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THE GENERATION OF LORRY TYRE NOISE

P.M. NELSON

TRANSPORT AND ROAD RESEARCH LABORATORY

1. INTRODUCTION

The noise generated by the action of vehicle tyres rolling on road surfaces can have a considerable influence on the total noise levels emitted by moving vehicles. It has been shown that tyre noise becomes the dominant noise source for most road vehicles operating at speeds above 100 km/h on dry roads and at much lower speeds on wet roads[1]. The effect is currently more pronounced for light vehicles where tyre noise can have a measurable influence at much lower speeds, eg during urban driving. Heavy vehicle noise is, generally, only affected at moderate and high speed ranges. However, as improvements in heavy vehicle design lead to quieter power unit components the contribution from the tyres will become more important over a wider range of operating conditions.

This paper reviews the research carried out at TRRL to examine the parameters affecting lorry tyre noise and the main sources and mechanism of noise generation.

2. PARAMETERS AFFECTING TYRE NOISE

The tyres tested at the Laboratory were size 10.00 x 20 with 16 ply rating cross-ply and radial ply lorry tyres inflated to a pressure of 690 Pa (100 lb/sq in). The tyre tread patterns were of 5 basic types: smooth tyres, rib tyres, traction tyres, rib/block tyres and ribtraction tyres. The smooth tyres were specially moulded and were of normal tread thickness. To investigate the effect of tread material, one set of cross-ply traction tyres and one set of cross-ply smooth tyres were duplicated in a high hysteresis rubber compound.

Six different road surfaces laid on the TRRL test track were studied. These surfaces were chosen to cover a wide range of materials, surface patterns and textures.

Two 6-wheeled, 2 axle rigid body lorries were used as test vehicles.

Figure 1 shows a sketch plan of the noise test site. The measurements for each set of tyres and surface combination were taken for vehicle speeds in the range 30-100 km/h. For each test run the lorry was accelerated to just above the target speed, then the engine was turned off, declutched, and the lorry coasted over the test surface. The noise at the monitoring position was recorded on a tape recorder and the average speed of the lorry passing through the test site was determined from the time taken to pass between two infra-red beams positioned 5 m apart.

For each tyre/surface combination a linear regression analysis was carried out of peak level against log speed and from the calculated regression equation

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the peak sound levels at a low speed, (30 km/h) and a high speed (100 km/h) were noted. These values were subsequently used to compare the different tyre and surface parameters examined.

2.1 Results

The results obtained as part of the parameter study are summarised in Table 1.

TABLE 1

Measured increases in tyre/surface noise levels with changes in the parameters studied (passby speed normally 100 km/h)

Parameter	Change from a to b			Increase in peak passby noise - dB(A)
Vehicle speed+	30	to	100 km/h	16-20
Load	5.9	to	13.2 tonnes	1-7
Tread pattern	Smooth	to	traction	~ 3
Tyre construction	Radial	to	crossply	~ 3
Tread belt material+	Steel	to	rayon	~ 3
	Steel	to	nylon	~ 5
Tread material	Natural rubber	to	high hysteresis rubber	~ 2
Wear	0	to	25 per cent	1-5
Road surface texture	Smooth concrete (low texture)	to	grooved concrete (deep texture)	5-6
Surface water	Dry surface	to	wet surface	1-10
Absorption by road surface*	Pervious surface	to	non pervious surface	~ 3

\+ not normalised to a passby speed of 100 km/h
* normalised to the same value of skidding resistance

It was found that speed has the greatest influence, with tyre noise levels increasing by 9 to 13 dB(A) per doubling of speed, depending on the tyre and road surface combination. An examination of the effects of tyre design (ie tread pattern, tyre construction and materials), and road surface design (ie surface texture and pattern and acoustic absorption qualities), showed that each of these factors generally affected the noise levels by less than 3 dB(A), except for load, surface texture and the effect of water which produced, typically, 5-10 dB(A) changes.

A pervious macadam surface with a porous wearing course was found to offer distinct advantages for both wet and dry surface conditions. This was attributed to the good drainage qualities and high acoustical absorption afforded by this surface.

3. SOURCES OF TYRE NOISE

The results of research reported by other workers have indicated several possible sources of tyre noise. These include noise from vibration of the tyre surface and wheel hub, the pressure fluctuations caused by pumping of air in the tread grooves in the contact patch[2] and noise from aerodynamic effects originating close to the surface of the wheel[3].

This section reports the results of an analysis carried out with the objective of establishing the relative importance of these sources of tyre noise.

