Urban Physics

7S0X0, Lecture A.7-2021 Quartile 3

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Urban Physics

Computing urban acoustics, I

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Contents

- Numerical versus geometrical acoustics modelling

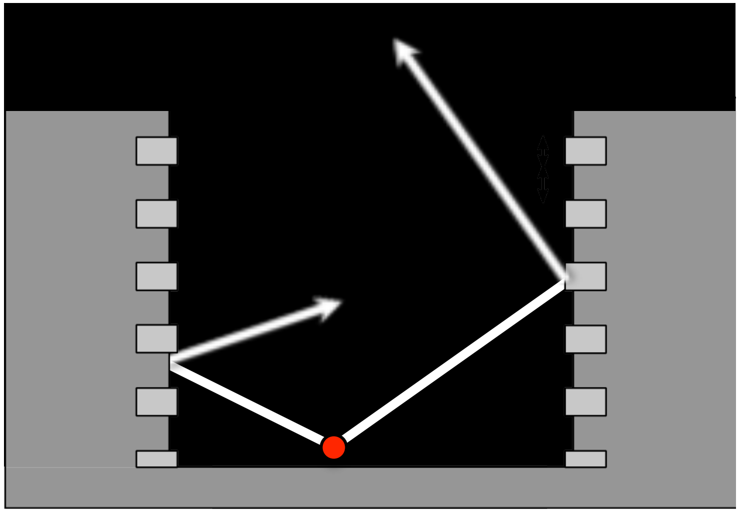
- Cnossos sound propagation model

- Sound power
- Atmospheric absorption
- Divergence term
- Screening term
- Ground reflection

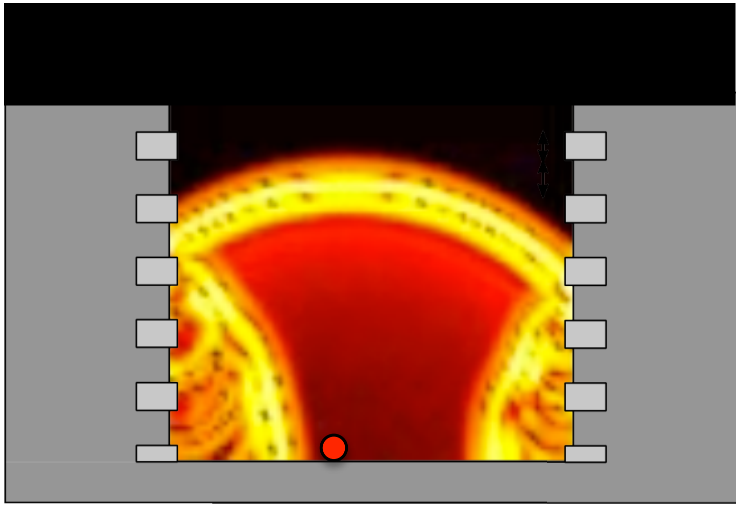
Numerical versus geometrical acoustics modelling

- Needed: Physical modelling of acoustic transfer function from source to receiver :
  - To compute noise maps of existing and future urban areas;
  - To evaluate noise abatement measures;
- All physical aspects (week 4) need to be captured
- Roughly two types of models for sound propagation

Geometrical acoustics
(including energy-based methods)



Wave-based acoustics



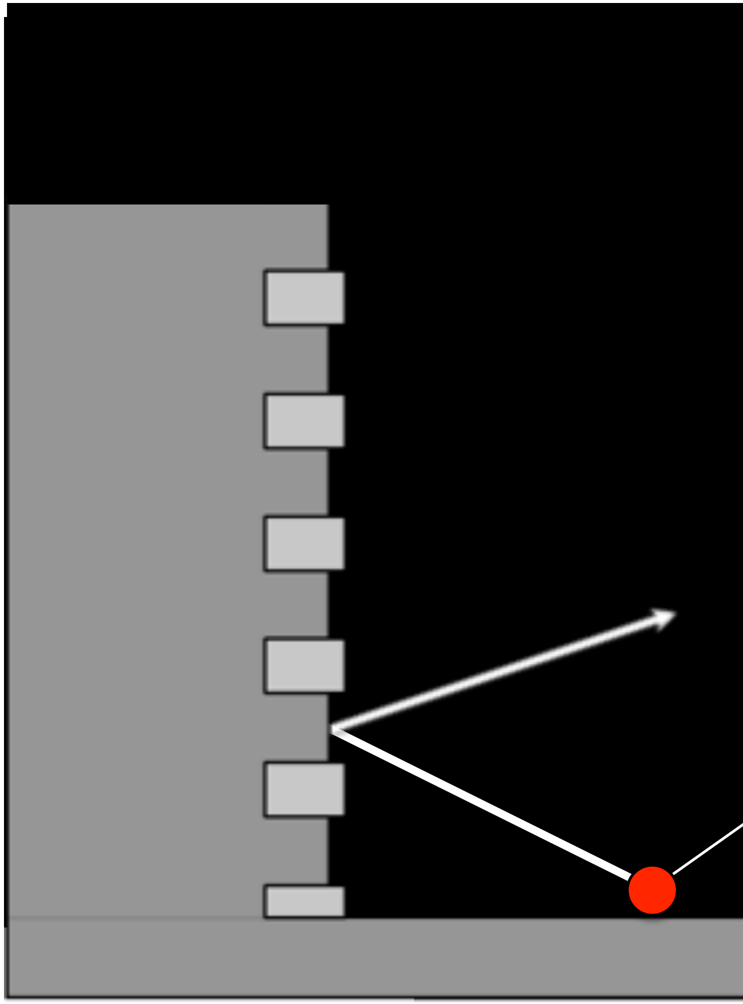
Numerical versus geometrical acoustics modelling

+ Fast
+ Complex geometry can be handled

- No implicit diffraction
- No explicitly modelled boundary media
- Interference effects limited
- Meteorological effects limited

Generally applicable for high frequencies (when waves may be approximated by rays)

Typically used for noise mapping purposes

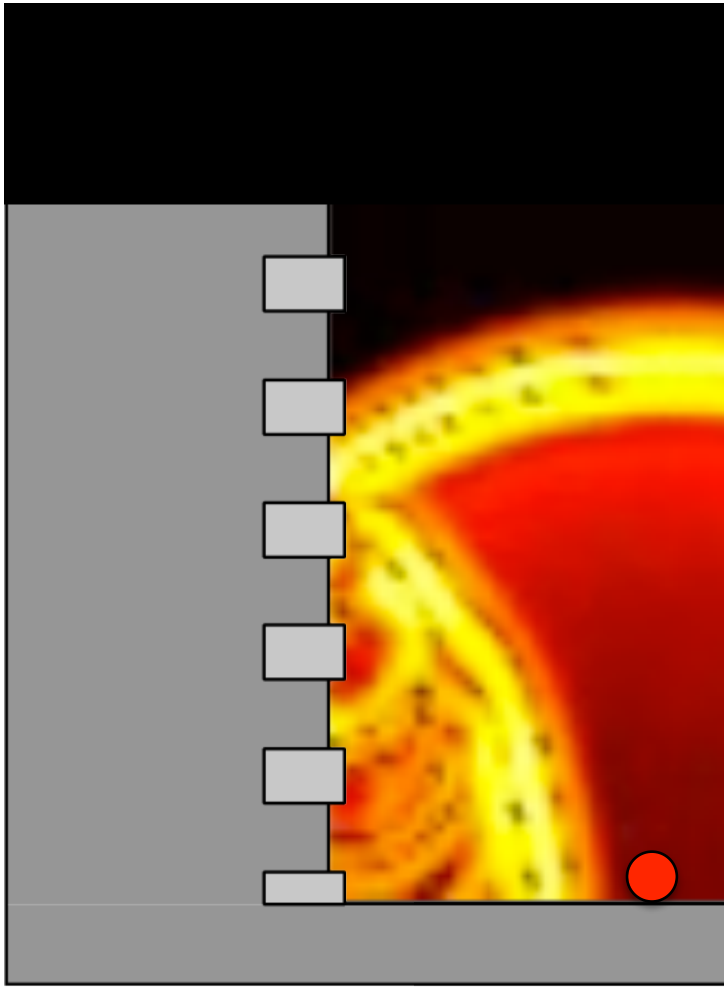


Numerical versus geometrical acoustics modelling

+ Complex geometry can be handled
+ All wave effects included
+ Boundary media modelled explicitly
+ Interference effects implicitly included
+ Diffraction implicitly included
+ Meteorological effects

