

Tire / Pavement Noise 101

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Outline

Introduction

Noise paths

Noise measurement methods

Noise generation / transmission mechanisms





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What is Noise?

Sound is a pressure variation in the air that travels from a source (e.g., tire / pavement) to a receiver (e.g., your ear)

Noise is any undesirable sound

Annoyance from the noise can be accentuated by volume and / or tonal content

Tire / pavement sound can be beneficial (i.e., not noise) in some cases — e.g., a pedestrian or bicycle rider hearing an oncoming vehicle before attempting to cross the road

Noise levels are typically reported in the unit of decibel (dB or dB(A))





What is dB?

Our ears hear the change in amplitudes of the sound pressure (i.e., the loudness) in a nonlinear fashion

The dB scale is a logarithmic function of the sound pressure to account for this

Sound Level
$$[dB] = 20 \times log_{10} \left(\frac{Pressure [Pa]}{0.00002 [Pa]} \right)$$

A 1-3 dB change is just noticeable

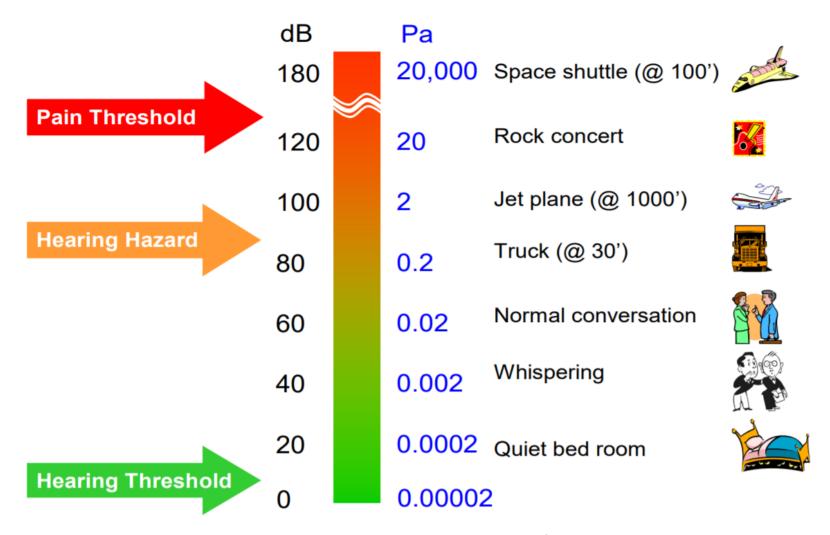
Doubling the sound pressure amplitude is a 6 dB change

If the sound pressure amplitude increases 10 times, this is a 20 dB change





Factor of 10 Changes in Sound Pressure





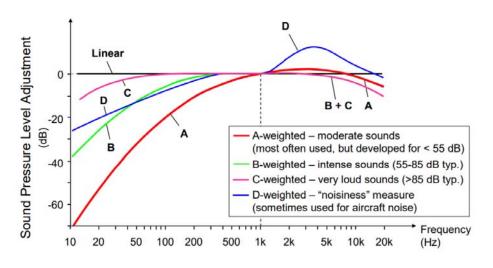


What is dB(A)?

Our hearing has less sensitivity to lower frequency sound than higher frequency sound

The dB(A) scale is a frequency-dependent adjustment of the dB scale to reflect this nonlinearity in the perceived loudness of the sound

 Low frequency sound levels are reduced in the dB(A) scale compared to the dB scale



The Little Book of Quieter Pavements, FHWA-IF-08-004, July 2007





Vehicle Noise Sources

Several sources of noise for a vehicle driving on a road

- Power Train (Engine, transmission, exhaust)
- Aerodynamic (Wind, air moving around the vehicle)
- Tire / pavement





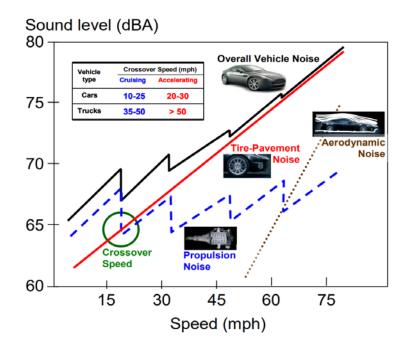


Vehicle Noise Sources

At low vehicle speed, power train noise is dominant (for non-electric vehicles)

At higher speeds, tire / pavement noise is dominant

The speed at which tire / pavement noise becomes dominant is higher for trucks than for cars



The Little Book of Quieter Pavements, FHWA-IF-08-004, July 2007





Tire / Pavement Noise

The pavement by itself does not make noise, so it can't be called pavement noise



The tire by itself does not make noise, so it can't be called tire noise



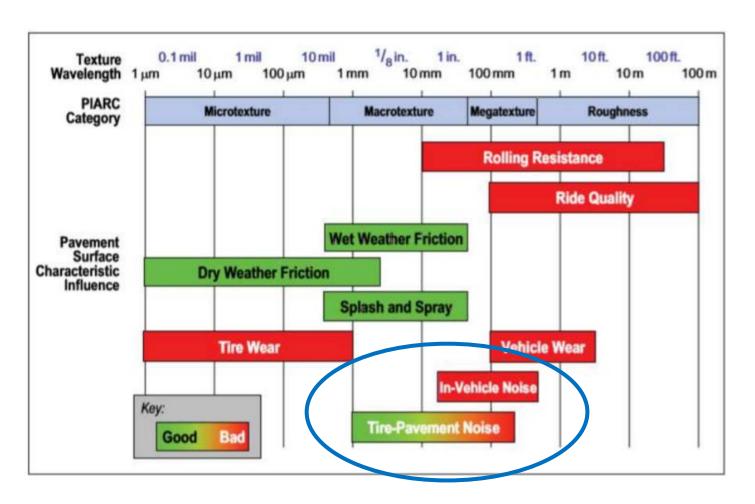
It is when the tire is rolled over the pavement that noise occurs, and so is properly called tire / pavement noise