3.1 Tyre Vibration

The tyres tested were rib-patterned (5 ribs) radial-ply tyres similar to the lorry tyres used as part of the parametric study.

Miniature accelerometers (2g) were attached to the sidewall, shoulder and in a tread groove of one of the outside rear tyres of the lorry. A magnetic disc was also attached to the tyre between the transducers which operated on a magnetic sensor to give information on the rate of rotation of the wheel and the position of the accelerometers relative to the tyre/road surface contact patch.

Vibration signals from the accelerometers were relayed to an FM tape recorder via a multichannel slip ring assembly attached to the wheel hub.

The test method adopted was virtually the same as employed previously. The driver of the lorry was asked to achieve target speeds ranging between 30 and 100 km/h on each of the test surfaces studied. Noise levels were monitored at a receiver located at a standard distance of 7.5 metres from the vehicle's path and signals from the accelerometers and magnetic sensor were relayed to the FM recorder which was installed in the cab of the vehicle.

3.1.1 Results. Figure 2 shows typical oscillograms of vibration amplitudes recorded in the tread, shoulder and sidewall for approximately 2 revolutions of the tyre when the vehicle was travelling at 64 km/h. The oscillograms clearly show the distinct rise in vibration amplitude as the region of the tyre tested passes through the contact patch. The greatest amplitudes were recorded in the tyre tread.

Figure 3 shows the 1/3rd octave sound level spectra obtained at the trackside microphone position for a passing speed of 81 km/h on the motorway surface together with the equivalent vibration levels recorded on the tyre surface. It can be seen that the sound level spectra and the tyre acceleration level spectra had similar shapes, both spectra were broad band with a peak level occurring at approximately 800 Hz.

3.1.2 Evaluation of the magnitudes of noise induced by tyre vibration. The similarity between the vibration frequencies excited in the tyre surface and the sound signals recorded at the tracksidemicrophone supports the contention that tyre vibration is, at least, a contributing factor governing the overall levels of tyre induced noise. In order to determine the extent of this contribution, ie to examine whether the recorded vibrational energy in the tyre is capable of producing sound signals of similar magnitudes to those observed, a theoretical evaluation of tyre vibration induced sound has been attempted.

Details of the formulation of the model are given in a previous publication[4]. Briefly , the tyre was considered to comprise of two vibrating components, the tyre tread and the sidewall, the latter including the shoulder and bead. An attempt was made to calculate the sound contribution from the components using a separate model surface for each, whose surface area was equal to that of the surface of the tyre being considered. The model surface eventually chosen was an oscillating sphere. The choice was influenced partly by the relative simplicity of calculation and partly by the similarity of behaviour of the radiating sphere and the lorry tyre. Both the sphere and tyre surfaces were poor radiators of low frequency noise.

The vibration levels on the surfaces of the spheres were calculated from an average of the rms velocity levels recorded at each of the tread and sidewall transducer positions. Each velocity input was determined by averaging arithmetically the 1/3rd octave band rms acceleration levels recorded at 20^{o} intervals around the tyre and then converting the average acceleration to velocity levels at the band centre frequency.

The averaged velocity levels were then used as input to the sphere model and the resulting sound field calculated at the trackside microphone position.

Figure 4 compares the combined sound levels calculated for the tyre with measured sound levels at the trackside microphone position.

The figure shows that the vibrating sphere model produced theoretical levels which were close to the observed trackside levels particularly at frequencies below 1000 Hz. Above 1000 Hz the model tends to progressively underpredict the observed levels. However, even with this underprediction of sound levels at higher frequencies it is quite clear that a spherical surface with the same area as the tyre vibrating with similar amplitudes and frequencies can produce sound levels of similar magnitudes to those observed at the trackside microphone position. This result taken together with the observed similarity between the tyre vibration and trackside sound level spectra (Fig. 3), gives further support to the suggestion that tyre vibration is the principal factor controlling the overall levels of tyre noise emission.

3.2 Wheel hub vibration

To investigate whether the wheel hub was acting as a radiator of noise originating from, say, the vehicle transmission, lead-lined shields were fixed to the rims of the rear wheels. Acoustic foam was attached to the inside face of the shields to reduce resonances in the enclosed air space and foam rubber was used to fill up the spaces between the edge of the shields and the rims of the wheels.

It was found that the overall reductions in sound level caused by the hub shields was small, eg less than 1 dB(A) at a passing speed of 80 km/h, consequently, the radiation of noise by the wheel hub was not considered to contribute significantly to the overall noise levels.

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3.3 Air pumping

Air pumping refers to the action of compression of air circulating in the tyre tread during contact with the road surface and the subsequent release of this pressure as the tread elements emerge from the contact zone. The pressure fluctuations caused by 'air pumping' has been suggested as a possible cause of tyre noise[2].