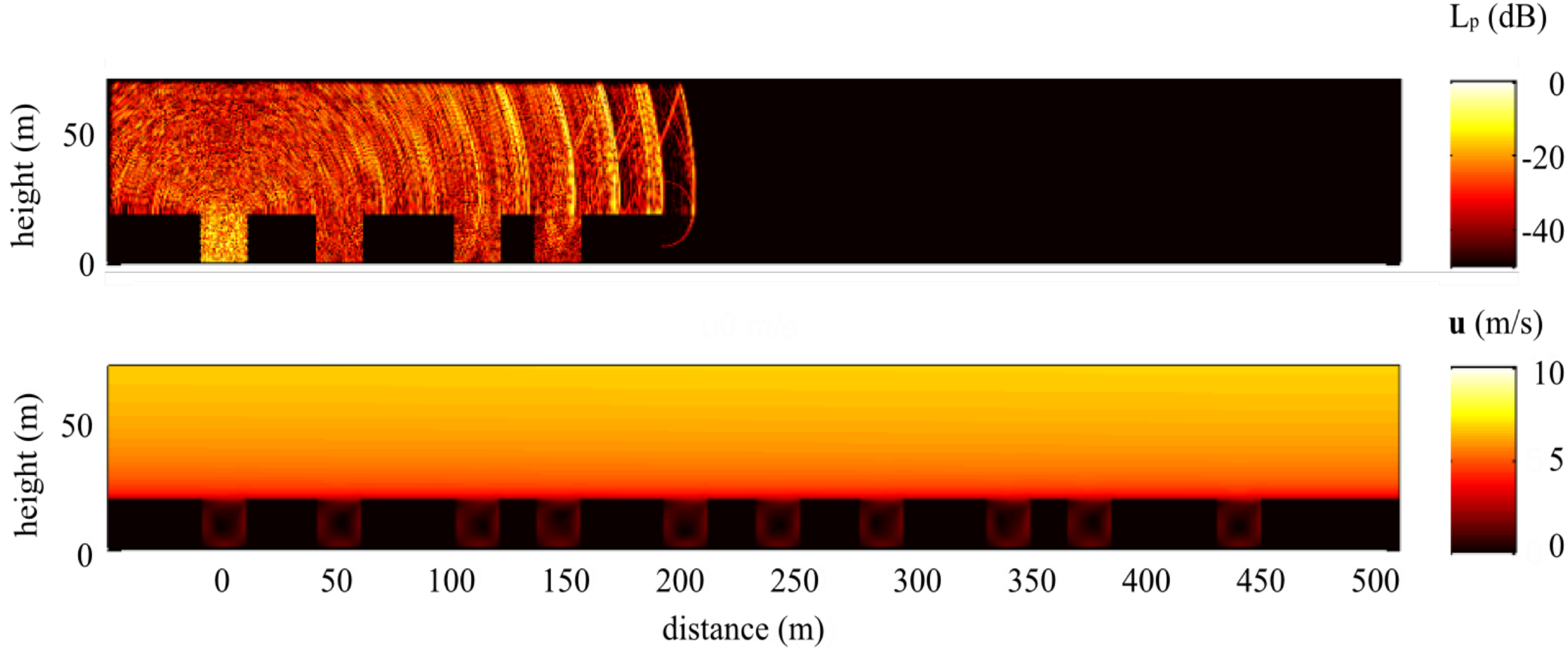
- Slow
- Detailed information at high frequencies impossible to reproduce

Typically used for complex situations and for validation of other models



Numerical acoustics modelling

- Urban topology and wind
  - Noise level difference due to downwind conditions, over roof propagation only



Hornikx, M., Dohmen, M., Conen, K., van Hooff, T. and Blocken, B., 2018. The wind effect on sound propagation over urban areas: Predictions for generic urban sections. *Building and Environment*, *144*, pp.519-531.

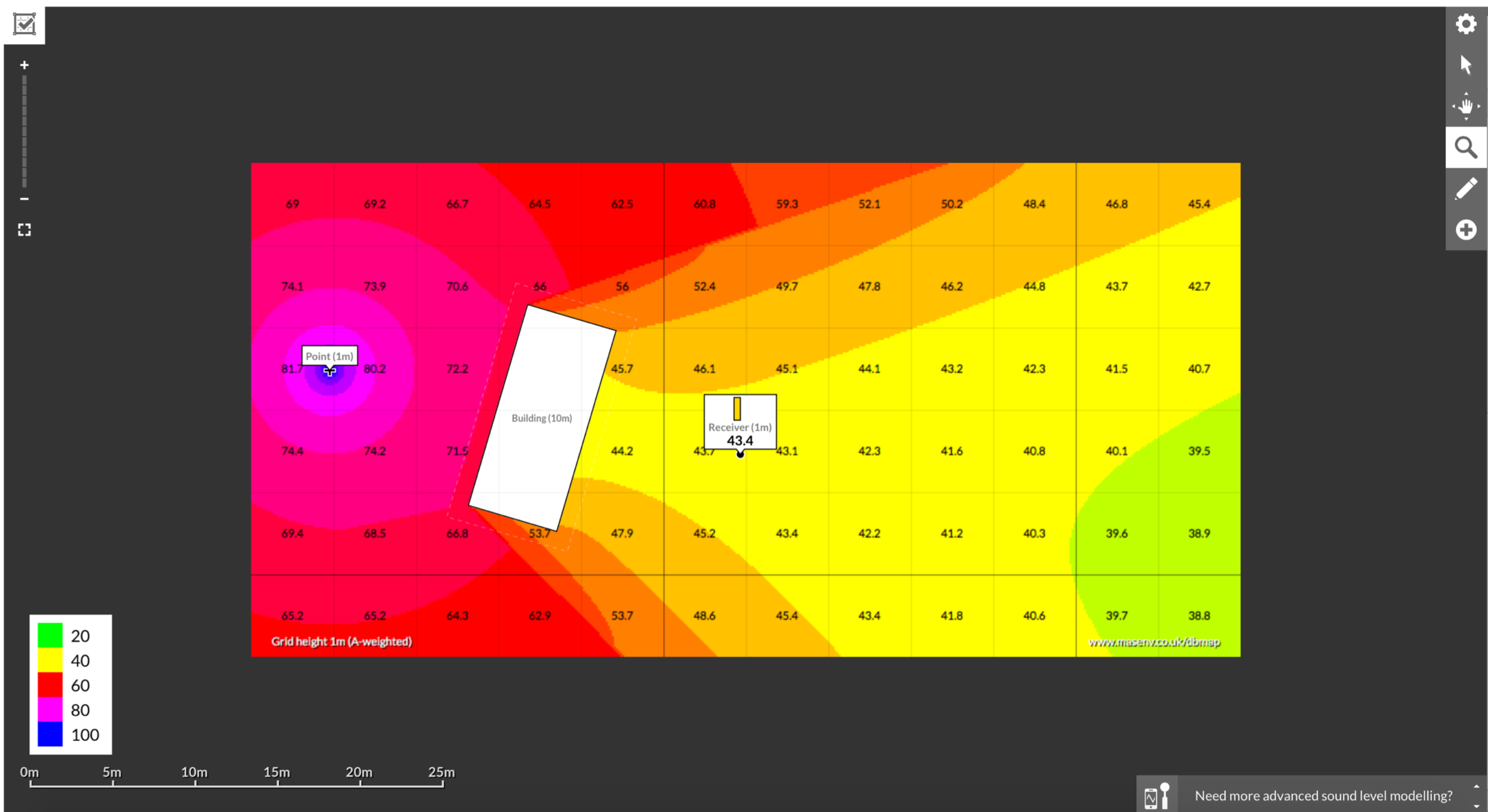
Cnossos sound propagation model

- Calculation model for noise mapping purposes
- Geometrical Acoustics model
- Developed by the European Commission in co-operation with the EU Member States
- To be used by EU Member States in the future

Common
Noise Assessment Methods
in Europe (CNOSSOS-EU)

ISO 9613 method predictions

- Calculation model for noise mapping purposes
- Similar to Cnossos model
- Online tool available



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Cnossos sound propagation model