Pavement Texture Effects

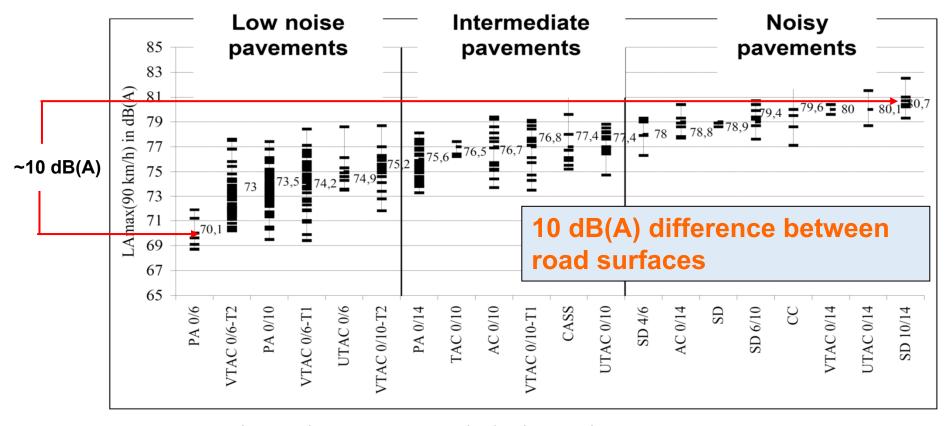


ISO, "Characterization of Pavement Texture by Use of Surface Profiles - Part 2: Terminology and Basic Requirements Related to Pavement Texture Profile Analysis," in ISO 13473-2, 2002.





Range of Noise Amplitudes by Pavement



low-noise pavements: 0/6 and 0/10 porous asphalt (PA), 0/6 and 0/10 type 2 very thin asphalt concrete (VTAC), 0/6 ultra-thin asphalt concrete (UTAC);

intermediate pavements: 0/14 porous asphalt (PA), 0/10 asphalt concrete (AC), 0/10 thin asphalt concrete, 0/10 very thin asphalt concrete (VTAC), cold-applied slurry surfaces (CASS);

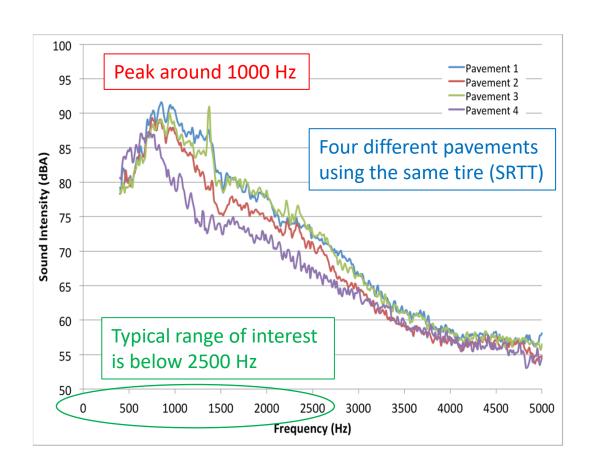
noisy pavements: 0/14 asphalt concrete (AC), surface dressings (SD), cement concrete (CC), 0/14 thin asphalt concrete and 0/14 ultra-thin asphalt concrete (UTAC).





Frequency Content of Tire / Pavement Noise

To help with assessment, the noise is often plotted as a function of its frequency content





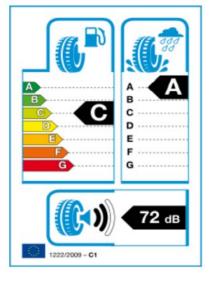


Noise Regulations

In the USA, there are government regulations for radiated noise that are imposed on the pavement industry, but none for the tire or vehicle companies

In Europe and some other countries, radiated noise (i.e., passby noise) requirements are imposed on the vehicle companies, and is part of the tire labeling

requirement







Tire Noise Requirements

Worldwide, OE vehicle manufacturers specify noise and vibration requirements for tires developed for their vehicles

- Noise and vibration levels and quality sensed by the vehicle driver and passengers inside the vehicle
- Not pass-by noise





Tire / Pavement Noise Goal

Reduce to an acceptable level the noise experienced by those

- Living and working near the roadways
- Inside the vehicles

DOT's, pavement, tire and vehicle industries all have a role in meeting this goal

Each of these stakeholders have different means to contribute to attaining the goal, as what they have the ability to control and modify in the noise generation and transmission system differs





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Noise measurement methods

Noise generation / transmission mechanisms





Tire / Pavement Noise Paths

There are two main paths of concern for noise created at the tire / pavement interface

- Radiated to the environment (passby noise)
 - Concern of government regulators and people living alongside the highways
- Transmitted to the vehicle driver and passengers
 - Concern of OE vehicle manufacturers and people inside the vehicles





Radiated to the Environment

Airborne noise radiated from the source to those near the roadway

Attenuated by distance and any obstacles (trees, buildings, sound walls, etc.)

This is the noise of interest to the pavement and highway industries and government agencies







Transmitted Into the Vehicle

There are two paths for the generated noise to get into the vehicle's passenger compartment

- Structure-borne through the tire, wheel, suspension, and other vehicle structural components
- Airborne through the air and then into the vehicle compartment through the windows or other vehicle panels







Structure-borne Into the Vehicle

Structure-borne noise passing through the tire and vehicle structure is typically below 400 Hz

Can be attenuated by tire and suspension damping and any other sound proofing put into the vehicle by the manufacturer

Can initiate other noise by exciting passenger compartment components (rattle and squeak, air cavity resonance)







Airborne Into the Vehicle

Airborne noise is typically over 400 Hz

Can be attenuated by closing the windows, and by any other sound proofing put into the vehicle panels by the manufacturer







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Tire / Pavement Noise Measurement

Tire / pavement noise measurement is of importance to pavement, highway, vehicle and tire industries and associated government agencies

However, their reasons for performing the testing are different, which affects the methods used

Pavement / highway industry: Assess the noise levels of pavement surfaces

 Measurements of public traffic flow, or for a standard tire/vehicle on pavement surfaces of interest

<u>Vehicle / tire industry</u>: Assess the noise levels of vehicle and / or tire designs

 Measurements of the vehicle or tire designs on standard pavement surfaces





Tire / Pavement Noise Measurement

Various measurement locations are used in recording noise levels, depending on the desired response

- Far field at a distance from the roadway, tire / vehicle
- Near field close to the tire / pavement interface
- Interior vehicle at driver or passenger locations

Measurements are also made to determine the vibration transmission function through the tire and vehicle paths (structure-borne and airborne) into the passenger compartment

 The noise transmission function is frequency dependent, and so some tones pass more readily than others, affecting the sound heard inside the vehicle compartment





Far Field Noise Measurement

Two approaches in far field noise measurement are used Roadway noise measurement

- Used to assess or grade the noise generated from a roadway due to passing traffic
- Performed via measurements made along side the roadway for a given period of time

Tire / vehicle noise measurement

- Used to assess or grade a particular tire and/or vehicle pass-by noise performance
- Performed via measurements made for a single vehicle on a specified pavement surface under controlled speed and ambient conditions





Measurements performed in areas located near an existing or proposed highway that are deemed to be noise sensitive



Vehicle counts, ambient weather conditions and vehicle speeds may also be required to help in interpreting and reporting the noise results

Microphone(s) are placed at one or more desired location(s) or distance(s) from the roadway to record the sound generated from passing vehicle(s) (e.g., near housing, 7.5 m, 15 m, etc.)

