameters required.. Apart from the Harmonoise model, some other examples of meso-scope models can be found in [12, 13].

2.3. Macro-scope models

In contrast with micro-scope and meso-scope, models in macro-scope category do not focus on the sound emitted from single vehicles. Instead, a traffic lane is treated as a line source without considering the specific conditions of each vehicle. The sound signal of the line source is simulated by filtered broadband noise with additional modulation techniques applied to create the perception of fluctuation due to single vehicle pass-bys. It is necessary to ensure the sound power of the filtered broadband noise corresponds to the practical traffic flow noise in each frequency band. In [14], modulation transfer functions (MTFs) are used

Table I. Recently published source models for traffic flow auralisation

Modelling Approach	*Typical Simulations*	*Example of Parameters Required*	*Category*
Physical Modelling Synthesis[8]	Road-tyre noise	Tyre geometry Tyre structure Tyre stiffness Tyre pressure Loss-factors Road surface roughness Road surface acoustic impedance Mechanical impedance Flow resistance	Micro-scope
Spectral Modelling Synthesis[9]	Engine noise	Engine speed Engine load Engine order & Order phase Vehicle mass Road inclination angle Vehicle acceleration Driving resistance Emission angle Location on straight road	Micro-scope
RoTraNoMo[10]	Tyre noise Engine noise	Vehicle speed Vehicle acceleration Vehicle category Time of the day Road surface type Gearshift prescription Location on road network Driving resistance Gear ration Power to mass ratio	Micro-scope
Harmonoise[11]	Tyre noise Engine noise	Vehicle speed Vehicle category Vehicle acceleration Road surface conditions	Meso-scope
Granular Synthesis[12]	Tyre noise Engine noise	Engine speed Vehicle speed Gear number Calibration gains	Meso-scope
Recording-based analysis-synthesis[13]	Tyre noise	Vehicle speeds and positions Directional pattern functions Spatial impulse responses	Meso-scope
Background noise synthesis[14]	Background traffic noise	Flow distribution Engine power profiles Modulation transfer functions	Macro-scope

to generate rippled spectra, resembling events of single vehicle pass-bys. The movement of vehicle between different positions can be represented by change of parameters within MTF equations, such as phase and ripple velocity.

The aim of macro-scope models is to synthesise background noise or traffic noise from a distance, without explicit simulation of the sound of each vehicle. This can dramatically save computational power and time, especially for auralisation of a complex traffic flow scenario consisting of a large number of vehicles, or where the scene to be auralised needs to have traffic noise as being far away from the listener.

In this section, a categorization of source modelling techniques for traffic flow auralisation has been presented, in addition to a comparative overview of some recently published models in each category. To summarize, both micro-scope and meso-scope models focus on the propulsion noise and tyre noise of sigle vehicles to simulate traffic flow noise, while macro-scope models calculate traffic flow as a line source without considering of the status of each vehicle. Micro-scope models have the most flexibility with and are the most computationally demanding, requiring the most detail and the use of low-level parameters; meso-scope models have limited flexibility but are less computationally intensive; macro-scope models can be useful for auralisation of heavy traffic or distant traffic noise.

3. IMPLEMENTATION OF TRAFFIC FLOW AURALISATION

This section presents a method for auralisation of traffic flow noise. Currently, propulsion noise is not considered, and only road-tyre noise is synthesized. As the aim of this work is to develop a flexible tool to synthesis traffic flow noise scenarios without considering the status of each vehicle in too much detail, the development of a meso-scope model should be suitable. Figure 1 presents an example traffic flow scenario for auralisation in this work, consisting of multiple vehicles driving across a straight road. Each vehicle is allocated a specific constant speed, from left to right (Vn), or vice versa (Vn'). A distribution function is used which describes the time of each vehicle entering and leaving the road. The length of the road is L(m), and the listening position is set at the position of L/2 on the roadside, with a distance of D(m) from the traffic lane. Figure 2 shows the auralisation framework implemented for this work, which is further explained in this section.

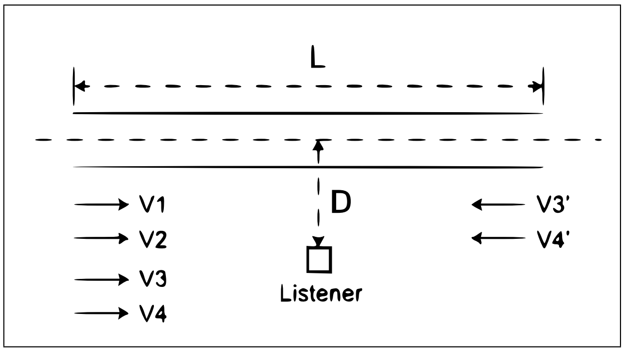

Figure 1. Example of traffic flow scenario for auralisation

3.1. Source synthesis

In this work, the Harmonoise model[11] is used for tyre noise generation. The tyre noise for each vehicle is generated by two point sources at heights of 0.01m and 0.3m (or 0.7m for heavy vehicles) above the road, with energy allocation of 80% and 20%, respectively. For each vehicle, the power level of tyre noise is calculated in multiple 1/3 octave bands by equation (1).