$L_{p,n,i} = L_{w,n,i} - A_{div,n} - A_{atm,n,i} - A_{ground,n,i} - A_{dif,n,i}$

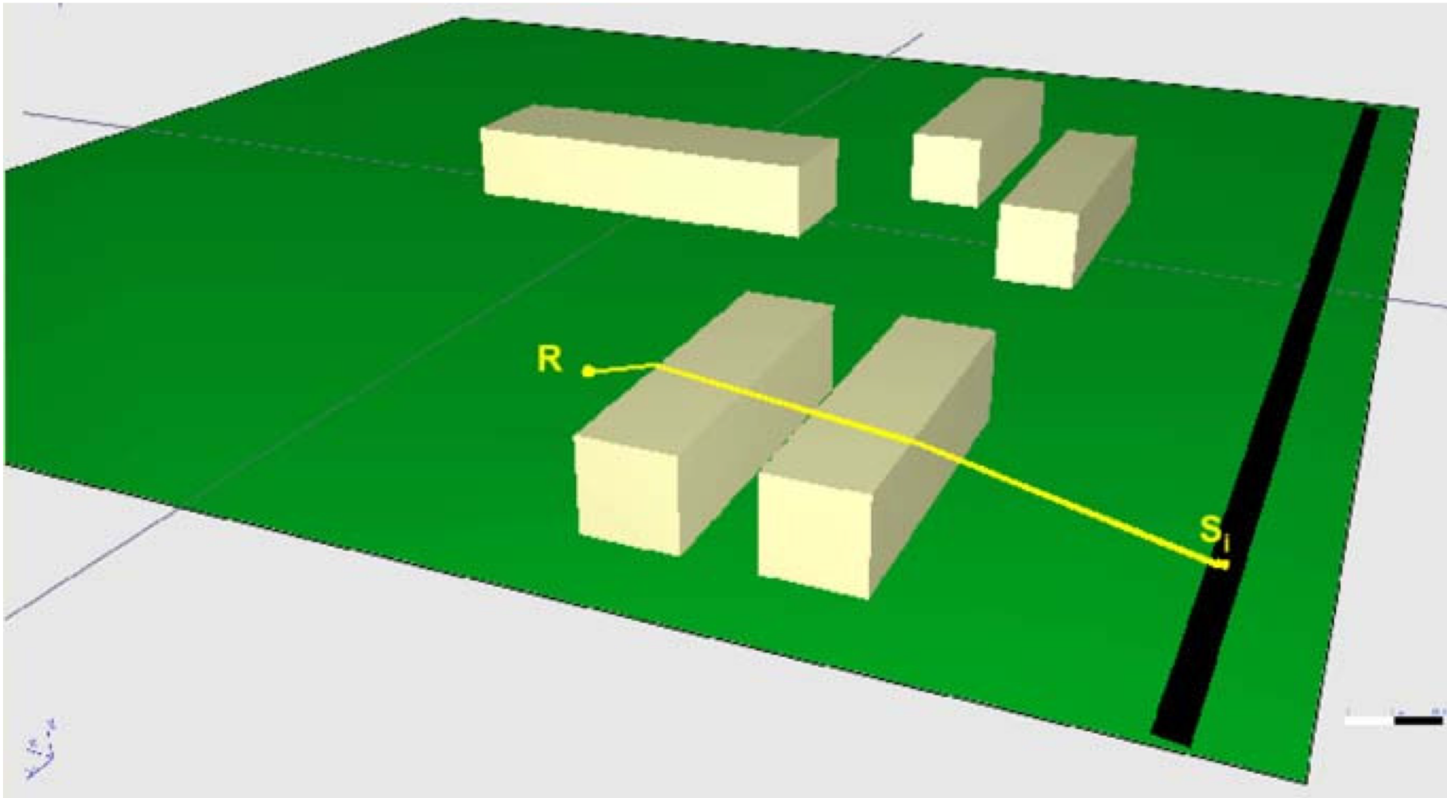
$L_{p,n,i}$	sound pressure level due to sound path n for frequency band i
$L_{w,n,i}$	sound power
$A_{div,n}$	attenuation due to geometrical divergence
$A_{atm,n,i}$	attenuation due to atmospheric absorption
$A_{ground,n,i}$	attenuation due to the ground in homogeneous conditions
$A_{dif,n,i}$	attenuation due to diffraction

$A_{ground,n,i}$ and $A_{dif,n,i}$ are different in the presence of wind
(subject of week 7)

Cnossos sound propagation model

Types of sound paths in Cnossos

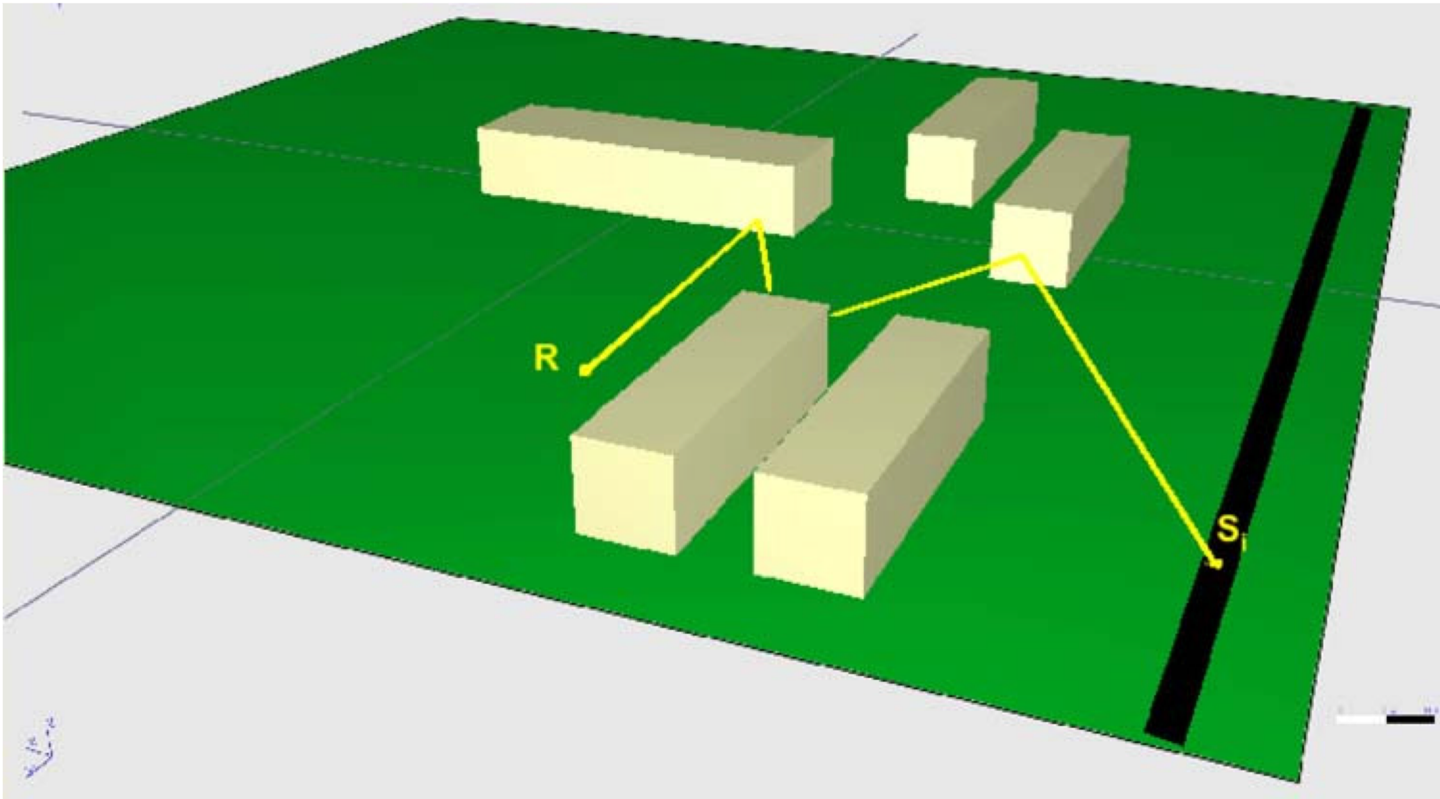
1) Direct source to receiver, including possible diffraction around horizontal edges



Cnossos sound propagation model

Types of sound paths in Cnossos

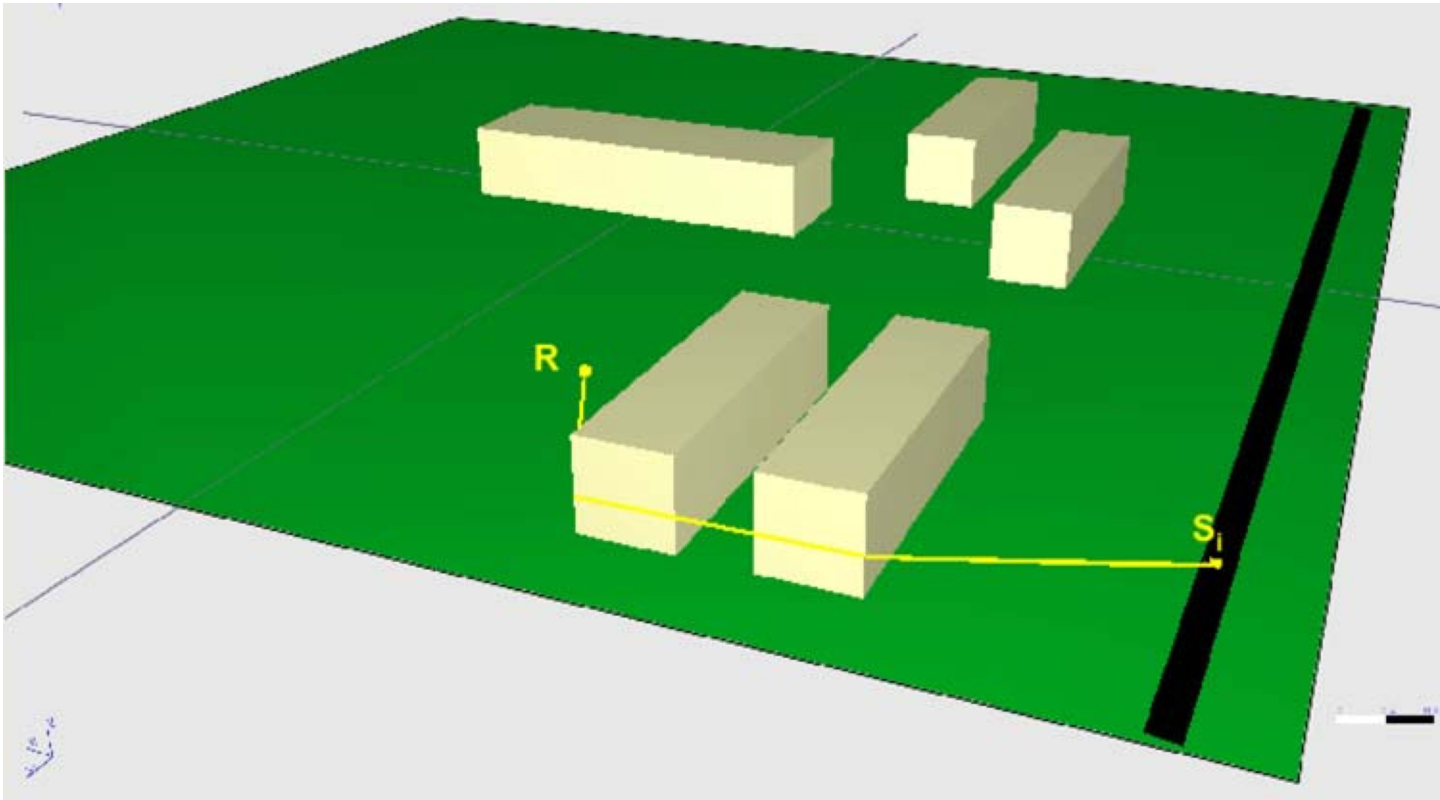
2) Paths reflected on vertical or slightly sloping (< 15°) obstacles, may also include diffractions on the horizontal edges