Microphones are placed at a specified height

- 5 feet, to approximate human ear level
- 3.9 feet, to approximate vehicle level
- 12 feet



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The sound is recorded for specific vehicles passing (for light traffic conditions) or over a desired time period to capture typical traffic noise at the location (e.g. 5 minutes, 90 minutes, 24 hours, worst noise hour, etc.)

Recorded sound includes all vehicle noise, not just the tire / pavement noise

The recorded sound history is then analyzed to report an appropriate noise quantity in the time period





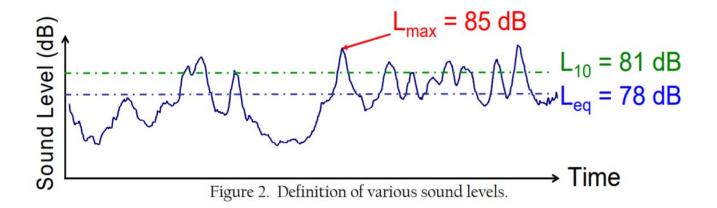


Several measures of the recorded noise are used

L_{max} – maximum sound level in the recording period

 L_{xx} – sound level which is exceeded xx% of the time

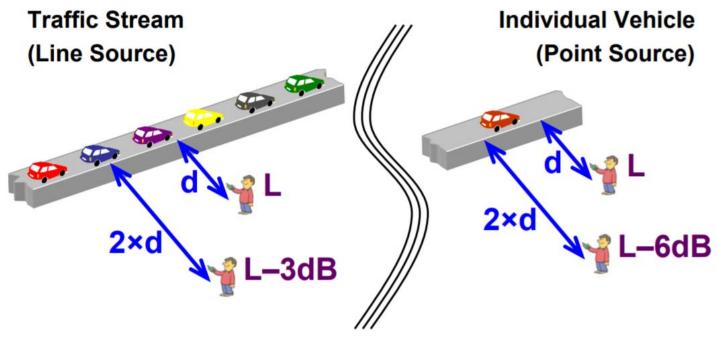
$$L_{eq}$$
 – equivalent sound level = $\frac{\sum sound\ energy}{measurement\ time}$





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The measured far field noise level is dependent on the amount of traffic passing and the distance from the roadway





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Tire / Vehicle Noise Measurement

Performed by tire and/or vehicle manufacturers, and possibly government agencies, to assess products in meeting government requirements or desired performance levels

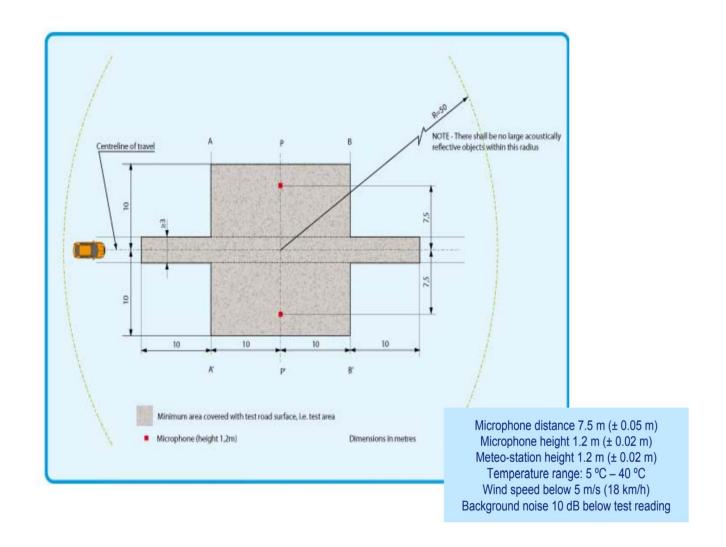
Standard measurement procedures are used (e.g., ISO 362) on a specified road surface (e.g., ISO 10844)

- Vehicle speed, acceleration,
- Sublayer and test surface type (dense asphalt, binder, aggregate, air void, etc.), construction and maintenance tightly controlled
- Mean surface profile of 0.5 mm ± 0.2 mm over the test length
- Ambient conditions (wind speed, account for temperature)





ISO 362 Tire / Vehicle Noise Measurement







Tire / Vehicle Noise Measurement

Tests are performed for the particular vehicle and/or tire designs for acceleration and constant speed conditions

Measured sound contains all vehicle noise, not just the tire/pavement noise

Maximum sound level (in db(A)) is reported

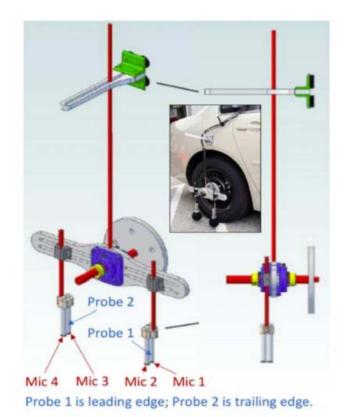
To focus on tire/pavement noise, the vehicle coasts past the microphone positions with the engine off (i.e., no drive train noise). Vehicle aerodynamic noise is still included in the measurements.