$$L_{WR}(f) = a_R(f) + b_R(f)\log(\frac{v}{v_{ref}}) \tag{1}$$

where a_R and b_R are regression parameters depending on vehicle type, v is the speed of vehicle, v_{ref}=70km/h is a pre-set reference speed, f is the centre frequency of each 1/3 octave band. For implementation of this equation, broadband white noise is converted to pink noise in order to produce a smoother spectrum in the resulting signal[9]. Then a series of tenth order Butterworth bandpass filters are used to obtain the noise component in each 1/3 octave band, and the sound level power of the signal in each 1/3 octave band is calculated. The output signal is generated by summing the signals in all frequency bands. These bandpass filters meet ANSI S1.11 and IEC 61260 standards.

The influence of road surface, such as material, age, and wetness, can be compensated by calculating additional empirical equations in the Harmonoise model. Directivity patterns can be either calculated by the empirical directivity functions, or extracted from measurement recordings. Encoding techniques such as [13] may be used to obtain directivity pattern functions from the measurement data.

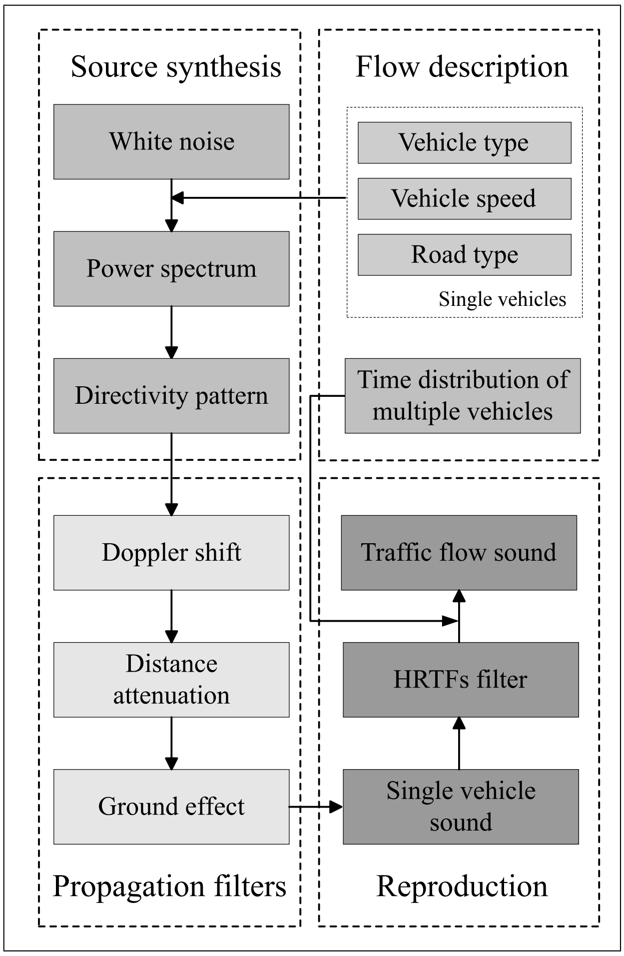

Figure 2. Framework of traffic flow auralisation (tyre only)

3.2. Propagation effects

Currently, propagation effects implemented here include Doppler shift, distance attenuation, and ground reflection. Other sound propagation effects, such as air absorption, the presence of buildings and vegetation, and air turbulence, are not considered at this time.

Doppler shift of each vehicle is simulated via a time-varying delay line[15]. Fractional delay techniques with interpolation approaches between samples are required in order to avoid audible artifacts (i.e. 'zipper noise'). In this work, a sinc function method is used for audio interpolation. This is a bandlimited interpolation method which is theoretically perfect for reconstruction of the sound signal[15]. Moreover, this method results in less non-linear distortion and spectral attenuation at high frequencies than a linear interpolation method[9].

The distance attenuation is modelled simply on a spherical wave equation in order to save computational time and power. Although this is audibly suitable for the auralisation of traffic flow scenario in Figure 1, more complex wave attenuation models (such as [16]) for outdoor sound propagation should be considered when conducting auralisation of an actual scenario.

The ground effect involves only ground reflections in this work. Compared with direct sounds, ground reflections have longer propagation distance and different power density, and different spectral patterns. The change of power density and spectral patterns can be calculated if the data of acoustic impedance of the road surface available. This, however, has not been included in this work at this time. The longer propagation distance is implemented by a fractional delay line with interpolation via sinc functions.

The tyre noise of each single vehicle is generated by summing the direct sound and the ground reflection signal for that vehicle, with Doppler shift and distance attenuation applied.

3.3. Sound reproduction

In order to enhance the plausibility of the auralisation, it is necessary to add some spatial audio effects. Currently, in this work, head-related transfer functions (HRTFs) are used as a binaural audio technique to create the spatial sound experience. The FABIAN HRTF database[17] is used here, which provides a two-degree azimuthal resolution. With the information of listening position and the single vehicle position at each sample, the time-varying angle between the listener and the vehicle can be calculated. These angle values are approximated by the HRTFs in the database, depending on the resolution available. The source audio is then divided into blocks corresponding to these angles, after which the blocks are convolved with the appropriate HRTFs. In order to avoid artefacts like 'clicks' due to the sudden change between HRTFs of two angles, some cross-fading is implemented to smooth the transition between blocks.