Cnossos sound propagation model

Types of sound paths in Cnossos

3) Paths diffracted by the lateral edges of obstacles



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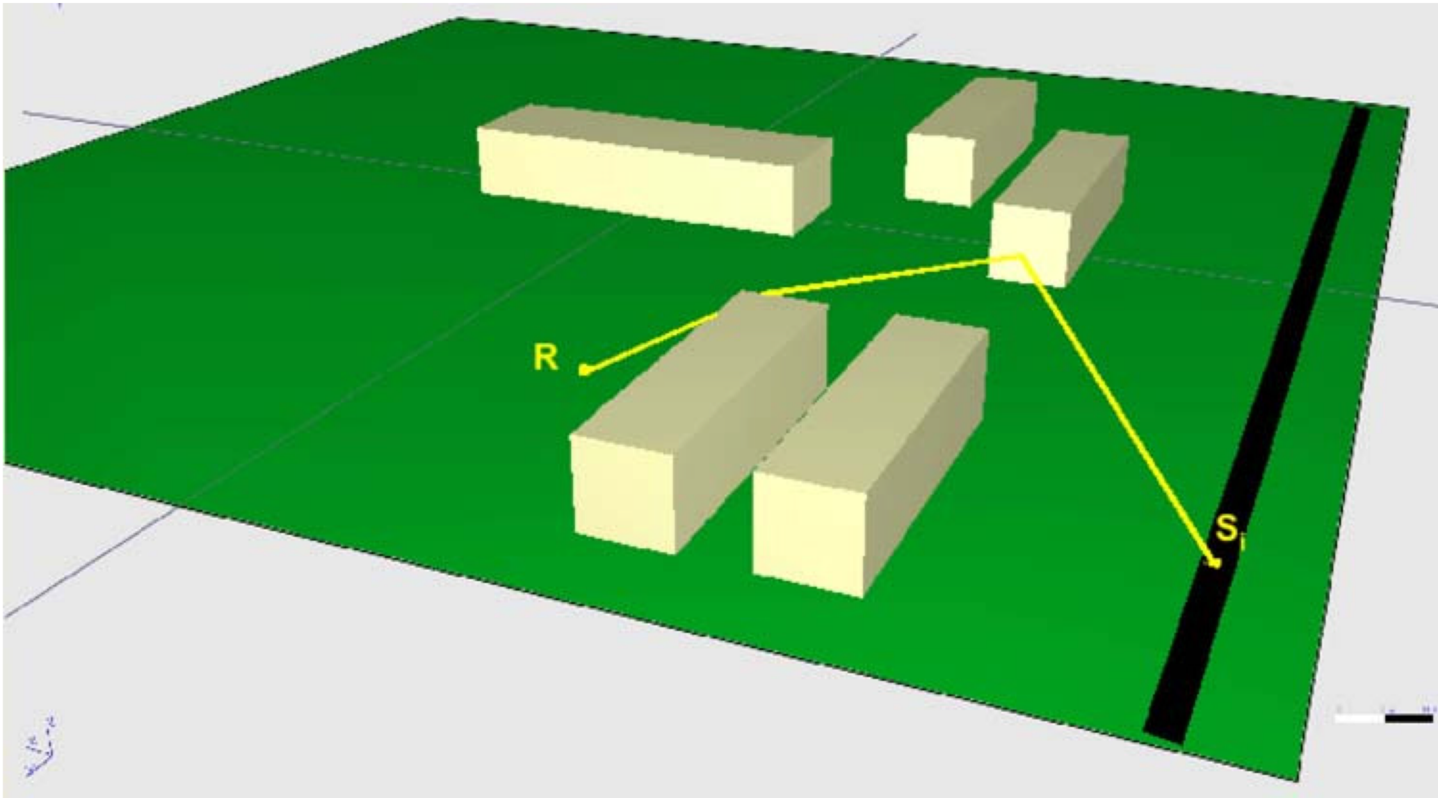
Cnossos sound propagation model

Types of sound paths in Cnossos

4) Mixed paths which are diffracted by the lateral edges of obstacles and reflected by vertical surfaces (< 15°)



Cnossos sound propagation model

Total sound pressure level per octave band *i* at receiver position:

$$L_{\mathrm{p,i}} = 10\log_{10}\left(\sum_{\mathrm{n}} 10^{\frac{L_{\mathrm{p,n,i}}}{10}}\right)$$

Summation over sound levels at a receiver position for multiple sound paths (see previous slides), **and** multiple noise sources

Total A-weighted sound pressure level

$$L_{\mathrm{p,A}} = 10\log_{10}\left(\sum_{\mathrm{i}} 10^{\frac{L_{\mathrm{p,i}}+W_{\mathrm{i}}}{10}}\right)$$

W_i is A weighting for octave band *i*

Cnossos sound propagation model

$L_{p,n,i} = \boldsymbol{L_{w,n,i}} - A_{div,n} - A_{atm,n,i} - A_{ground,n,i} - A_{dif,n,i}$

$L_{p,n,i}$ sound pressure level due to sound path n for frequency band i

L_w sound power

$A_{div,n}$ attenuation due to geometrical divergence

$A_{atm,n,i}$ attenuation due to atmospheric absorption

$A_{ground,n,i}$ attenuation due to the ground in homogeneous conditions

$A_{dif,n,i}$ attenuation due to diffraction

$A_{ground,n,i}$ and $A_{dif,n,i}$ are different in the presence of wind
(subject of week 7)

Sound power term road traffic

Rolling noise

$$L_{WR,i,m} = A_{R,i,m} + B_{R,i,m} \log_{10}\left(\frac{v_m}{v_{ref}}\right) + \Delta L_{WR,i,m}\left(v_m\right)$$

$A_{R,i.m}$ and $B_{R,i,m}$: vehicle m and frequency i dependent coefficients

$v_{ref} = 70$ km/h

$\Delta L_{WR,i,m}\left(v_m\right) =$ sum of all corrections to be applied to rolling noise including corrections for road surface, studded tyres, speed variation and temperature. 0 for reference conditions.

Sound power term road traffic

Table III.A.1: Coefficients for **category *m*=1** vehicles (passenger cars)

Octave band centre frequency (Hz)	A_R	B_R	A_P	B_P	a	b
63	79.7	30.0	94.5	-1.3	0	0
125	85.7	41.5	89.2	7.2	0	0
250	84.5	38.9	88.0	7.7	0	0
500	90.2	25.7	85.9	8.0	2.6	-3.1
1000	97.3	32.5	84.2	8.0	2.9	-6.4
2000	93.9	37.2	86.9	8.0	1.5	-14
4000	84.1	39.0	83.3	8.0	2.3	-22.4
8000	74.3	40.0	76.1	8.0	9.2	-11.4

a and b for studded tyres correction

Murphy, E., & King, E. (2014). *Environmental noise pollution: Noise mapping, public health, and policy*. Newnes.

Sound power term road traffic

Table III.A.2: Coefficients for **category *m*=2** vehicles (medium heavy vehicles)

Octave band centre frequency (Hz)	A_R	B_R	A_P	B_P
63	84.0	30.0	101.0	-1.9
125	88.7	35.8	96.5	4.7
250	91.5	32.6	98.8	6.4
500	96.7	23.8	96.8	6.5
1000	97.4	30.1	98.6	6.5
2000	90.9	36.2	95.2	6.5
4000	83.8	38.3	88.8	6.5
8000	80.5	40.1	82.7	6.5

Murphy, E., & King, E. (2014). *Environmental noise pollution: Noise mapping, public health, and policy*. Newnes.

Sound power term road traffic

Table III.A.3: Coefficients for **category *m*=3** vehicles (heavy duty vehicles)

Octave band centre frequency (Hz)	A_R	B_R	A_P	B_P
63	87.0	30.0	104.4	0.0
125	91.7	33.5	100.6	3.0
250	94.1	31.3	101.7	4.6
500	100.7	25.4	101.0	5.0
1000	100.8	31.8	100.1	5.0
2000	94.3	37.1	95.9	5.0
4000	87.1	38.6	91.3	5.0
8000	82.5	40.6	85.3	5.0

Murphy, E., & King, E. (2014). *Environmental noise pollution: Noise mapping, public health, and policy*. Newnes.