Near Field Noise Measurement

To focus on tire / pavement noise, microphones are placed near the tire / road interface at the leading and trailing edges of the tire footprint



OBSI – On-Board Sound Intensity measurement system

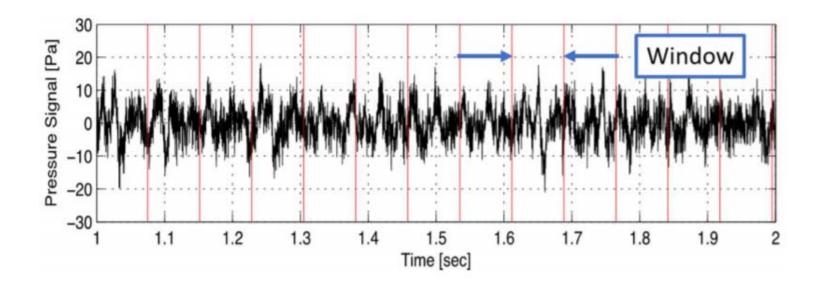
Because there are two microphones at each position, sound directionality can be determined





Near Field Noise Measurement

Vehicle is driven over the road surfaces of interest and noise measurements are recorded

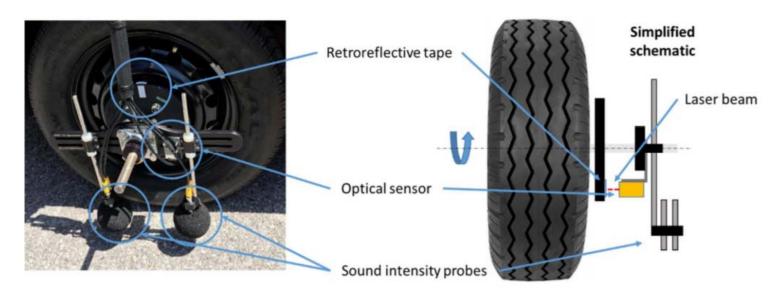


Use of a once-per-revolution sensor allows windows of data to be identified to further investigate the noise signal and separate tire from non-tire sourced noise





Separating Tire & Pavement Noise



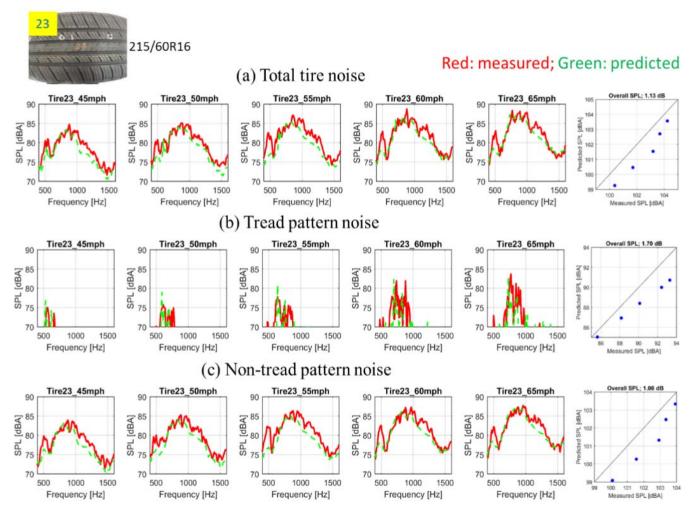
"A Machine-Learning Based Tool to Predict Tire Noise Using Both Tire and Pavement Parameters", Lucas Daniel Spies, Masters Thesis, Virginia Tech, May, 2019

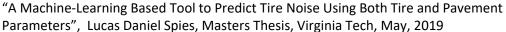
The once per revolution repeating signal (due to the tire) is mathematically separated from the non-repeating signal (due to the pavement)





Separated Tire & Pavement Noise









Interior Vehicle Noise Measurement

Vehicle and tire companies are very interested in the noise coming into the vehicle driver and passengers

Microphones are placed close to the ear locations of a person at the seat position









Interior Vehicle Noise Measurement

The vehicle is driven over specially selected road surfaces to measure the sound and assess the vehicle and/or tire performance

Medium coarse road surface



Coarse road surface









Interior Vehicle Noise Measurement

Special binaural microphone systems are available to measure the sound

Allows assessment of the sound as how a person's two ears will hear it (loudness, frequency content, and directionality)

Aachen head binaural noise measurement system (Head Acoustics)







Subjective Interior Vehicle Noise Assessment

Vehicle and tire companies also employ specially trained driver evaluators to subjectively rate the sound as they drive the vehicle over the selected road surfaces

Test surfaces and procedures are specified by the OE vehicle manufacturer, and are different from one company to another

Specially constructed road surfaces with different roughness, cracks and joints are made at the vehicle manufacturer's test facility to provide repeatable test conditions for noise assessment





Subjective Interior Vehicle Noise Assessment

Ratings of various noise characteristics are given by the evaluator for the sounds arising from driving over the various road surfaces - loudness and sound quality

The specified noise characteristics are defined by the vehicle manufacturer.

Some examples of noise characteristics they have named that occur at different frequency ranges:

• Thump

Whine

Slap

Howl

• Boom

Sha

Roar

Sizzle

Growl

• Etc.

Ping





Lab Noise Measurement

Vehicle and tire companies also perform tire noise measurements in their semi-anechoic chambers

Tire is rolled on a large drum (typically 10 foot diameter) with specified surface roughness characteristic









Rough Asphalt

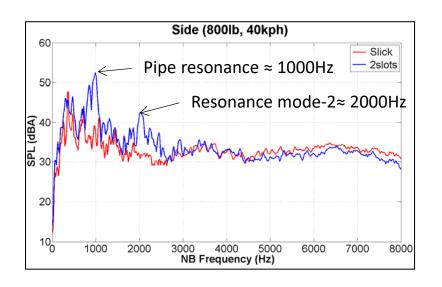
Vehicles can also be tested in the lab on the drums





Lab Noise Measurement

Far field or near field microphone measurements are made of the airborne noise to assess tire designs for noise generation performance



Noise signals as a function of frequency from two tires

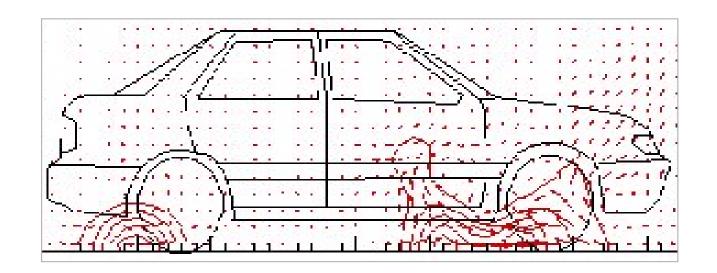
- slick (i.e., no tread pattern)
- with simple tread slots

Wheel hub force or acceleration measurements can also be made for structure-borne noise transmission assessment



Lab Noise Measurement

An array of microphones at set positions can be used for noise source identification







We're Halfway Through Any Questions So Far?





