Demonstrating Solar Noise Barriers on The Ray

August 2017

Innovia TECHNOLOGY

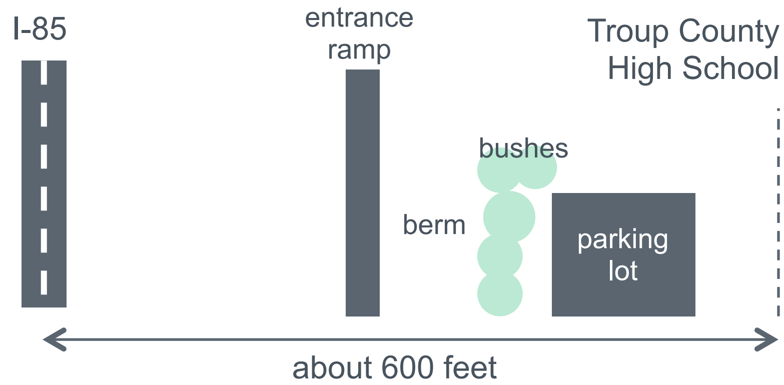
Contents

Background

- The Ray asked Innovia to explore if, and how, it should demonstrate a solar noise barrier on The Ray, and specifically to understand:
  - The different designs and technologies
  - The key technology providers / innovators
  - The cost-benefit analysis (approximately)
  - Whether the technology meets The Ray's criteria – sustainability, feasibility, The Ray can make a difference
  - How we can best demonstrate solar noise barriers through The Ray project

Overview

- In principle, solar noise barriers are a great technology for The Ray to demonstrate. They:
  - reduce noise pollution;
  - generate renewable energy;
  - are fairly new to the US; and
  - novel transparent solar panels can improve the aesthetic, which is often critical to acceptance of noise barriers.
- We tried to find a suitable site on The Ray to demonstrate a real reduction in noise, and the Troup County High School initially looked promising. However the noise levels aren't sufficient to justify a barrier – it's too far from the road and we expect the existing berm is reducing noise levels already.
- We propose demonstrating the technology at the Visitor's Center. This can show potential investors, DOTs, and other stakeholders that the technology can effectively block noise and generate electricity whilst having aesthetic advantages over traditional noise barriers.



The economics of solar noise barriers

- The financial case for a solar noise barrier depends on:
    - the value placed on the noise reduction
    - the value placed on the aesthetics
    - the value/cost of solar energy vs. grid energy
- The options:
    - If you only want to reduce noise, you'd install a cheap concrete barrier (or perhaps a more expensive absorptive barrier if you're concerned about reflected noise)
    - If you only want to generate renewable energy, on the ROW, as cost-effectively as possible, you'd install more conventional solar i.e. PV panels facing the sun
    - If you want the most cost-effective solar noise barrier, and don't care about aesthetics, you'd install conventional silicon solar panels on a standard barrier
    - If you need a noise barrier and want to make an aesthetic statement, there are lots of examples of good-looking architecturally designed (and expensive) barriers
    - If you want to reduce noise, produce renewable energy AND care about aesthetics, then a barrier made from novel transparent solar cells *may* be the best option (depending on your aesthetic preference). It is this option that we think it would be most useful for The Ray to demonstrate

What is a solar noise barrier?

- There are currently over 30 solar noise barriers installed worldwide. The majority are in Germany and Switzerland with a few in The Netherlands, Italy, Austria and France. Outside Europe, there is a single installation in Australia.
- They range in peak power (kW) from 24-2065 kW peak power
- The energy output of the PV system depends on the area covered in PV panels, the orientation of the panels (in terms of azimuth e.g. South and pitch, angle from the vertical) and the amount of solar radiation at the site.
- Standard solar noise barrier lifetime is assumed to be 25 years. Cost benefit is often framed in the payback time from solar power generation to pay for cost of capital and installation of the barrier.
- There are three main technologies used for solar noise barriers:
  - Retrofitting standard polycrystalline solar panels onto existing noise barriers, usually made of concrete
  - Bifacial polycrystalline solar panels surrounded by toughened glass
  - Thin film solar cells encased in toughened glass.

Reminder of The Ray's Criteria

Sustainability

- Must have a real and positive sustainability impact.
- And no adverse impacts.

Feasibility

- Must have the potential to work.
- What are the technical challenges? Is it TRL 5-6?
- Does it have long-term mass market commercial potential?
  - i.e. could it ever be cost-effective, and is it scalable?

Can the Foundation help make it happen?

- Is it relevant to the I-85?
- Is it achievable by the Foundation?
- Can it tell a great story?
- Could it attract additional investment dollars?
- Does it have the potential to inspire change beyond The Ray?
- Would it be financially scalable beyond The Ray?

Do Solar Noise Barriers meet The Ray's criteria?