Sound power term road traffic

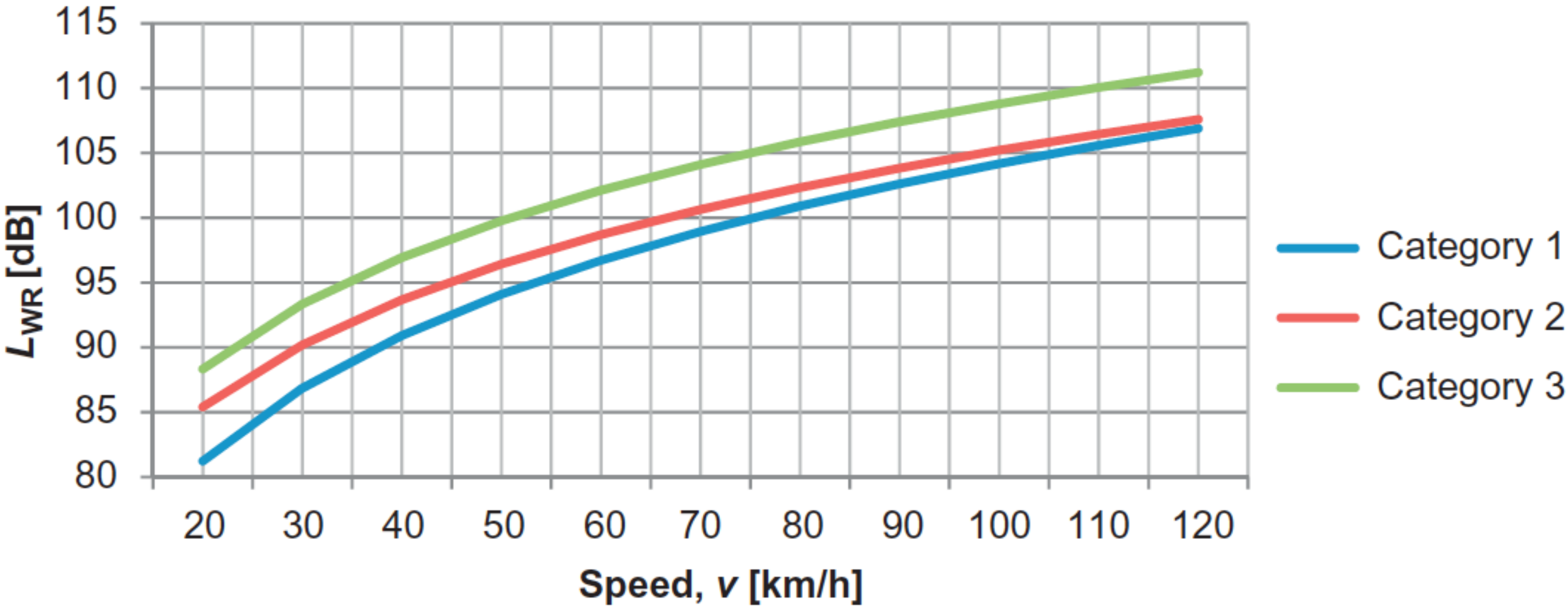
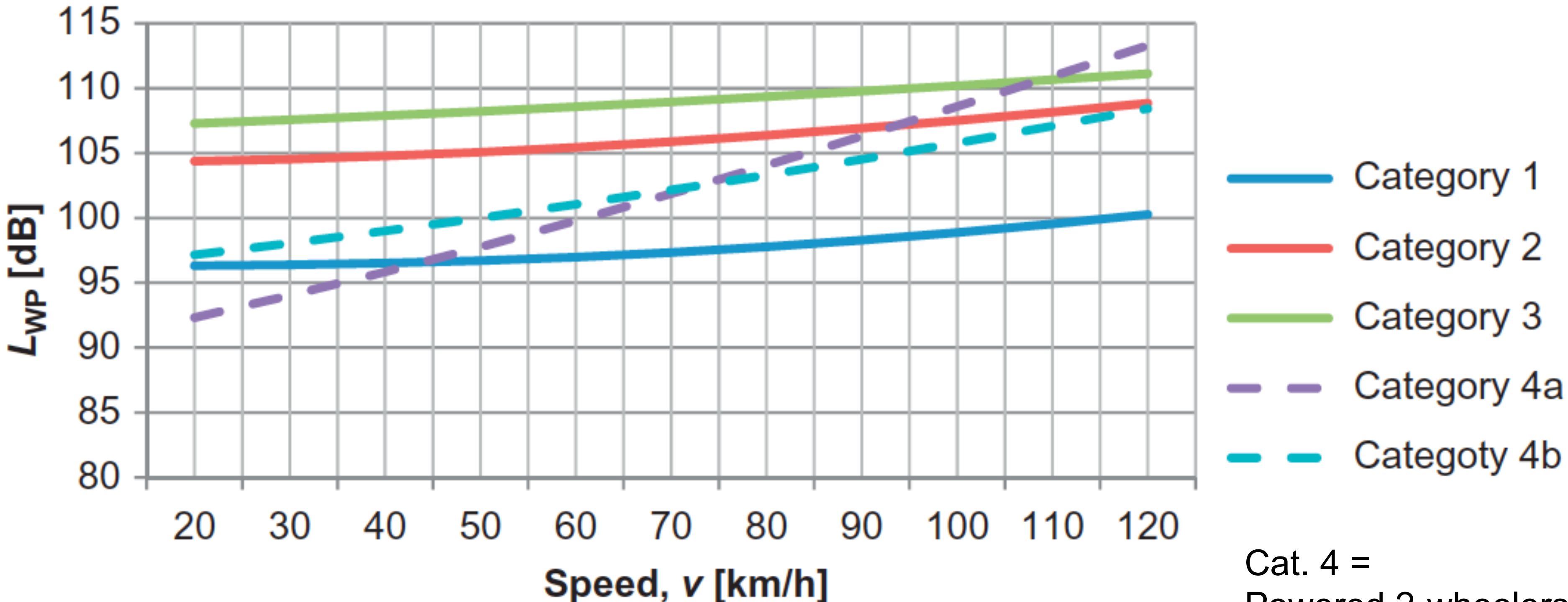


FIGURE 5.4 The variation of rolling noise with speed for the first three categories. Note that the CNOSSOS-EU method does not calculate rolling noise for powered two wheelers.

Murphy, E., & King, E. (2014). *Environmental noise pollution: Noise mapping, public health, and policy*. Newnes.

Sound power term road traffic



Cat. 4 =
Powered 2-wheelers

FIGURE 5.5 The variation of propulsion noise with speed for each vehicle category.

Murphy, E., & King, E. (2014). *Environmental noise pollution: Noise mapping, public health, and policy*. Newnes.

Sound power term road traffic

Total sound power per vehicle, rolling and propulsion noise

$$L_{W,i,m} = 10\log_{10}\left(10^{\frac{L_{WR,i,m}}{10}} + 10^{\frac{L_{WP,i,m}}{10}}\right)$$

Line source, sound power per meter

$$L_{W,eq,m} = L_{W,i,m} + 10\log_{10}\left(\frac{Q_m}{1000 v_m}\right)$$

$Q_m =$ number of vehicles per hour

Cnossos sound propagation model

$L_{p,n,i} = L_{w,n,i} - \mathbf{A_{div,n}} - \mathbf{A_{atm,n,i}} - A_{ground,n,i} - \mathbf{A_{dif,n,i}}$

$L_{p,n,i}$ sound pressure level due to sound path n for frequency band i

L_w *sound power*

$\mathbf{A_{div,n}}$ ***attenuation due to geometrical divergence***

$\mathbf{A_{atm,n,i}}$ ***attenuation due to atmospheric absorption***

$A_{ground,n,i}$ attenuation due to the ground in homogeneous conditions

$\mathbf{A_{dif,n,i}}$ ***attenuation due to diffraction***

$A_{ground,n,i}$ and $A_{dif,n,i}$ are different in the presence of wind (subject of week 7)

A_{atm} attenuation due to atmospheric absorption

A_{atm} = d/1000

d = source receiver distance

TABLE 2.8 Sample Values for α for a Temperature of 15 °C and a Humidity of 70% at One Standard Atmosphere (101,325 kPa)

Centre Frequency [Hz]	125	250	500	1000	2000	4000
α [dB/km]	0.381	1.13	2.36	4.08	8.75	26.4

Murphy, E., & King, E. (2014). *Environmental noise pollution: Noise mapping, public health, and policy*. Newnes.

A_{atm}, A_{div} and A_{dif}

A_{div} *attenuation due to geometrical divergence*

$A_{div} = 20\log_{10}(d) + 11$ *point source*

$A_{div} = 10\log_{10}(d) + 8$ *line source*

d = source receiver distance

Frequency independent!

