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6-12-2017

Overview of Ingard and Maling's1974 Paper on Physical Principles of Noise Reduction: Energy Considerations, Noise Reducing Elements and Sound Absorbing Materials

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Classic Papers in Noise Control

Overview of Ingard and Maling's 1974 paper on Physical principles of noise reduction: Energy considerations, noise reducing elements and sound absorbing materials

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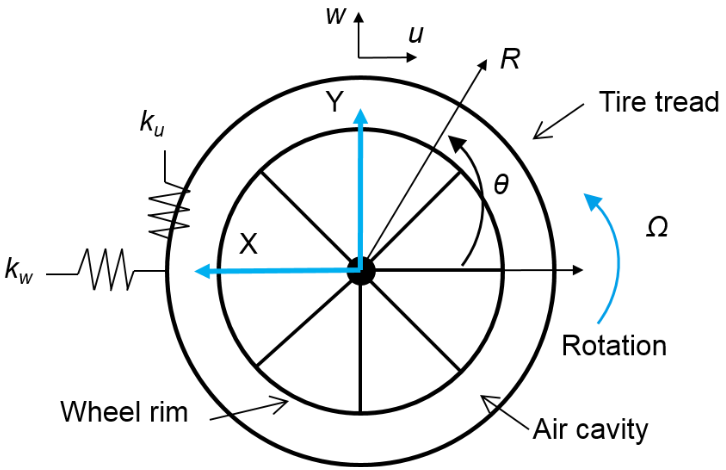
My research

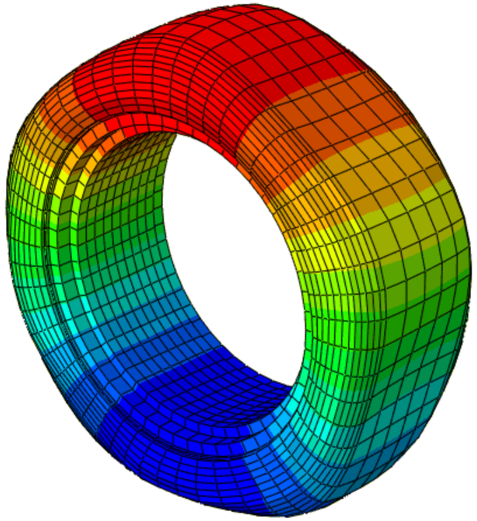
Tire noise and vibration

Analytical modeling

Testing

Finite element modeling





Paper background

This is the third in a series articles on the principles of noise reduction

Part I – Theory into practice: A physicist’s helpful view of noise phenomenon
Part II – Physical principle of noise reduction: Properties of sound sources and their fields

http://web.mit.edu/physics/images/history/classroom.jpg

http://community.bowdoin.edu/news/wp-content/uploads/2013/05/Maling52-web.png

Objective: available to engineers and other professionals in noise control field

Content

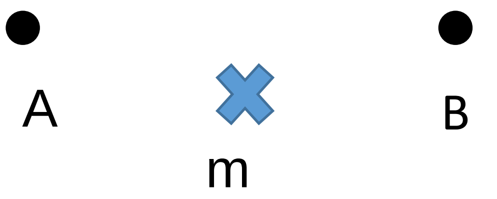
- **Noise source energy specification**
  - Motivation
  - Measurement of source strength
  - Examples of sound field calculation

- **Noise reduction specification**
  - Insertion loss/Noise reduction

- **Characteristics of noise reduction elements**
  - Partition walls and enclosures
  - Sound absorbing materials
  - Sound attenuating mufflers and ducts

Specification of noise source:

Acoustic power + Directivity pattern



$p_m \neq p_a + p_b$? Phase difference ϕ

$$p_m^2 = p_a^2 + p_b^2 + 2 p_a p_b \cos\phi$$

Uncorrelated sources $\langle \cos\phi \rangle = 0$

$$\langle p_m \rangle^2 = \langle p \rangle_a^2 + \langle p \rangle_b^2$$

$\langle p \rangle^2 \sim I$ →

$$I_m = I_a + I_b$$

Individual intensities can be added

Obtaining the acoustic power of a source

- Free space measurement – pressure measured sufficiently far from the source (anechoic chamber)
- Diffuse field method (reverberation room)

https://www.bksv.com/-/media/Images/Products/PULSE-analysis-software/acoustic-application-software/Product-noise-emission-software/TYPE-7884_1180x674.ashx