Sustainability

- Produces low carbon, renewable energy. Reduces noise and thereby enhances the quality of life for people living or working near The Ray. The noise reduction can benefit wildlife too.

Feasibility

- The technology has been deployed elsewhere, is at TRL 5 or above and could be scaled across the U.S.
- Assuming a value is placed on the noise reduction, the barrier can be financially viable, and the energy produced can help pay for the capital investment of the noise barrier.

Can The Ray Make It Happen?

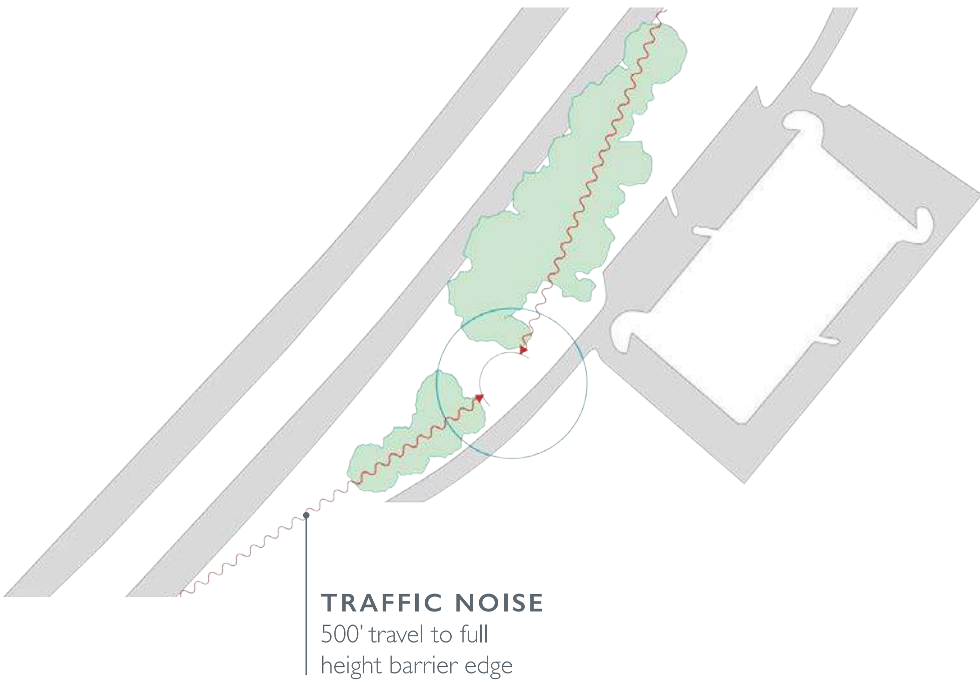
- We haven't found a suitable location on The Ray for a 'real-life' demonstration.
- However we think there's value in demonstrating the technology at the visitor's center, where The Ray could install a demonstration project in about 6 months for <$100k.
- This demonstration could show that aesthetically attractive transparent solar noise barrier can effectively block noise, and produce energy. It would also increase general awareness, go someway to addressing concern about safety, and show the aesthetic potential and options to architects and other highway professionals

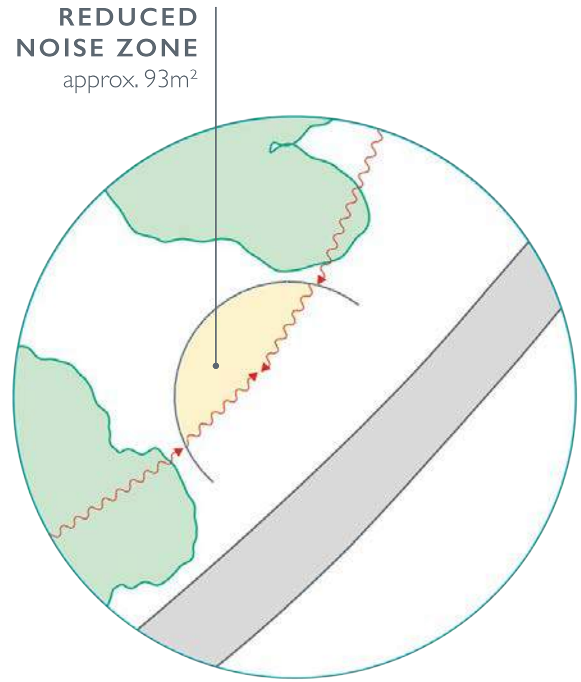
Proposal for Visitor’s Center demonstrator


OPTION 1
WRONG WAY

OPTION 1:

Single arc structure, near the entrance to the Visitor Centre



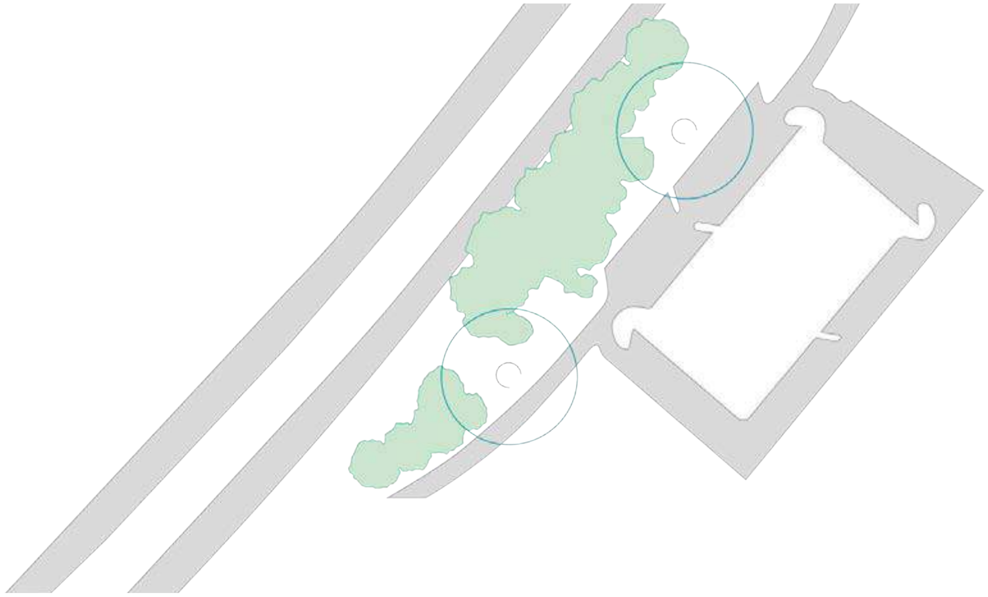


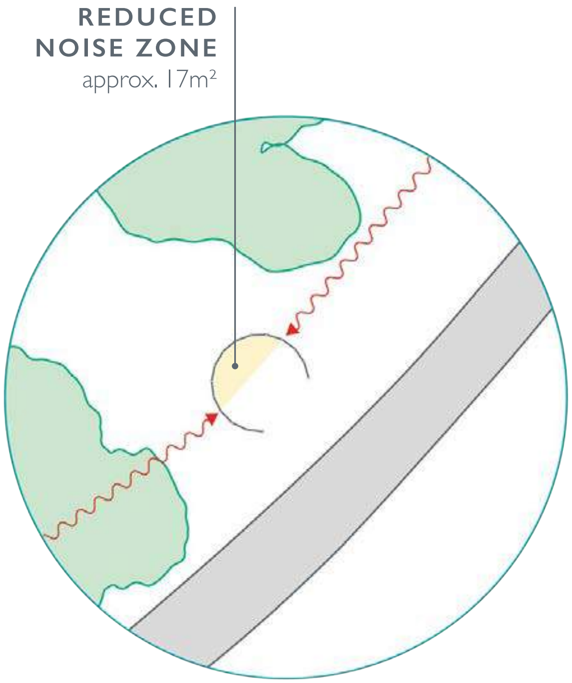
- 10m radius arc, approx. 32m long
- 80x solar panels
- room for 3x seating areas
- possible uses for this space:
  picnic area / resting area, garden, music, lighting


OPTION 2
Proprietary to The Ray

OPTION 2:

Two smaller separate arc structures, near the entrance to the Visitor Centre and by the car park

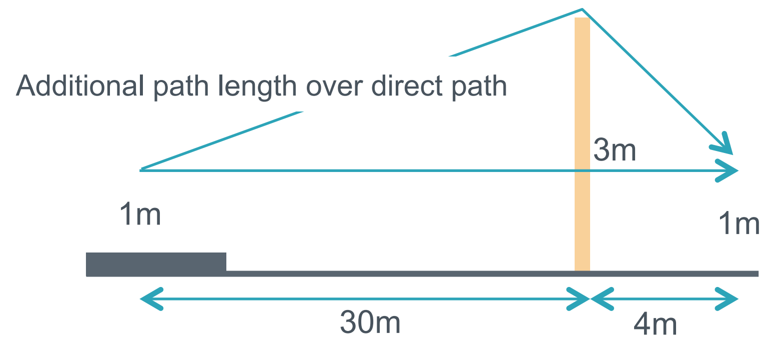




- 4m radius arc, approx. 18m long
- 44x solar panels
- room for 1x seating areas
- possible uses for this space:
  picnic area / resting area, garden, music, lighting

Noise reduction calculation 1

Distance from highway to barrier	30m
Distance from barrier to end of quiet zone	4m
Additional height of barrier over source and receiver	2m (3m high barrier, source and receiver 1m above ground)
Additional path length	0.45m
Wavelength	~0.33m (assuming traffic frequency of ~1000Hz)
Fresnel number N (additional wavelengths added to path)	~1.4
Insertion loss	**~15dB**



$$\text{Insertion Loss} = 5dB + 20\log\left[\frac{\sqrt{2\pi N}}{\tanh\sqrt{2N}}\right]dB \quad \text{up to N} = 12.5$$