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Tire / Pavement Noise Mechanisms

There is not one single source of tire / pavement noise, but rather several mechanisms are at play that generate the noise that is heard

These mechanisms can be influenced by the features of the road surface and design of the tire

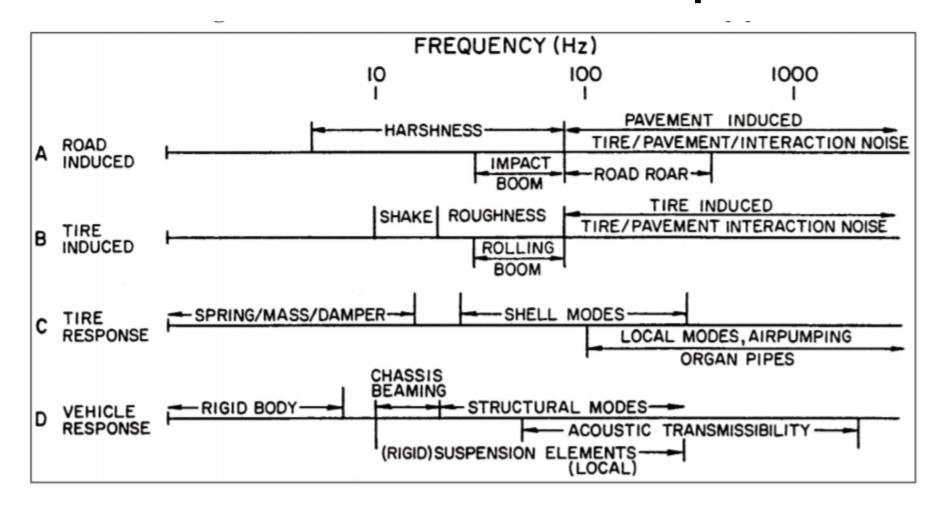
For internal vehicle noise, its content and loudness is also influenced by

- How well the vehicle transfers the sound (i.e., though the tire, wheel, suspension, and other internal vehicle systems and sound proofing)
- Whether other passenger compartment components are excited and create sound (e.g., rattle and squeak, air cavity resonance)





Pavement / Tire / Vehicle Aspects



The Pneumatic Tire, Edited by A. N. Gent & J. D. Walter, U Akron, Published by the National Highway and Traffic Safety Administration, US Department of Transportation, DOT Contract DTNH22-02-P-07210, August 2005





Tire / Pavement Noise Mechanisms

Noise generation mechanisms

- Impact
- Stick / slip
- Stick / snap
- Air pumping
- Pipe resonance
- Helmholtz resonance
- Air turbulence

Noise amplification mechanisms

- Horn effect
- Tire resonance
- Tire air cavity resonance



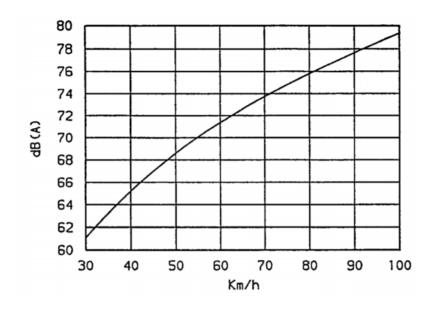


Effect of Speed

Vehicle speed is a major factor in the noise generated

Sound Level =
$$a \log_{10}(v) + b$$

where v is the vehicle speed and a and b are constants







Effect of Speed

The effect of speed has also been found to be dependent on the noise generation mechanism:

Sound Level =
$$10 n \log_{10}(v) + b$$

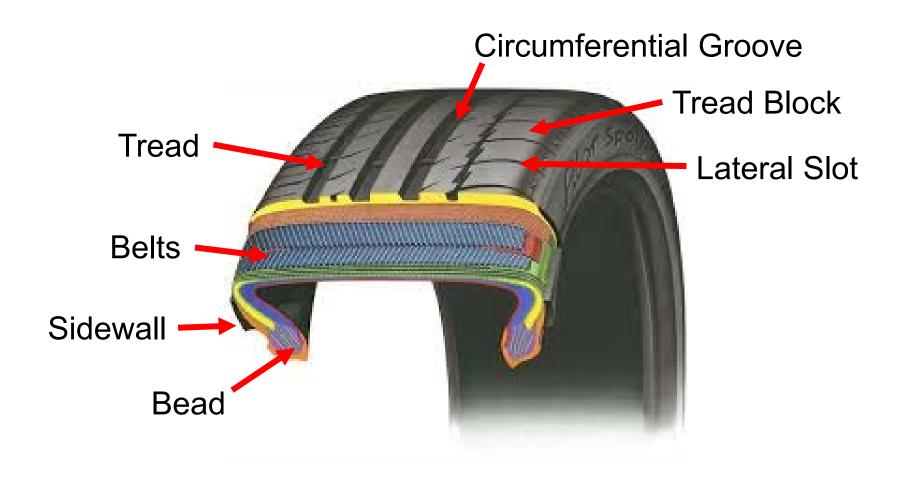
TPIN Mechanism	Speed Exponent
Tread Impact	2.0-3.0
Texture Impact	3.0-3.5
Stick/Slip (Friction)	3.0-5.0
Stick/Snap	3.0-5.0
Air Pumping	4.0 - 5.0
Air Turbulence	5.0-6.0
Pipe Resonance	0.0
Helmholtz Resonance	0.0

Kuijpers, A.; van Blokland, G. Tyre/road noise models in the last two decades: A critical evaluation. In Proceedings of the Inter-Noise, The Hague, The Netherlands, 27–30 August 2001; p. 2494.