Requirement:

- Power output remains the same in another environment
- The sound field from the source in another environment can be determined from the power output

Need to accept approximate results

http://cdn.speednik.com/wp-content/blogs.dir/1/files/2015/01/5_0l_nissanraw_cam07.jpg

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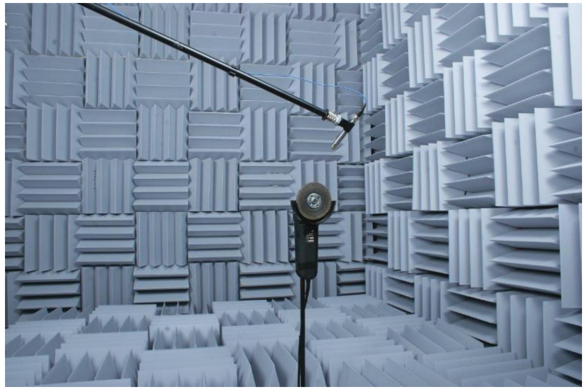

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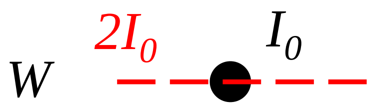
https://cdn.shopify.com/s/files/1/0105/4542/products/a4-bamboo_grande.jpg?v=1440166124

Sound intensity and power

a). Noise source in free field

$$W = 4\pi r^2 I \qquad I \sim 1/r^2 \qquad \langle p \rangle \sim 1/r$$

b). Noise source on a reflecting plane



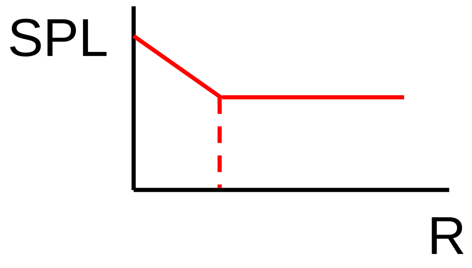
$$\Delta SPL = 10\log(2I_0 / I_0) = 10\log 2 = 3\text{dB}$$

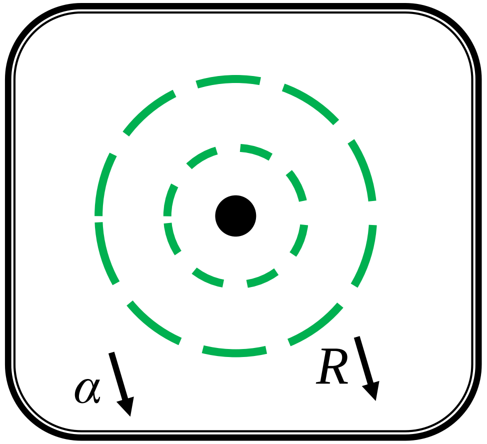
c). Noise source in a room

Near the source: $I = W / 4\pi r^2$

Near the interior surfaces: $I_r = W / (\alpha A)$

$$R = (\alpha A / 4\pi)^{1/2}$$





Noise reduction and insertion loss

A quantitative way of measuring the reduction of sound pressure

Insertion Loss $$IL = SPL - SPL'$$

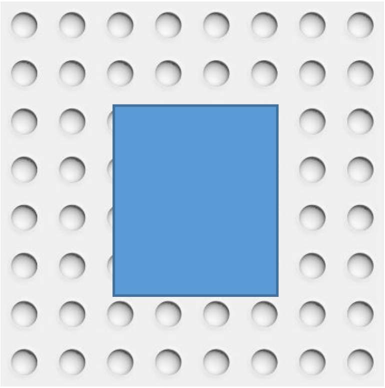
position

frequency

measurement environment

Noise reduction (NR)