N = Fresnel Number

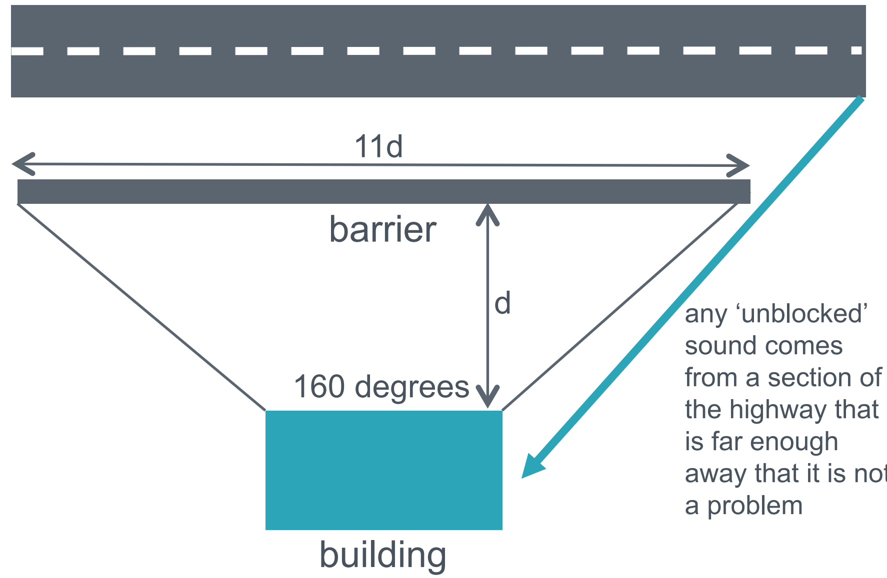
= Number of additional wavelengths the sound must travel around the barrier

Reference: Design guide for highway noise barriers.
(TxDOT in cooperation with FHWA)

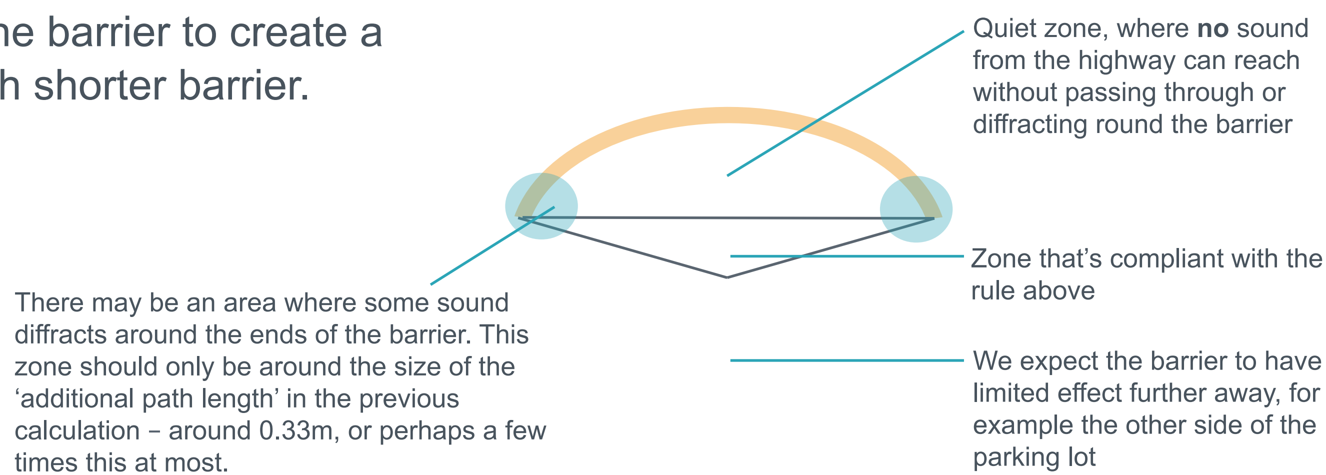
http://ctr.utexas.edu/wp-content/uploads/pubs/0_1471_4.pdf

Noise reduction calculation 2

- Conventional noise barrier design principles state that the noise barrier must subtend an angle of at least 160º from the receiver.