In order to determine the approximate contribution to tyre noise of air pumping in the contact patch region, an experiment was devised which modified the air flow in the tyre grooves without affecting other aspects of performance of the tyre. To restrict the air flow, the rib tyre on the outer offside rear wheel of the lorry was modified by filling the tread grooves with an acoustic foam material. The foam was a fairly dense closed cell structure sufficiently light to avoid altering the natural vibration of the tyre. Coasting noise was measured close to the treated tyre using a microphone mounted on a boom attached to the lorry.

It was found that by adding the foam material the overall sound levels were changed by less than 1 dB(A).

3.4 Tyre noise source location using noise barriers

A study of source location was carried out using noise barriers. The barriers were constructed with railway sleepers (0.25 m high and 0.13 m wide) which were laid on the road surface as close as possible to the path of the nearside wheel with a length of approximately 23 metres. The barriers were built up in steps of 0.25 m to a height of 1 metre approximately, and recordings of noise spectra were taken after each layer had been added.

The results showed that band level frequencies above 1.5 kHz were not markedly affected by increasing the barrier height beyond 0.25 m, whereas frequencies below 1 kHz were attenuated progressively at each stage.

This result was consistent with the observation that tyre surface vibration was the principal source of tyre noise since tyre vibrations, at high excitation frequencies, are more localised to the lower portions of the tyre and were, therefore, well screened by the first layer of the barrier. The lower frequency vibrations were found to be more evenly distributed over the tyre surface and greater barrier height was, therefore, needed to screen these frequencies.

4. TYRE SLIPPAGE AND TYRE VIBRATION - AN EVALUATION OF TYRE EXCITATION

This section is concerned with describing the motion of the tyre in the region of contact with the road and the effect of this motion on the generation of tyre surface vibration. The discussion attempts to account for tyre vibration by drawing comparisons between the degree of tyre slippage in the contact patch and the noise levels generated by the rolling tyre.

4.1 Longitudinal and lateral slippage

Tyre slip occurs whether or not a tyre is cornering, braking severely, driven or allowed to roll freely. As a tyre rolls freely and flattens in the contact patch, the continually changing radial deflection produces tangential forces between tyre and road apart from those produced by torque. These forces are resisted by frictional adhesion and tyre stiffness and any residual forces are dissipated by slip of the tyre material over the road surface. The greatest slip velocities tend to occur towards the rear of the contact zone and are caused by the increasing velocity of the tread elements as they emerge from the contact patch and the tyre returns to its undeflected rolling radius.

The bending of the sidewalls in the flattened region cause an inward lateral displacement, again, resisted by frictional adhesion between the tyre and road surface and stiffness of the tyre material, and lateral slip then occurs where the opposing forces do not balance.

4.2 Tangential excitation of the tyre by tyre slippage

The sliding of tread elements in the contact patch is controlled by friction forces between the tyre and the road surface. During relative sliding between a polymer and a hard base, the separate chains in the surface layer attempt to link with molecules in the hard base, forming local junctions. Sliding causes these bonds to stretch, rupture and relax before new bonds are made, so that effectively the elastomer molecules jump a molecular distance to their new equilibrium position. Thus a cyclic 'stick-slip' process on a molecular level is fundamentally responsible for frictional adhesion[5].

As the degree of slip becomes very large as in locked wheel braking or severe cornering, sound levels, often of large magnitudes, can occur. Investigation of tyre squeal have established that a slip of the tread elements in the contact patch is responsible for tyre vibrations which give rise to the observed sound levels.

Examination of the sliding processes in the tyre contact area is supplemented in the literature by contributions concerning fundamental tests on rubber specimens. Schallamach[6] has examined the slipping process using a hemispherical rubber block and a transparent glass plate. Wavelike movements were observed in the contact area which were attributed to local lifting of the rubber under the action of the sliding forces as adhesion is overcome. Kummer and Meyer[7], have also examined the sliding process of a rubber block over a smooth glass surface. They observed that as the sliding speed increases, adhesion forces diminish and, above a critical sliding speed, intermittent sound emission occur. They also found that as the degree of slip increased the magnitude of the emitted sound levels also increased.

These experiments demonstrate the importance of slip in the contact area of the tyre in determining tyre vibrations and hence audible air pressure fluctuations. However, slip alone cannot give rise to tangential excitations of the tyre. It is rather the combination of slip of the tread elements as adhesion is lost followed by the build up of the hysteresis frictional force as deformation of the tread occurs, which gives rise to the vibration input. In practice, the cyclic 'slip-stick' processes occurring in the contact patch are complex and are not coherent so that at normal tyre rotation speeds the vibrations produced are observed as continuous and not discrete bursts of energy.