- IL is not necessarily positive
- Does not necessarily imply reduction of sound power
- May depend on the source and the environment also



http://viapanels.eu/images/katalog/hole/hole.jpg

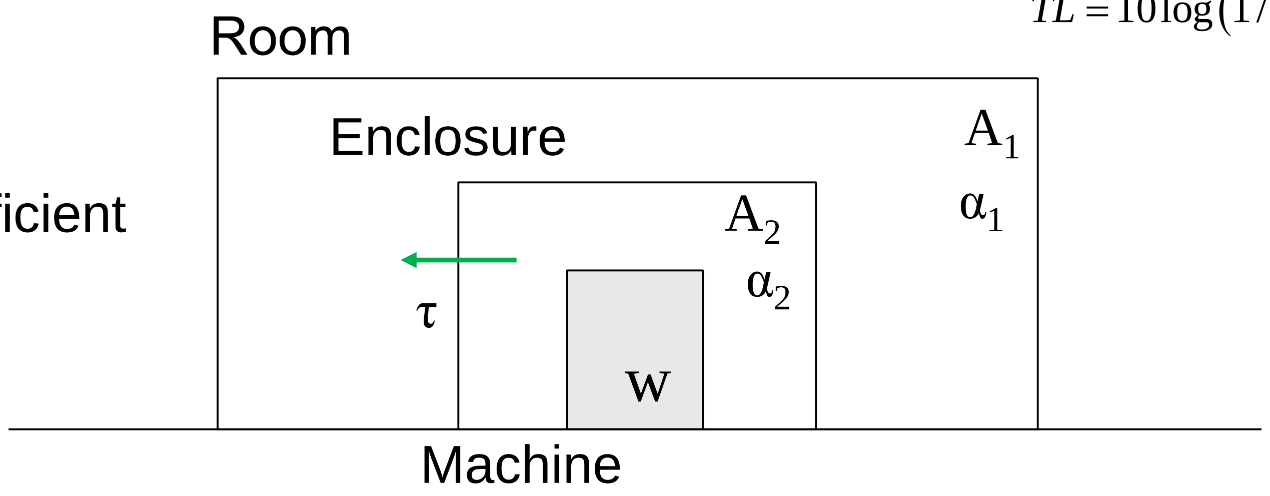
Example

Transmission Loss

$TL = 10\log(1/\tau)$

A - surface area

α - absorption coefficient



$$I_{room} = W / \alpha_1 A_1$$

$$I_{enclosure} = W / (\alpha_2 A_2 + \tau_2 A_2)$$

$$I'_{room} = \tau_2 A_2 W / (\alpha_2 A_2 + \tau_2 A_2) / (\tau_1 A_1)$$

$$IL = 10\log\left(I'_{room} / I_{room}\right) = TL + 10\log(\alpha_2 + \tau)$$

<1

$IL = 0, \alpha_2 = 0$

Cover the inside surface with absorbing material

Noise reduction methods

Noise reduction at source

- Vibrating surfaces
  - Reduce driving force
  - Preventing resonances
  - Mismatching impedances
  - Change re[illegible]ve phase
  - …
- Moving air/objects moving through air
  - Reduce discharge speed
  - Boundary layer control
  - …
  - Smooth flow
  - Splitting jet into smaller jets

Receiver

Noise reduction along paths

- Reflection
  - Partition wall, enclosures
- Absorption
  - Absorption material
  - Ducts, mufflers