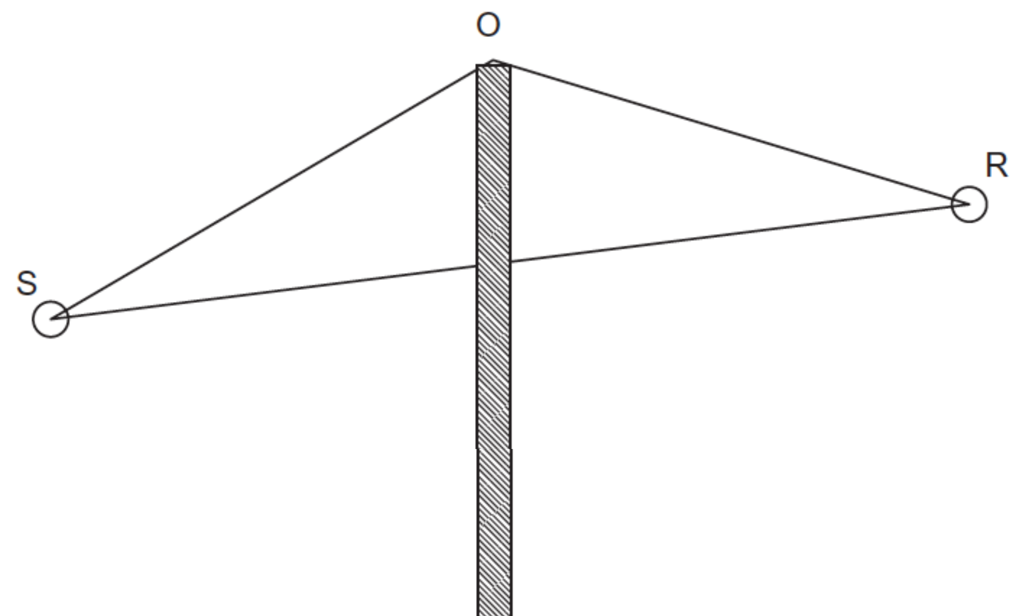
A_{atm}, A_{div} and A_{dif}

A_{dif} attenuation due to diffraction

Without ground surface:

$$A_{dif} = \Delta_{dif,SR} = \begin{cases} C_h 10\log_{10}\left(3 + \dfrac{40\delta}{\lambda}\right) & \text{if } \dfrac{40\delta}{\lambda} \geq -2 \\ 0 & \text{otherwise} \end{cases}$$

$$C_h = \min\left(\frac{f_m h_0}{250}, 1\right)$$



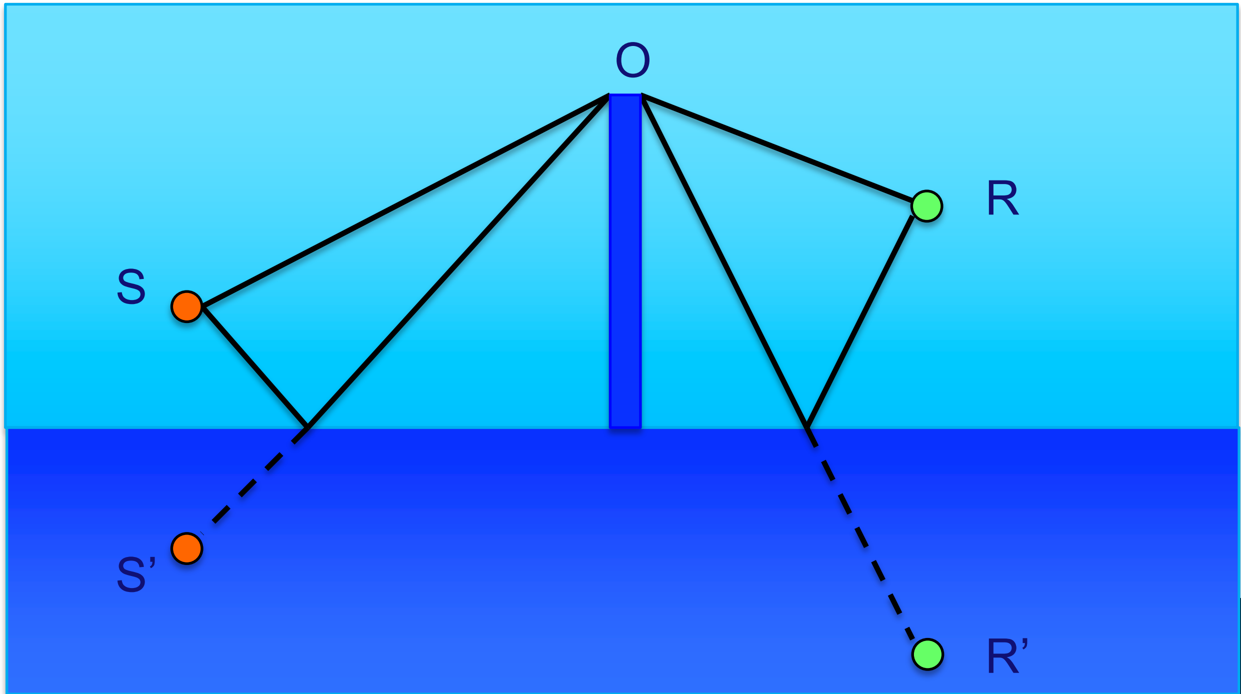
δ = *(SO+OR)-SR*

λ = *c/f* = wavelength (m^{-1})

A_{atm}, A_{div} and A_{dif}

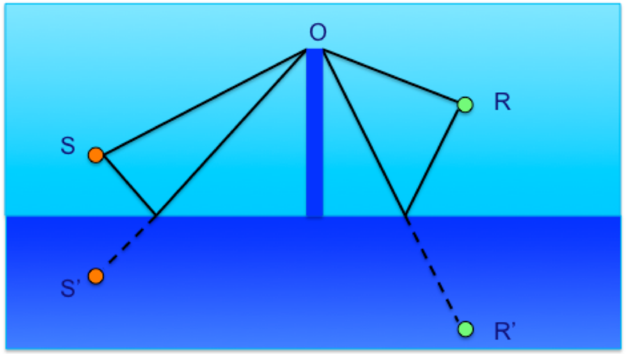
A_{dif} ***attenuation due to diffraction***

$$A_{dif} = \Delta_{dif,SR} + \Delta_{ground,SO} + \Delta_{ground,OR}$$



A_{atm}, A_{div} and A_{dif}

A_{dif} *attenuation due to diffraction*



$$A_{dif} = \Delta_{dif,SR} + \Delta_{ground,SO} + \Delta_{ground,OR}$$

$$\Delta_{ground,SO} = -20\log_{10}\left(1+\left(10^{\frac{-Aground(S,O)}{20}}-1\right)10^{\frac{-\left(\Delta_{dif,S'R}-\Delta_{dif,SR}\right)}{20}}\right)$$

attenuation due to the ground effect on the source side, weighted by the diffraction on the source side

$$\Delta_{ground,OR} = -20\log_{10}\left(1+\left(10^{\frac{-Aground(O,R)}{20}}-1\right)10^{\frac{-\left(\Delta_{dif,SR'}-\Delta_{dif,SR}\right)}{20}}\right)$$

attenuation due to the ground effect on the receiver side, weighted by the diffraction on the receiver side

Cnossos sound propagation model

$L_{p,n,i} = L_{w,n,i} - A_{div,n} - A_{atm,n,i} - \boldsymbol{A_{ground,n,i}} - A_{dif,n,i}$

$L_{p,n,i}$ sound pressure level due to sound path n for frequency band i

L_w *sound power*

$A_{div,n}$ *attenuation due to geometrical divergence*

$A_{atm,n,i}$ *attenuation due to atmospheric absorption*

$\boldsymbol{A_{ground,n,i}}$ ***attenuation due to the ground in homogeneous conditions***

$A_{dif,n,i}$ *attenuation due to diffraction*

$A_{ground,n,i}$ and $A_{dif,n,i}$ are different in the presence of wind (subject of week 7)

Attenuation due to the ground

A_{ground} attenuation due to the ground in homogeneous conditions

Depends on:

- Properties of ground surface, including all surfaces between source and receiver
- Frequency
- Angle of incidence of sound wave with ground
- Distance between source and receiver, source and receiver heights
- ***This term is non-existent if a barrier is present!***

Ground attenuation

Ground factor G

G = 1 is acoustically soft ground

G = 0 is acoustically hard ground

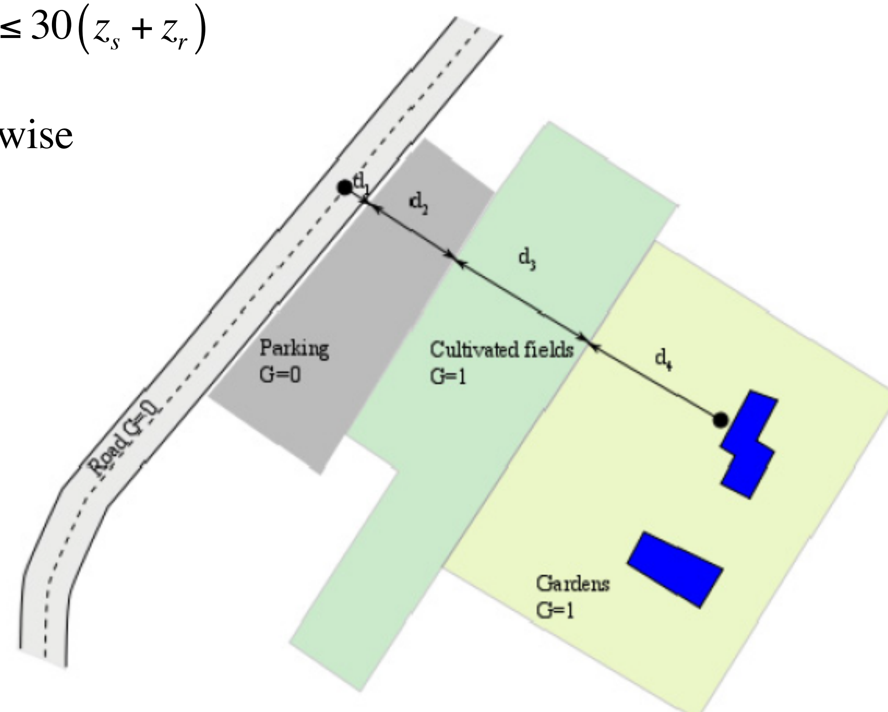
Table VI.1: *G values for different types of ground*