4.3 Comparisons of the factors affecting tyre slippage and tyre noise

In order to test the hypothesis that tyre noise is associated with tyre friction and, in particular, the velocity of slip in the contact zone, it is useful to compare trends in both tyre slippage and tyre noise levels resulting from variations in both tyre and surface design and operating characteristics of the vehicle.

The parameter study indicated that increasing the rolling velocity of the tyre had a marked effect on tyre noise for all tyre/surface combinations studied. Increases of the order of 10-22 dB(A) were observed over the vehicle speed range 30-100 km/h. Similarly, as the rolling velocity of the tyre increased, the frictional adhesion between the tyre and the road surface decreased, so that slip in the contact zone also increased progressively with increasing vehicle speeds.

Increasing the depth of tread or road surface pattern also gives rise to increasing noise levels. Increasing the profiling of the tyre tread reduces adhesion of the tyre material with a dry road base and, hence, tends to promote slip. The profiling of tyres also leads to greater elasticity of the contact area compared with the smooth tyre so that a greater deflection of the tread rubber is possible. Further, increasing the texture or pattern on a road surface also tends to reduce the adhesion component of surface friction yet increases the hysteresis component and the associated deformation of the tyre tread. Consequently, by increasing the patterning of the tyre and/or the road surface, greater slip velocities are induced, partly by reducing the adhesion qualities of the contact and partly by increasing the mobility of the tyre rubber.

With respect to tyre construction, it was found that radial tyres were quieter than equivalent cross or diagonal-ply tyres. In operation, the diagonal plies flex and rub producing a wiping action between tread and road known as 'tread shuffle' which is one of the main sources of tyre wear. With the radial tyre, flexing of the sidewalls involves no relative movement of the plies and tyre wear is greatly reduced. A comparison between diagonal-ply and radial tyres has shown that under similar operating conditions the tread motion in the contact area is greatly reduced for the radial tyre despite the fact that the radial tyre has lower longitudinal and lateral stiffness. Therefore, the lower noise levels produced by radial tyres are also consistent with the lower slip velocities encountered in the tread contact area.

Finally, increasing the size of the tread contact patch by, for example, increasing the wheel loading has been shown to give rise to increased tyre noise levels. Increasing the wheel loading also gives rise to greater deformation of the tyre during contact, with the result that both lateral and longitudinal slip increase. Similar changes in tyre slip occur with reduced inflation pressure of the tyre or reduced diameter of tyre. Again increases in tyre noise have been observed following reductions in inflation pressure and tyre diameters although these experiments were not reviewed in the parameter study of this paper.

Clearly, there is a considerable degree of consistency between changes in tyre/surface friction and, in particular, tyre slippage in the contact patch and the changes in noise level for the various tyre, road surface and vehicle parameters studied. These observations, therefore, support the contention that tyre vibration induced by tangential excitations of the tyre tread in the contact region is fundamentally responsible for tyre noise generation.

5. CONCLUSIONS

The following main conclusions can be drawn from this study:

1. The noise produced by lorry tyres rolling on a range of road surfaces was affected mainly by the rolling speed of the tyre: tyre noise increased at between 9 to 13 dB(A) per doubling of speed depending on the tyre and road surface condition.

2. Other factors which significantly affected tyre noise were tyre tread and road surface pattern, tyre construction (radial or cross-ply), acoustic absorption of the road surface and the presence of surface water.

3. The main source of tyre noise was tyre surface vibration. A simple theoretical model relating tyre vibration with tyre noise levels was found to give good agreement with noise levels measured at the trackside. Other sources of tyre noise including air pumping and wheel hub vibration were not found to contibute significantly to tyre noise.

4. It is suggested that tyre vibration is controlled by the degree of slip of the tread elements in the contact region during rolling which, in turn, is controlled by frictional adhesion between the tyre and road surface and the deformation of the tyre tread in the contact region.