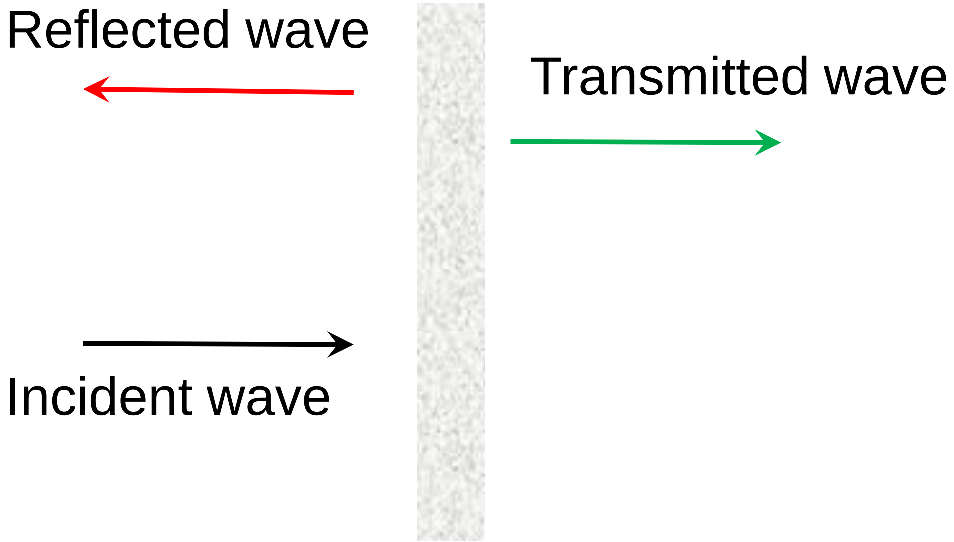
Property of noise reducing elements

Partition walls

- Reflect the incident sound, so it does not reach the observer
- A function of frequency, incident angle
- Affected by partition density, stiffness

http://www.creatif.org.uk/functions/watermark.php?filename=Leeds-PCC-1.jpg

Porous board good for insulation?

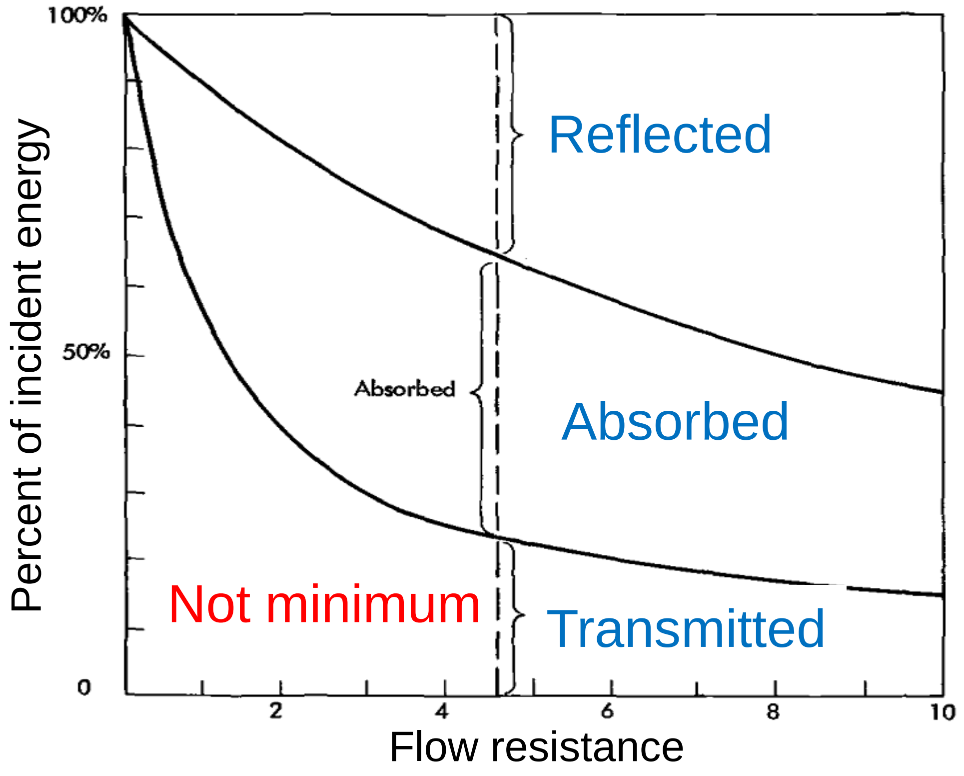


- Glass wool board
- Thickness is small compared to the wavelength
- In a diffuse sound field
- Flow resistivity is the only variable

Property of noise reducing elements

Partition walls

100 Hz

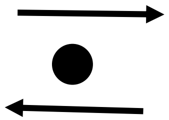


- Transmitted energy decrease rapidly with increasing flow resistance
- Reflected energy increases monotonically with flow resistance
- Absorbed energy increases to a maximum and then decrease to zero at very high flow resistance

Impervious partition for largest transmission loss (sound insulation)