Description	Type	(kPa·s/m^2)	*G* value
Very soft (snow or moss-like)	A	12.5	1
Soft forest floor (short, dense heather-like or thick moss)	B	31.5	1
Uncompacted, loose ground (turf, grass, loose soil)	C	80	1
Normal uncompacted ground (forest floors, pasture field)	D	200	1
Compacted field and gravel (compacted lawns, park area)	E	500	0.7
Compacted dense ground (gravel road, car park)	F	2000	0.3
Hard surfaces (most normal asphalt, concrete)	G	20 000	0
Very hard and dense surfaces (dense asphalt, concrete, water)	H	200 000	0

Ground attenuation

Total G for a propagation path calculated:

$$G'_{path} = \begin{cases} G_{path} \dfrac{d_p}{30(z_s + z_r)} + G_s \left(1 - \dfrac{d_p}{30(z_s + z_r)}\right) & \text{if } d_p \le 30(z_s + z_r) \\ G_{path} & \text{otherwise} \end{cases}$$

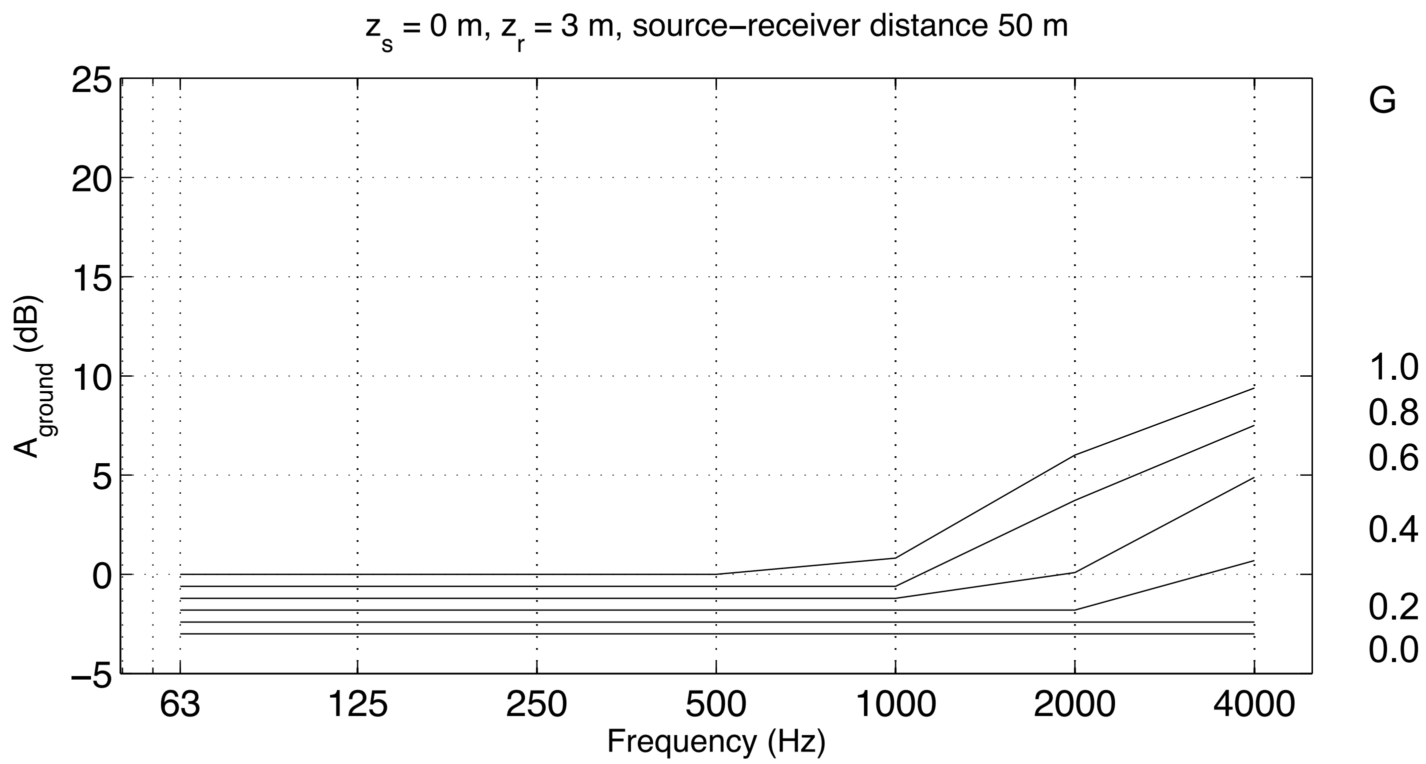


$$d = d_1 + d_2 + d_3 + d_4$$

$$G_{path} = {(0 \cdot d_1 + 0 \cdot d_2 + 1 \cdot d_3 + 1 \cdot d_4)}/{d} = {(d_3 + d_4)}/{d}$$

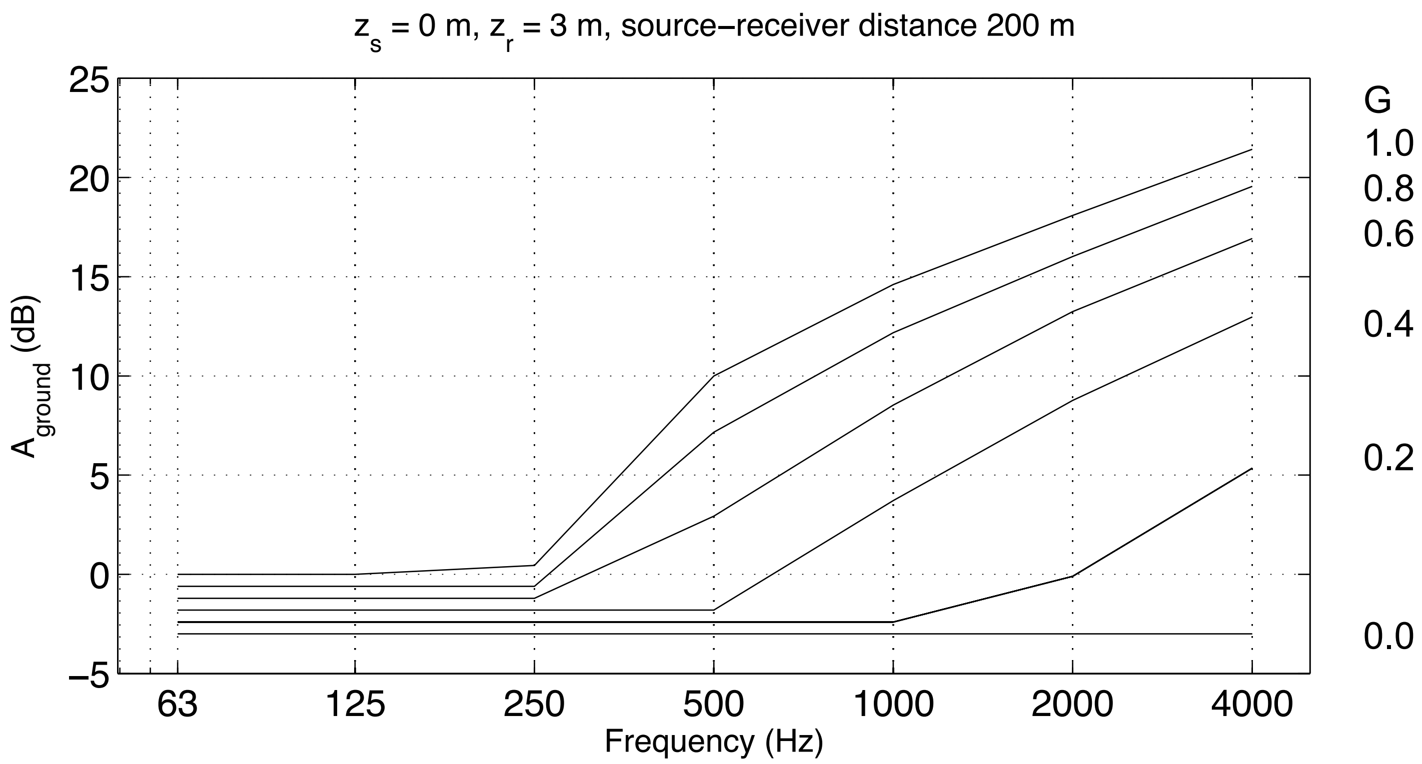
Ground attenuation

A_{ground}



Ground attenuation

***A**ground*



Calculation example

Example

What are the maximum sound levels in $L_{p,A}$ due to the pass by of
1) Car at 120 km/h
2) Truck at 80 km/h

Configuration:

- Shortest distance road to receiver point = 50 m
- Ground between source and receiver: type ‘uncompacted loose ground’
- Asphalt: type ‘very hard and dense’
- No meteorological effects
- Reference conditions for sound power
- z_s = 0 m, z_r = 3 m