Tire Definitions







Tire Definitions







Tire / Pavement Noise Mechanisms

Noise generation mechanisms

- Impact
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- Helmholtz resonance
- Air turbulence

Noise amplification mechanisms

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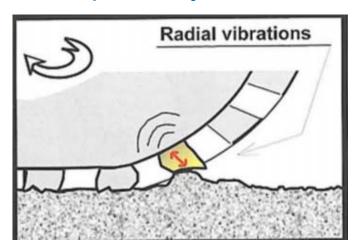


Impact Mechanism

Noise is generated by tire / pavement impacts

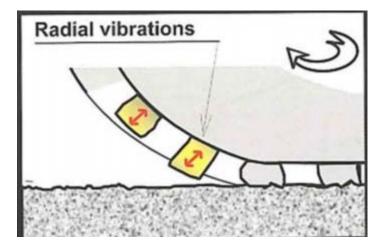
Pavement texture impacts

- Roughness
- Cracks
- Expansion joints



Tire tread pattern impacts

Pattern design



Noise is from the impact, and also from exciting the tire's structural and air cavity resonances





Pavement Impact Example

Extreme example of pavement impacts – rumble strips



Groove spacing is nearly equal, so noise is very tonal

Good to alert the driver, but irritating to others

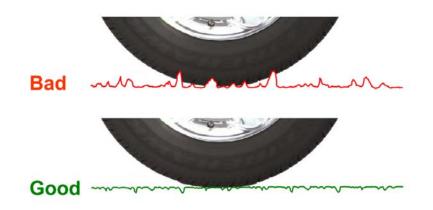




Pavement Impact Reduction

To reduce pavement impact noise, improve road surface smoothness (i.e., lower macrotexture)

- Smooth repairs
- Minimize expansion joints
- Keep any larger surface texture roughness negative



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Softer pavements are also beneficial

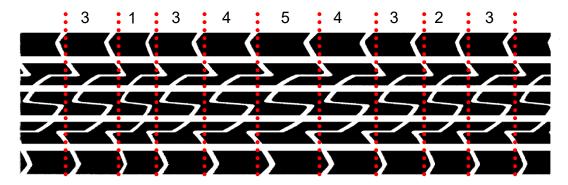




Tread Pattern Impact

Tread patterns are designed to randomize the impact

- Number of tread blocks around the circumference
- Number of different block sizes
- Relative ratio of sizes
- Sequence of the block sizes around the circumference



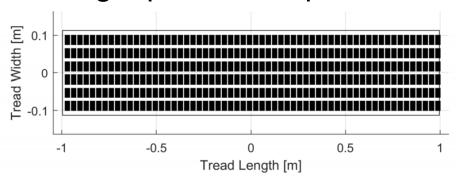
Computer analyses are run for these tread pattern features before the tire is made to minimize the noise



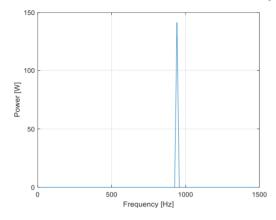


Tread Pattern Impact Reduction

Single pitch tread pattern

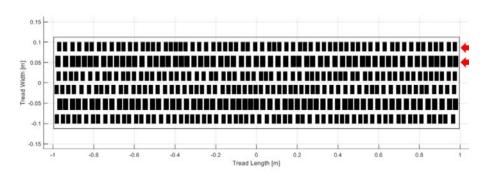


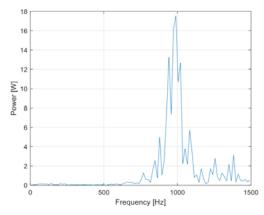
Sound Power vs. Frequency



Single tone sound

Multi- pitch tread pattern





Multiple frequency sound at much lower amplitude

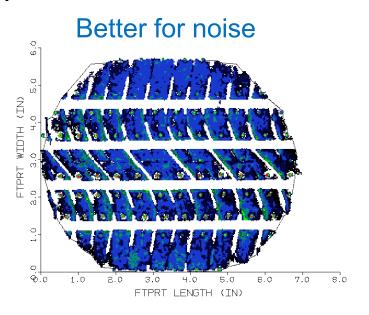


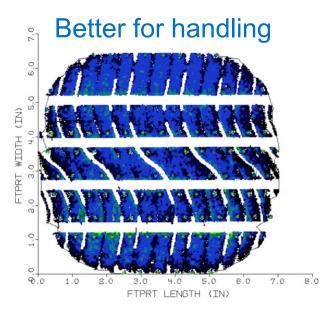
"A Wave Propagation Approach for Prediction of Tire-Pavement Interaction Noise", Sterling McBride, PhD Dissertation, Virginia Tech, August, 2019



Tread Pattern Impact Reduction

Rounding the leading edge of the footprint lessens the impact, and hence the noise





Changing the lateral slot angles in the tread pattern, so they do not match the footprint leading edge, can also reduce the impact level and noise, as well as softer tread rubber

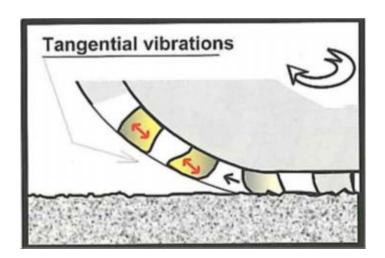




Stick / Slip Mechanism

Noise is generated by

- The tire tread block slipping on the pavement surface
- The tread block vibrating after leaving the footprint



A "slip zone" is always present at the trailing edge of the footprint, and can increase in area due to cornering or braking





Stick / Slip Example

Extreme examples – creating squeal noise:

- Taking a corner too fast
- Hard braking
- Too rapid acceleration







Stick / Slip Reduction

Pavement surface improvements to reduce stick / slip noise:

 Increase friction level – see Tire / Pavement Friction & Grip 101 presentation by Brian Schleppi

Tire improvements to reduce stick / slip noise:

- Increase friction level (tread rubber hysteresis and adhesion)
- Increase tread pattern stiffness (block geometry, rubber stiffness)

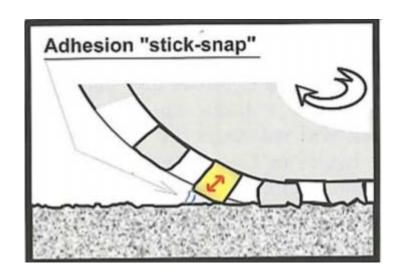




Stick / Snap Mechanism

Noise is generated by the tire tread blocks pulling off the road surface

- Adhesion "pop" when the tread block releases
- Tread block vibration after contact is released







Stick / Snap Reduction

Pavement surface improvements to reduce stick / snap noise:

 Stick / snap noise is more likely to occur on very smooth pavement surfaces, so increase the pavement surface microtexture

Tire improvements to reduce stick / snap noise:

- Decrease tread rubber adhesion property
- Changing tread block geometry or rubber stiffness can change the resonant frequency

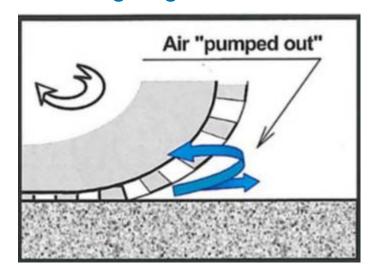




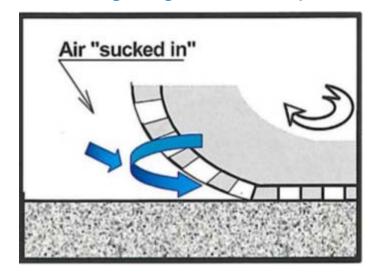
Air Pumping Mechanism

Noise is generated by air being moved in and out of the tread pattern grooves and slots as they deform when entering and leaving the footprint

Leading edge – slots close



Trailing edge – slots open



The mechanism can be likened to how sound is made when whistling





Air Pumping Reduction

Pavement surface improvements to reduce air pumping noise:

 More porous pavements will provide an alternative path for the air, and be non-reflective

Tire improvements to reduce air pumping noise:

 Changing tread slot geometry or rubber stiffness can change air channel deformation





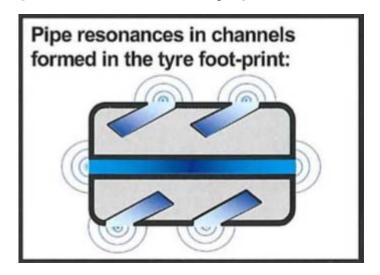
Pipe Resonance Mechanism

Similar to the sound generation mechanism in organ pipes

The resonance can occur as the air moves in or out of the lateral slots of the tread pattern as they pass through

the footprint





The frequency of the sound is dependent on the geometry of the slots

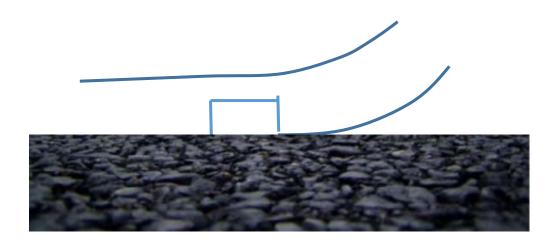




Pipe Resonance Reduction

Pavement surface improvements to reduce the pipe resonance noise:

 Porous pavements or increased macrotexture (especially negative) can change the air channel, and hence the amplitude of the noise







Pipe Resonance Reduction

Tire improvements to reduce the pipe resonance noise:

- Tread pattern lateral slot geometries can be altered to change the resonant frequency
 - Slot width
 - Slot depth
 - Slot curvature
 - Multi-angled along length



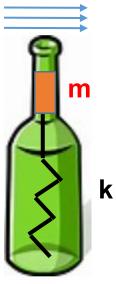






Helmholtz Resonance Mechanism

Air moving across an opening to a contained volume can create a resonance, as in blowing across the opening of a bottle



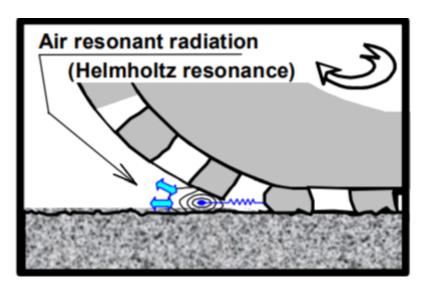
The air in the neck of the bottle acts as the mass and the air below it in the bottle acts as the spring, creating a resonant sound





Helmholtz Resonance Mechanism

Air moving across the tread pattern slots at the trailing edge of the footprint as the slot opening lifts off the pavement can likewise create a resonant sound



The air just outside the tread pattern slot acts as the mass and the air inside the slot (still in contact with the pavement) acts as the spring





Helmholtz Resonance Reduction

Pavement surface improvements to reduce the Helmholtz resonance noise:

The resonance amplitude can be lessened by a porous pavement

Tire improvements to reduce the Helmholtz resonance noise:

- The resonant frequency can be altered by modifying the tread pattern slot geometry (width, thickness)
- The resonance phenomena can also be altered by changing the slot geometry to change the air movement characteristics



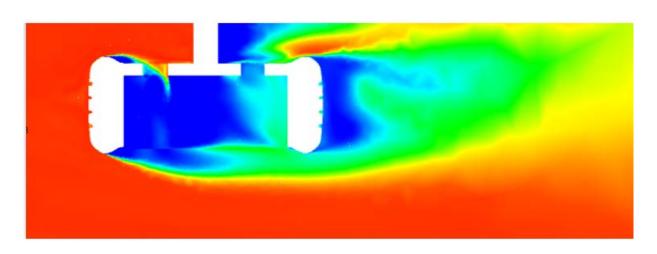


Air Turbulence Mechanism

Not strictly a tire / pavement noise source

Noise is generated by the turbulence of air moving over the surface of the tire and wheel as they rotate and move along the roadway

Can be a significant noise source at highway speeds



Predicted air pressure flow around a tire / wheel model

"Investigation on the Modelling of Tire Rotating Using Computational Fluid Dynamics", Fu, G. and Untaroiu, A., Proceedings of ASME Fluids Engineering 2020, Orlando, FL, June 20-26, 2020





Tire / Pavement Noise Mechanisms

Noise generation mechanisms

- Impact
- Stick / slip
- Stick / snap
- Air pumping
- Pipe resonance
- Helmholtz resonance
- Air turbulence

Noise amplification mechanisms

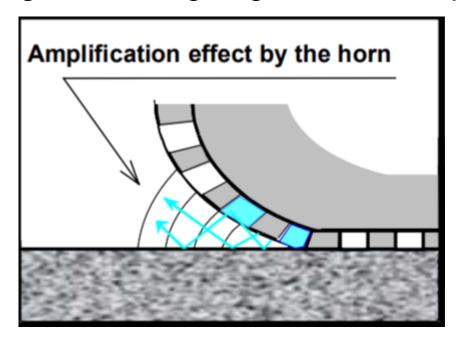
- Horn effect
- Tire resonance
- Tire air cavity resonance