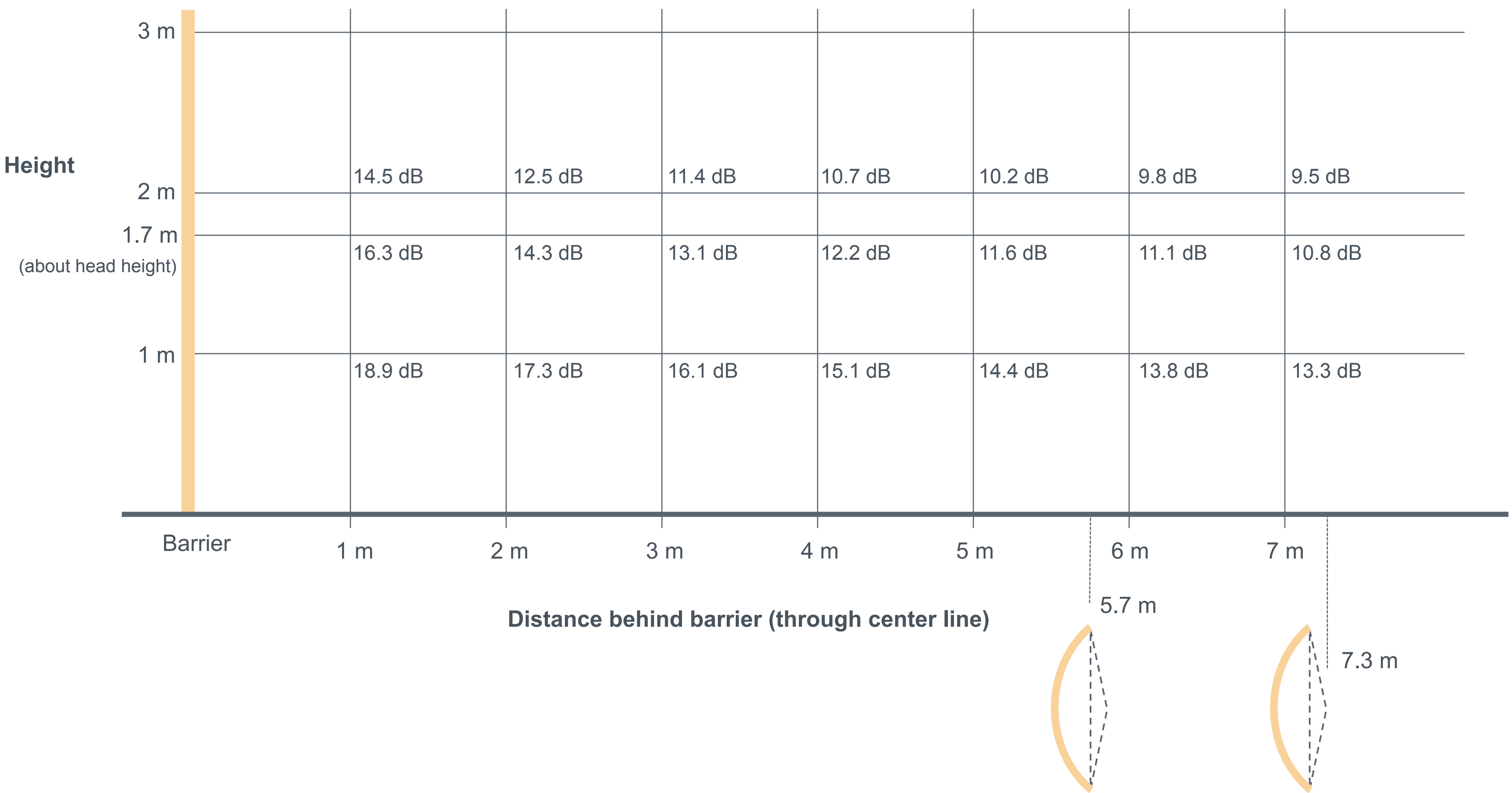


- We propose curving the barrier to create a quiet zone with a much shorter barrier.