Calculation example

Calculation of frequency dependent sound pressure level per vehicle using

$$L_p = L_w - A_{div} - A_{atm} - A_{ground} - A_{dif}$$

Car

$$L_{WR,i.m} = A_{R,i.m} + B_{R,i.m} \log_{10}\left(\frac{v_m}{v_{ref}}\right) + \Delta L_{WR,i.m}\left(v_m\right)$$

$A_{R,i.m}$ and $B_{R,i.m}$: see tables

$v_m = 120$ km/h

$\Delta L_{WR,i.m}\left(v_m\right) = \quad 0$

Calculation example

Car

$$L_{WP,i.m} = A_{P,i.m} + B_{P,i.m}\left(\frac{v_m - v_{ref}}{v_{ref}}\right) + \Delta L_{WP,i.m}\left(v_m\right)$$

$A_{P,i.m}$ and $B_{P,i.m}$: see tables

$v_{ref} = 70$ km/h

$v_m = 120$ km/h

$\Delta L_{WP,i.m}\left(v_m\right) = 0$ dB

$$L_{W,i,m} = 10\log_{10}\left(10^{\frac{L_{WR,i,m}}{10}} + 10^{\frac{L_{WP,i,m}}{10}}\right)$$

Calculation example

Car

f (Hz) (Hz)	Ar (dB)	Br (dB)	Ap (dB)	Bp (dB)	LWR,i (dB)	LWP,i (dB)	LW,i (dB)
63	79.7	30.0	94.5	-1.3	86.7	94.2	94.9
125	85.7	41.5	89.2	7.2	95.4	90.9	96.7
250	84.5	38.9	88.0	7.7	93.6	89.8	95.1
500	90.2	25.7	85.9	8.0	96.2	87.8	96.8
1000	97.3	32.5	84.2	8.0	104.9	86.1	105.0
2000	93.9	27.2	86.9	8.0	100.3	88.8	100.6
4000	84.1	39.0	83.3	8.0	93.2	85.2	93.9
8000	74.3	40.0	76.1	8.0	83.7	78.0	84.7

Calculation example

Car

A_{div} $= 20\log_{10}(d)+11 = 20\log_{10}(50)+11 = 45.0$ dB
for all frequency bands

A_{atm} $= \alpha\, d/1000$

Neglect air absorption for 63 Hz

TABLE 2.8 Sample Values for α for a Temperature of 15 °C and a Humidity of 70% at One Standard Atmosphere (101,325 kPa)

Centre Frequency [Hz]	**125**	**250**	**500**	**1000**	**2000**	**4000**
α [dB/km]	0.381	1.13	2.36	4.08	8.75	26.4

Calculation example

Car

A_{ground}

Ground between source and receiver: type 'compacted field and gravel'

$G_{path} = 1$

Asphalt: type 'very hard and dense'

$G_s = 0$

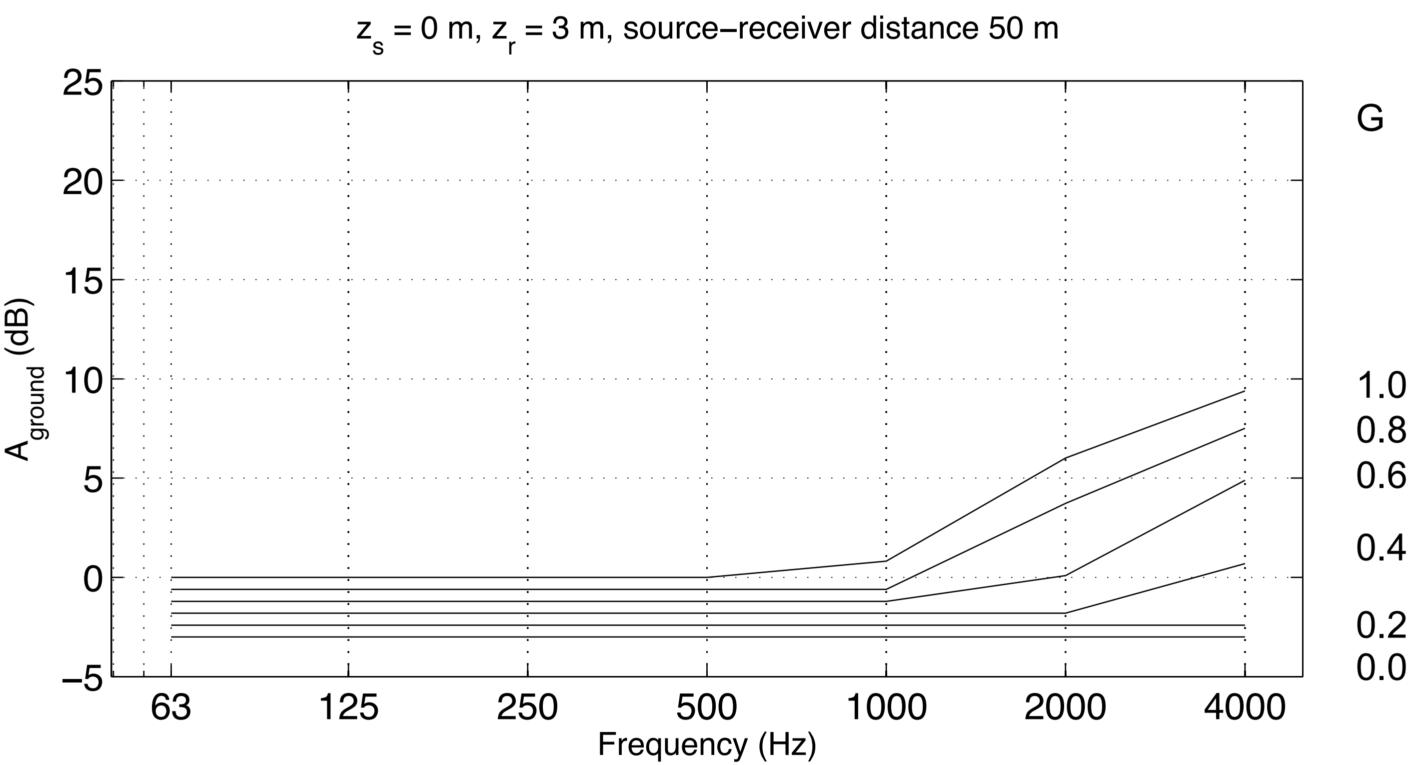
$$G'_{path} = \begin{cases} G_{path}\dfrac{d_p}{30(z_s+z_r)} + G_s\left(1-\dfrac{d_p}{30(z_s+z_r)}\right) & \text{if } d_p \le 30(z_s+z_r) \\ G_{path} & \text{otherwise} \end{cases}$$

$d_p < 30(z_s+z_r) \Rightarrow G'_{path} = 0.3$

Calculation example

Car

Graph interpolation => $\boldsymbol{A_{ground}}$



Calculation example

Car

f (Hz) (Hz)	LW,i (dB)	Adiv (dB)	Aatm (dB)	Agr (dB)	Adiff (dB)	Lp,i (dB)
63	94.9	45.0	0.0	-2.5	0.0	52.4
125	96.7	45.0	0.0	-2.5	0.0	54.2
250	95.1	45.0	0.1	-2.5	0.0	52.6
500	96.8	45.0	0.1	-2.5	0.0	54.2
1000	105.0	45.0	0.2	-2.5	0.0	62.3
2000	100.6	45.0	0.4	-2.5	0.0	57.6
4000	93.9	45.0	1.3	-1.0	0.0	48.6

Calculation example

Car

f (Hz) (Hz)	LW,i (dB)	Adiv (dB)	Aatm (dB)	Agr (dB)	Adiff (dB)	Lp,i (dB)	Wi (dB)
63	94.9	45.0	0.0	-2.5	0.0	52.4	-26.0
125	96.7	45.0	0.0	-2.5	0.0	54.2	-16.0
250	95.1	45.0	0.1	-2.5	0.0	52.6	-9.0
500	96.8	45.0	0.1	-2.5	0.0	54.2	-3.0
1000	105.0	45.0	0.2	-2.5	0.0	62.3	0.0
2000	100.6	45.0	0.4	-2.5	0.0	57.6	1.0
4000	93.9	45.0	1.3	-1.0	0.0	48.6	1.0

$$L_{p,A} = 10\log_{10}\left(\sum_i 10^{\frac{L_{p,i}+W_i}{10}}\right) = 64.3 \text{ dB(A)}$$

Calculation example

Heavy vehicle (class 3)

f (Hz) (Hz)	LW,i (dB)	Adiv (dB)	Aatm (dB)	Agr (dB)	Adiff (dB)	Lp,i (dB)	Wi (dB)
63	105.4	45.0	0.0	-2.5	0.0	63.0	-26.0
125	101.5	45.0	0.0	-2.5	0.0	59.0	-16.0
250	102.9	45.0	0.1	-2.5	0.0	60.4	-9.0
500	104.8	45.0	0.1	-2.5	0.0	62.2	-3.0
1000	104.7	45.0	0.2	-2.5	0.0	62.0	0.0
2000	99.3	45.0	0.4	-2.5	0.0	56.4	1.0
4000	93.6	45.0	1.3	-1.0	0.0	48.3	1.0

$$L_{p,A} = 10\log_{10}\left(\sum_i 10^{\frac{L_{p,i}+W_i}{10}}\right) = 65.1 \text{ dB(A)}$$