Property of noise reducing elements

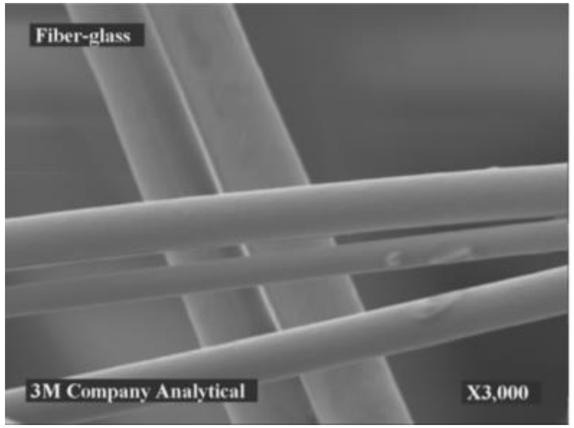
Sound absorbing material



Friction

Sound → Heat

Boundary surfaces



http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1050&context=herrick

Avg particle speed	Contact area Coef	Friction constant
u_{av}	γ	R
Flow resistivity	thickness	frequency kinematic viscosity

Power dissipated unit area $I_\alpha = R u_{av}^2 \gamma$

Incident intensity $I_i = \rho c u_i^2$

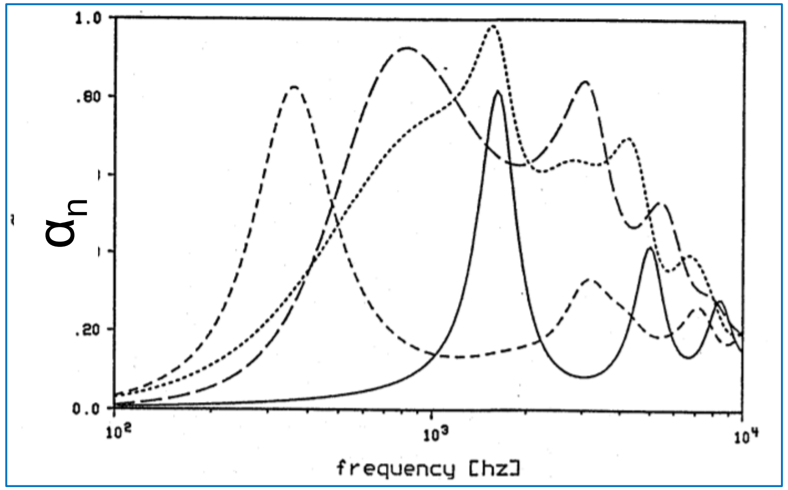
Incident angle

Absorption coefficient $\alpha = I_\alpha / I_i \cos\phi$

Sound absorbing material

$$\alpha = I_\alpha / I_i \cos\phi = \gamma \left(R/\rho c\right)\left(u_{av}^2 / u_i^2\right)\left(1/\cos\phi\right)$$

- γ ~1 for relatively smooth boundary
- $R/\rho c$ ~ 1/2500 at 400 Hz



http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1050&context=herrick

u_{av}^2 / u_i^2

- ❑ Small open area
- ❑ Resonators

- High α near resonance frequency
- Narrow bandwidth

γ

- ❑ More layers
- ❑ Porous absorber

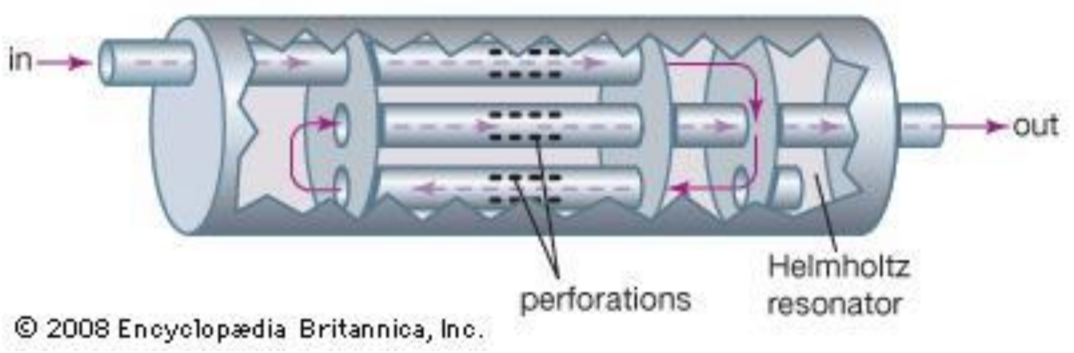
- At low frequency, mounted on rigid wall $\alpha \sim t^3 f^2$
- Optimization on rt