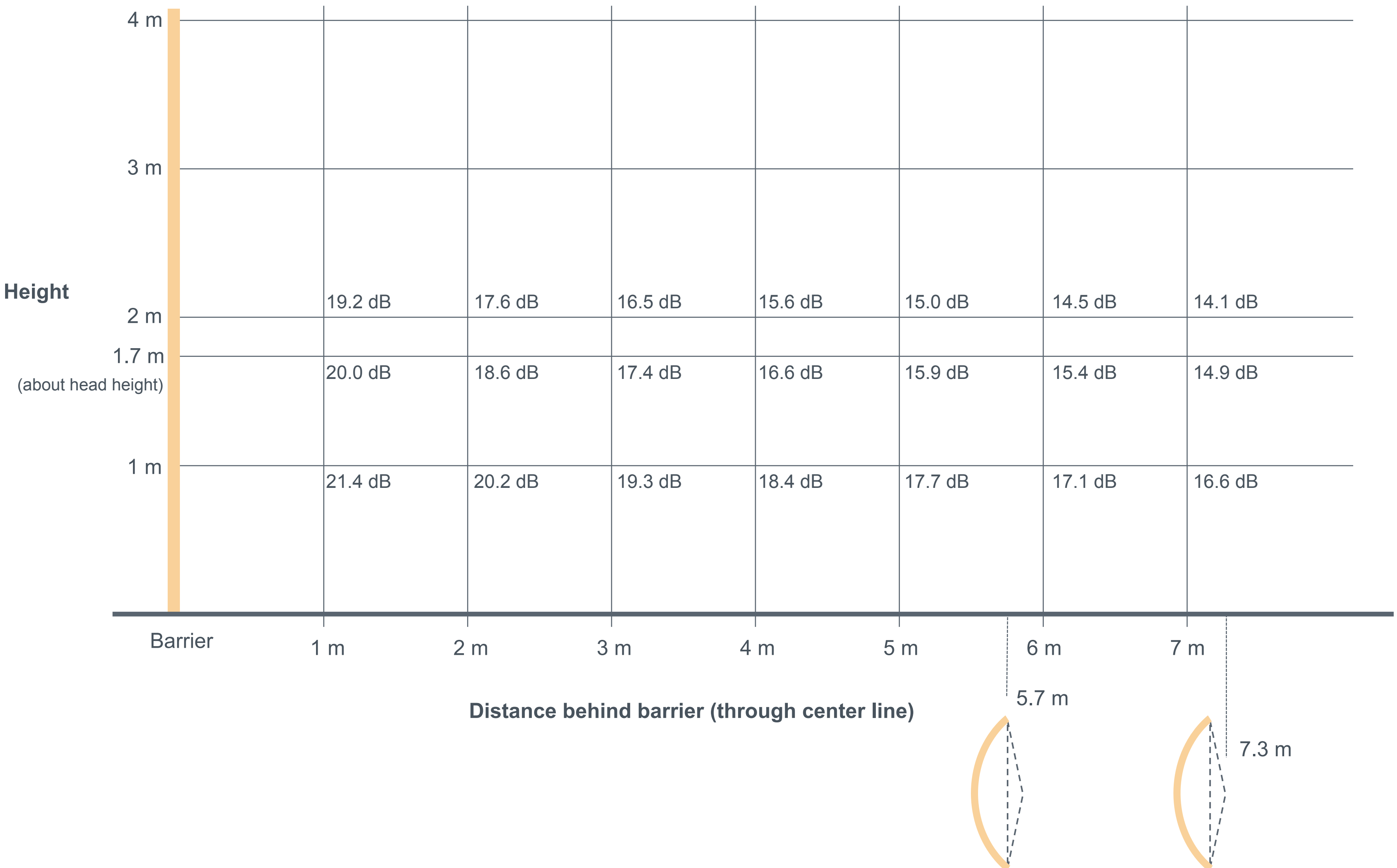
Noise reduction cross section

3m high barrier



Noise reduction cross section

4m high barrier



Noise reduction calculation

- We are fairly confident that the design we've proposed (3m high) will make a significant reduction to the noise level of around 15dB (at head height around 1-2m from the barrier), and that this should be highly noticeable as someone walks into the quiet zone
- A significant uncertainty in our calculation of noise reduction is in the height of the source and receiver. We've assumed the source is 1m above the ground, which is a fairly standard assumption, and shown the sound reduction at different heights behind the barrier
- It may be prudent to design the barrier so that its height can be extended if the noise reduction proves insufficient. Or alternatively, to build the barrier higher to start with to be more confident in the noise reduction. A 4m high barrier would give a 15dB reduction at head height around 6-7m behind the barrier
- If The Ray would like to be more confident in this before building the demonstration, we'd recommend either doing some computational analysis, and/or finding someone with specific expertise in acoustics or highway noise barrier design

Glass specification

- We need to design the barrier so that the amount of sound passing through the glass is much less than the amount of sound diffracting around it
- As we are seeking a ~15dB overall reduction, we should specify glass that attenuates sound by *at least* 25dB
- The sound attenuation of glass is not simple – it depends on thickness, frequency, lamination, and the fixing at the sides of the panel
- However most glass of >10mm thickness tends to have an attenuation of >30dB:
  - Saint Gobain brochure on noise control glazing
    - http://ememento.saint-gobain-glass.com/app/webroot/img/assets/19/products/pdffiles/19_1481029911_1.pdf
    - 10mm glass with attenuation of 38dB
  - Pilkington Optiphon brochure
    - http://assetmanager-ws.pilkington.com/fileserver.aspx?cmd=get_file&ref=8222&cd=cd
    - Attenuation around 30dB for a range of thicknesses from 4-12mm, and the table here clearly gives figures for both high speed traffic (higher frequency) and urban traffic (lower frequency)
  - "Feasibility of Transparent Noise Barrier". Rocchi and Pedersen. 1990
    - A trial of transparent glass and plastic noise barrier, for Ontario MoT
    - "Glazing materials have no difficulty in meeting the MTO s minimum <noise attenuation> requirements (see Table 1)."
    - Table 1 shows a 7.24mm glass with an attenuation of 35dB, and a 12.25mm glass with an attenuation of 39dB
    - We assume the trial used these thicknesses, and no significant damage was reported