While HRTFs provide external sound source localisation, they also bring colouration to the input sound, resulting in timbral changes. There is research showing that colouration caused by non-individual HRTFs without appropriate tuning can be significantly effect the quality of reproduction[7]. Some preliminary investigation into the plausibility issues caused by HRTF processing is conducted in this work. The main idea is to evaluate the plausibility of the synthetic traffic noise before and after HRTF processing. Apart from some informal pilot listening tests did by the authors, Zwicker's sharpness metric has also been used as it is relevant with the perceived sound quality of an automobile, and therefore the plausibility of synthetic traffic noise. Mathematically, sharpness can be calculated by equation (2)[18]:

$$S = 0.11 \cdot \frac{\int_0^{24Barks} N' g'(z) \cdot z \cdot dz}{\int_0^{24Barks} N' \, dz} \tag{2}$$

Where S is sharpness (in acum), N' is the specific Loudness for the critical band, z is the critical band rate (in Bark), $g'(z)$ is a weighting function (the example weighting function provided in [18] was used in this work).

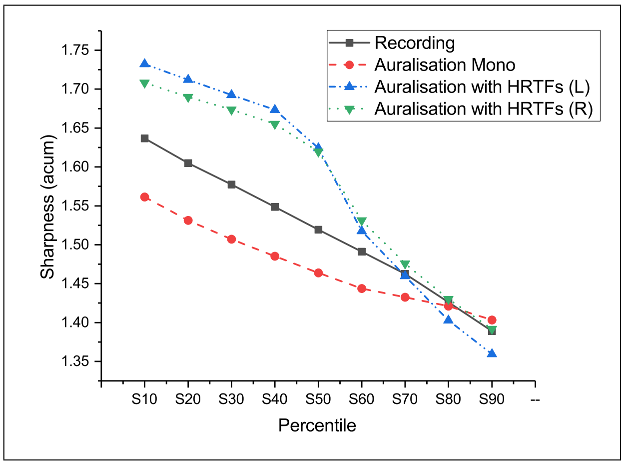

Figure 3. Percentile statistics of sharpness calculation of recording and synthetic sound, before and after HRTF processing (L: left channel, R: right channel)

Figure 3 shows the sharpness calculation results for a single vehicle pass-by as synthesized by the model presented in this section, before and after HRTF processing. For reference, the sharpness results of a pass-by recording which is at the similar speed in an open environment is also demonstrated. As can be seen from Figure 3, the percentile statistics of sharpness rise after filtering with HRTFs, as the emphasis on high frequencies makes the sound 'sharper'. The differences between the synthetic sound and the recording become more obvious after HRTF processing. As the FABIAN HRTF database used in this model is non-individual, the plausibility will decrease when listen to the sound with headphones because of the colouration of HRTF processing. This problem may be solved by an extra selection and tuning process of HRTFs, such as [7], or an alternative spatial audio technique, such as vector based amplitude panning (VBAP), or Ambisonics, etc.

4. CONCLUSIONS

This paper gives a comparative overview of the recently published traffic flow source modelling approaches used for auralisation, specifically focusing on the level of detail required for running different models. According to the level of detail, these models can be divided into three categories: micro-scope, meso-scope, and macro-scope. Both micro-scope and meso-scope models focus on single vehicles in terms of propulsion noise and tyre noise to simulate traffic flow noise, while macro-scope models calculate traffic flow as a line source without considering of the status of each vehicle. Micro-scope models have the most flexibility and are therefore the most computationally demanding, requiring the most detail, including low-level parameters describing the physical characteristics of individual vehicles; meso-scope models have limited flexibility but can generate acoustic scenes faster; macro-scope models can be useful for auralisation of heavy traffic or far distance traffic noise.

Based on the comparative overview, a specific traffic flow auralisation framework is presented and implemented. The aim of this work is to develop a flexible tool to synthesis traffic flow noise scenarios without considering the status of each vehicle in as much detail as a micro-scope model. Therefore, a meso-scope model, such as Harmonoise source model, is suitable for this work. Some preliminary investigation into the plausibility issues caused by HRTF processing was conducted with the implemented model, and the results show that the synthetic traffic noise becomes 'sharper' after HRTF processing, resulting in a less plausible auralisation with headphones.

The traffic flow auralisation model presented in this work is still under development. More functions will be integrated into the source generation model in order to simulate more complex traffic flow scenarios (e.g. acceleration/decelerating, turning vehicles), and some propagation effects (e.g. distance attenuation, ground effect) need to be improved to enhance the plausibility of the auralisation. Quantitative and qualitative evaluation of sound colouration caused by HRTF processing is worth exploring, while other spatial audio techniques such as VBAP or Ambisonics may be more appropriate for this framework as they do not cause distortion in the timbre of sound.

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