Sound-attenuating ducts and mufflers

- not impeding gas motion

Reactive (non-dissipative)

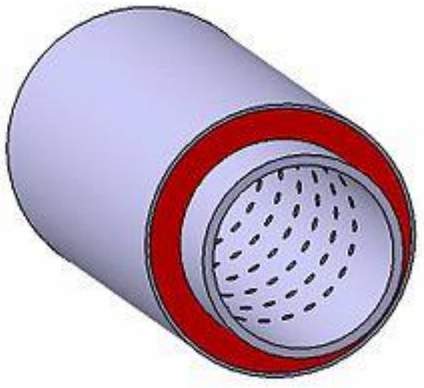
❖ Impedance mismatch at source



- Works at relatively low frequency
- Reduce source power
- Need detailed source knowledge for design

Resistive (dissipative)

❖ Sound absorptive material as linings
❖ Micro-perforated panels



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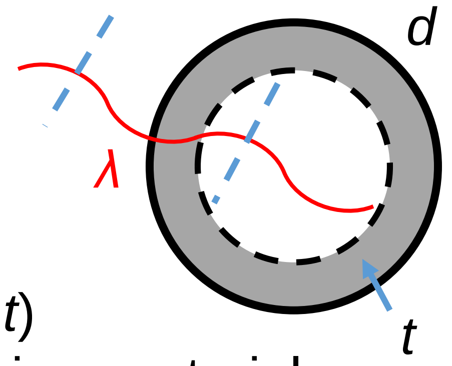
http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1125&context=herrick

Property of noise reducing elements

Sound-attenuating ducts and mufflers

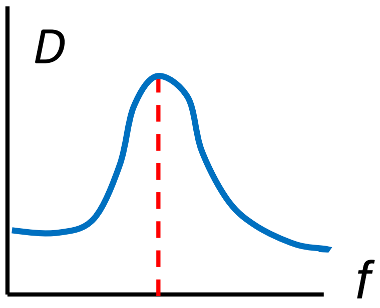
Basic design guideline – circular tube muffler

- μ – boundary conductance
- δ – pressure distribution parameter
- *C* – the part of circumference of the cross-section covered by absorption material
- *A* – duct cross-sectional area



Sound pressure level decrease per unit length: $D = 4.4(C/A)(\mu\delta)$

f ↑	μ ↑	
	δ ↓	

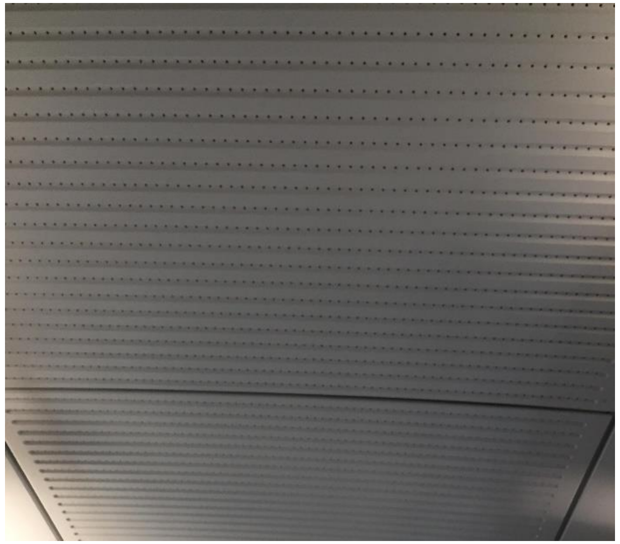


- Choice of porous lining (*r*, *t*)
- Good attenuation at λ requires material thickness > *λ/10*
- Good attenuation at λ requires *d* < *λ*

Application

- ❖ Airplane fuselage

http://www.skandiainc.com/demo.php



- ❖ High speed train ceiling

- ❖ Traffic screen

- ❖ Vehicle mufflers

https://upload.wikimedia.org/wikibooks/en/0/09/ProRacer.jpg