Horn Effect Mechanism

Noise is amplified due to the reflection of the sound waves in an air wedge formed by the tire and pavement at the leading and trailing edges of the footprint



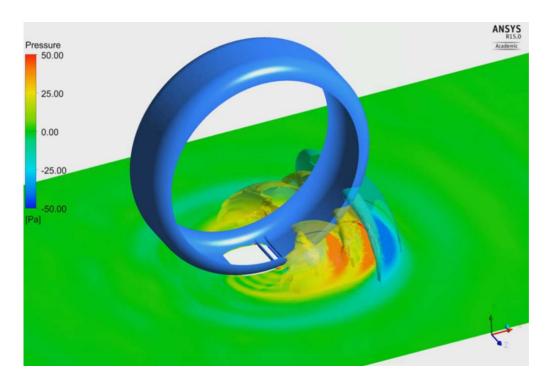
The amplification is greater for sound radiating in the fore / aft directions

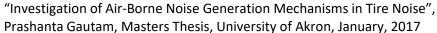




Horn Effect Example

Computer simulation of radiated sound amplification as a single lateral tread slot has just rotated out of the footprint and another is still within the footprint









Horn Effect Reduction

Porous pavements, or pavements with included rubber or other polymers, can reduce the noise amplification by absorbing rather than reflecting the sound waves, in much the same way as soundproofing panels in concert halls or anechoic chambers





Narrower tires will lessen the size of the horn, reducing the noise amplification



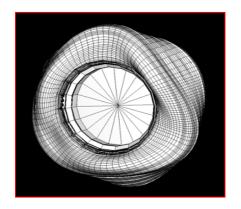


Tire Resonance Mechanism

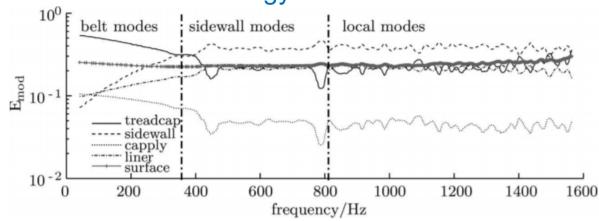
Tire and pavement impacts can excite tire and wheel resonance modes

- Aid transmission of the vibration and noise into the vehicle (especially radial and fore/aft modes)
- Radiate noise to the environment (especially modes with tire sidewall out-of-plane motion)

3rd radial mode



Energy of tire modes



REFERENCE: Brinkmeier, M. and Nackenhorst, U., "Computational Investigations on the Dynamics of Tires Rolling on Rough Roads," *Tire Science and Technology*, TSTCA, Vol. 37, No. 1, January – March 2009, pp. 47-59.





Tire Resonance Reduction

Attempt is made to tune the tire's natural frequencies away from those in which the vehicle transfer is sensitive

Tire natural frequencies and modes are controlled by the

tire stiffness and mass

- Tire size and cross-section shape
- Component thicknesses
- Belt angles
- Material moduli

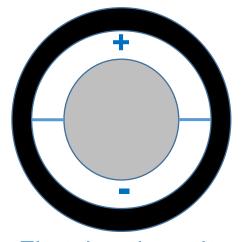
Vibration transmission through the tire can be reduced by increasing the damping (i.e., more hysteretic rubber compounds)



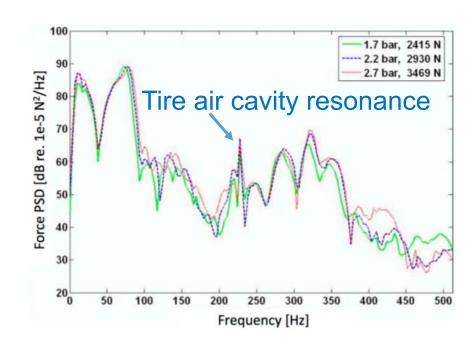


Tire Air Cavity Resonance Mechanism

Tire and pavement impacts can also excite the tire air cavity resonances, adding to the vibrations transmitted into the vehicle



First tire air cavity mode -approximately 200 - 250 Hz



Transmission sound is like that of a highly inflated basketball (ping)



Tire Air Cavity Resonance Reduction

Resonant frequency is controlled by the air cavity geometry (cross-sectional area and circumference)

Cavity vibration amplitude can be reduced by adding foam material along the inner tire surface

This is effective for reducing structure-borne noise transmitted into the vehicle, especially if the vehicle is sensitive to the tire cavity resonance frequency

This noise source is of less importance to radiated airborne noise





Wrap-up

Tire / pavement noise reduction can improve the comfort of those living or working near heavily traveled roadways, and has captured the attention of government rule makers around the world

The noise is also a concern to those inside the vehicles, and so vehicle manufacturers seek its reduction

The pavement, vehicle and tire industries all play a role in reducing the tire / pavement noise level and characteristics

Understanding the multiple mechanisms that create tire / pavement noise can help in developing strategies for its reduction





For Further Reading:

Pavement focused:

- The Little Book of Quieter Pavements, FHWA-IF-08-004, July 2007
- Noise Measurement Handbook, FHWA-HEP-18-065, June 2018
- ISO 11819 Acoustics Measurement of influence of road surfaces on traffic noise – Part 1: Statistical passby method, 2013
- AASHTO TP99, Statistical Isolated Pass-By (SIP) method, 2013 (may be a later version)





For Further Reading:

Tire focused:

- The Pneumatic Tire, Edited by A.N. Gent and J.D. Walter, NHTSA, DOT Contract DTNH22-02-P-07210, August 2005
- ISO 362-1, Measurement of noise emitted by accelerating road vehicles – Engineering method, 2015-09-15
- ISO 10844 Acoustics specification of test tracks for measuring noise emitted by road vehicles and their tyres, 2014-05-15
- A Review on Physical Mechanisms of Tire-Pavement Interactive Noise; T. Li; SAE Int. J. Veh. Dyn., Stab., and NVH; 3(2):2019, doi:10.4271/10-03-02-0007
- Influencing Parameters on Tire—Pavement Interaction
 Noise: Review, Experiments, and Design Considerations; T.
 Li; Designs 2018, 2, 124; doi:10.3390/designs2040124