Glass specification

- The specification of the glass is therefore likely to be determined by the structural/safety requirements rather than by the acoustic requirements
- We recommend that the glass is:
  - tempered, to toughen it and to avoid shattering in the event of a collision;
  - laminated – essential to incorporate and protect the solar panel anyway. This will also provide some extra sound insulation; and
  - around 12mm thick. This should be thick enough to attenuate the sound and provide sufficient strength. Any extra thickness would seem to add unnecessary cost.
- This won't be resistant to gunshots but should be resistant to a thrown rock:
  - "The bus shelters used throughout Metropolitan Toronto are required to be shatterproof as well. To be able to withstand the force of a thrown rock, they are made of 0.5 in. (12.7mm) tempered glass."
  - "Feasibility of Transparent Noise Barrier". Rocchi and Pedersen. 1990
- Polysolar's standard panel comes with 10mm glass panel at the back, giving a total thickness of ~14mm. Heijmann's trials of a solar noise barrier had bifacial solar cells sandwiched between two 8mm piece of glass, giving a total thickness of ~20mm.

Estimate of electricity production

Transparency	kWp	kWh/year	$/year at $0.05/kWh
10%	4,838	4,210	$210
20%	4,301	3,742	$187
30%	3763	3,274	$164
40%	3,225	2,807	$140
50%	2,688	2,339	$117

Assumptions:

- curved barrier design – this has reduced the yearly energy production to ~0.87 kWh/kWp, from ~1.18 kWh/kWp for a straight E-W noise barrier, a ~25% reduction.
- south facing site (2 or 3 on photo), so ~84% unshaded exposure based on Hannah Solar's shade analysis
- Polysolar's CdTe panels, and their estimate of energy generation that neglected any shading

We hope that this demonstration will…

- Build awareness of solar noise barriers in general (not just transparent ones)
- Demonstrate that transparent solar panels can effectively block noise and generate energy
- Provide a genuinely useful quite space for visitors, and provide some engagement with The Ray project
- Showcase the aesthetic potential of transparent solar panels, and highlight the fact they’re available in a range of colors and transparencies. We imagine that town planners, architects, DOT people will be especially interested in this
- Start to address concerns about the safety of glass panels near roads
- Start a conversation on other applications for transparent solar panels e.g. Building Integrated Photo-Voltaics (BIPV)

Brief review of the economics of solar noise barriers

Headlines

- Solar panels cannot fully pay for the sound barrier. They will only justify the additional cost over a non-solar barrier in ideal conditions - favorable electricity price, sunny location, south facing, standard cheap Si panel etc.
- The benefit of noise reduction, and of the aesthetics, must be part of the cost-benefit calculation.
- Costs for attractive architectural barriers can be much higher than for either standard or solar barriers

Comparison of business cases

assuming ~270m, 3m high, in an E-W orientation (as for the Troup County High School location)

Technology	Cost of barrier	Electricity Generated MWh/year	NPV of Electricity*	Residual cost of barrier
Basic concrete barrier (~$150/m2)	~$120,000	0	0	~$120,000
Architecturally designed barrier (~$1350/m2, estimate from Heijmans)	~$860,000	0	0	~$860,000
Concrete plus standard PV panels	~$180,000	146	$107,000	~$73,000
Bifacial PV with toughened glass	~$600,000	116	$86,000	~$514,000
Polysolar thin film noise barrier 40% transparency	~$300,000	60	$64,000	~$236,000

Assumptions: 25 year life, 8% discount rate, 0.05c per kWh cost of electricity, 3% annual electricity price inflation Source: https://us.sunpower.com/sites/sunpower/files/media-library/white-papers/wp-valuing-return-solar-projects-businesses-government-agencies.pdf.

Potential for solar noise barriers in the US

- Existing noise barriers can be upgraded to solar noise barriers.
    - Solar noise barriers do not require additional dedicated land like solar farms do. This is particularly relevant as noise barriers are typically found in built up areas, where land is at a premium.
    - The majority of existing noise barriers are found in CA, CO, GA, MD, MN, NJ, NY, OH, MI. If retrofitted, the peak power potential of these is estimated to be 7-9 GW with an annual production of 700 GWh.
    - The US produced 3.9 million GWh of electricity in 2016, of which 36,000 GWh was solar (~1%). Retrofitting all existing noise barriers could generate 1-2% of current solar output.
- Deployment of noise barriers is likely to increase in the US.
    - Increasing traffic, awareness of health and growing populations will increase the demand for noise barriers.
    - Electric vehicles will reduce overall noise levels. However, large transport vehicles and heavy rail is responsible for high level noise. These vehicles are furthest from complete adoption of electric technology.