6. ACKNOWLEDGEMENTS

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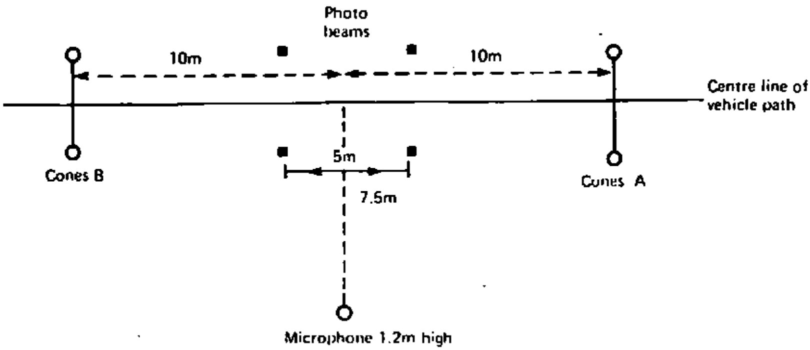

Fig. 1 Plan of test site for coasting noise tests

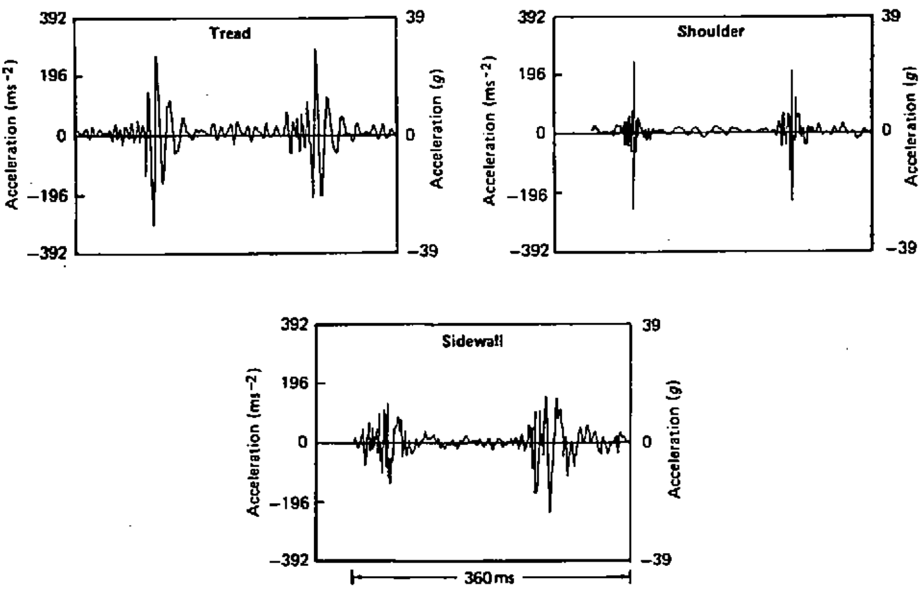

Fig. 2 Oscillograms of typical tyre surface vibration signals
(Vehicle speed = 64km/h)

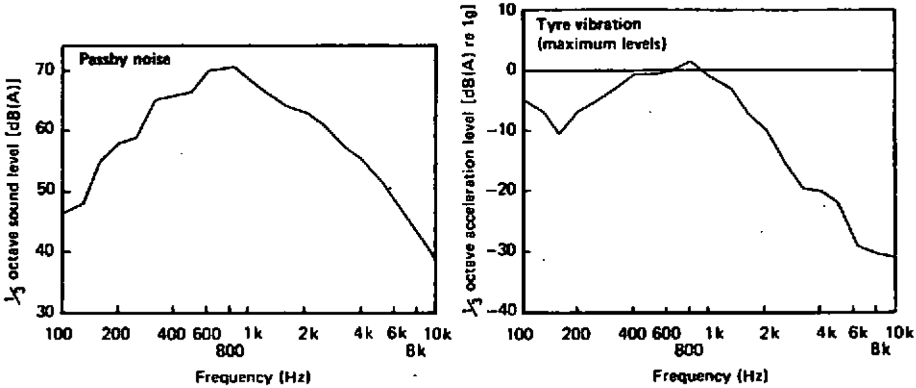

Fig. 3 ⅓ Octave band tyre vibration levels and passby noise (81 km/h on motorway surface)

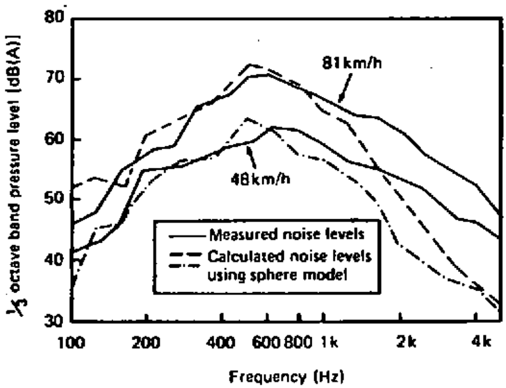

Fig. 4 Comparison of measured and calculated sound levels for passing speeds of 48km/h and 81km/h on motorway surface