Appendix

Design options for solar barriers

Headlines

- If the aesthetics are valued, PolySolar looks like a good option
- If not, standard crystalline silicon is more cost effective
- Perovskite solar cells look promising for the future. Might PolySolar demonstrate the potential of thin film transparent panels in preparation for Perovskite?

Solar Noise Barrier Technologies

1 https://www.solarchoice.net.au/blog/news/bifacial-solar-cells-the-two-sides-of-the-story-050515
2 https://cleantechnica.com/2015/02/04/sampling-roadway-renewable-energy-designs/
3 http://www.polysolar.co.uk/Technology/thin-film

Technology Comparison

Technology	Description	Pros	Cons
Retrofitting standard PV panels on a standard noise barrier	Standard polycrystalline solar panels are placed on an existing noise barrier made of e.g. concrete. Widely deployed in Europe.	Efficiency of up to 22%. Low additional cost of capital.	Vulnerable to theft or vandalism. Less energy generated than same size solar array due to vertical positioning and directional alignment and coverage fraction. Technology is not novel.
Bifacial PV in toughened glass	Standard polycrystalline solar panels are mosaiced between two panes of thick toughened glass. This allows light to reach the PV cells from both sides of the barrier. Deployed in Europe.	No need for existing concrete structure. Efficiency of ~15% depending on orientation. Solar panels are protected from vandalism. Can be semi-transparent for aesthetic appeal, but this reduces efficiency.	Higher cost that other options, mostly due to cost of thick toughened glass. Only really suited for E-W orientation. Has been demonstrated in Europe.
Thin film based noise barrier (Polysolar CdTe Technology)	Thin film solar cells are sandwiched between two panes of toughened glass. This has 20% light transmission. Two small deployments in Asia.	No need for existing concrete structure. Efficiency is about half that of standard solar panels. Can be semi-transparent. Cost is between that of bifacial PV and retrofitting.	Higher cost than retrofitting. Efficacy as a noise barrier not proven?

Technology Comparison

Technology	Efficiency	Novelty	Business Case (cost of barrier – NPV of electricity produced)	Performance of noise barrier
Retrofit with standard solar panels				
Bifacial solar panels with toughened glass				
Thin Film base noise barrier (Polysolar)				

Design options for solar barriers

- Solar PV technologies
- Barrier designs and materials

Headlines

- We recommend that The Ray demonstrates thin film solar technology on a noise barrier e.g. Polysolar's CdTe or aSi panels
- Although conventional silicon currently has the best cost-efficiency trade off, thin film technology…
  - is less well established and has more to benefit from a demonstration;
  - can offer transparency and a better aesthetic, which can be critical;
  - will likely become more cost effective in the future as volume scales up; there's no fundamental reason why it is more expensive
  - emerging thin film technologies (e.g. Perovskite) may offer significant efficiency improvements over current thin film technologies; and
  - may start a conversation about wider use of thin film in Building Integrated PV.

Potential for solar noise barriers in the US

- Thin-film solar cells are second generation cells that seek to improve on standard polycrystalline option. They are produced by depositing one or more thin layers of photovoltaic material on a substrate. The substrate can be a range of materials to suit the application such as metal, glass or plastic.
  - Thin-film cells are typically lower mass than polycrystalline alternatives. As such, they do not require significant structural support so can be mounted easily or overlaid onto existing structures.
  - Developments of perovskite based cells have the potential to increase the efficiency of thin film panels beyond the current 15%.
  - Thin-film solar cells are currently significantly more expensive than polycrystalline panels. However, thin-film technology is much less developed so costs can be expected to reduce as it grows.
- Thin-film technology can be used to create solar panels that are visually more acceptable to the public than traditional polycrystalline panels.
  - Thin film can be deposited between layers of hardened glass to form partially transparent solar panels. These panels are more subtle and blend into the surrounding environment so could be more suited to an urban environment.

Power generation and architecture

- In a PV, power is generated by converting a photon into free charge carriers that an be collected when a voltage is applied.
  - There are many different materials that can be used for the conversion process. These materials have different capabilities, which lead to big differences in the application of the technology. There are also different trade-offs with respect to efficiency, cost, manufacturing etc.
  - It is also important to note the orientation of a PV – it can be necessary for one of the electrodes to be transparent in order to have a reasonable quantity of power generated (e.g. in a thin-film configuration).

Types of PV material

- **First generation** - Bulk inorganic semiconductors. Almost of all of these are doped silicon.
- **Second generation** - Thin film inorganic semiconductors. Key technologies are:
    - amorphous silicon
    - cadmium telluride
    - copper indium diselenide
    - copper indium gallium diselenide
- **Third generation** - Essentially these are the technologies that are emerging, and are not yet produced on a commercial scale. Technologies of note are:
    - Dye-sensitized solar cells (DSSCs), also known as Gratzel cells
    - Perovskites
    - Quantum dot PV
    - Semiconducting polymers have not shown much promise after many years of research and have been superseded by the other technologies above.

First generation PV

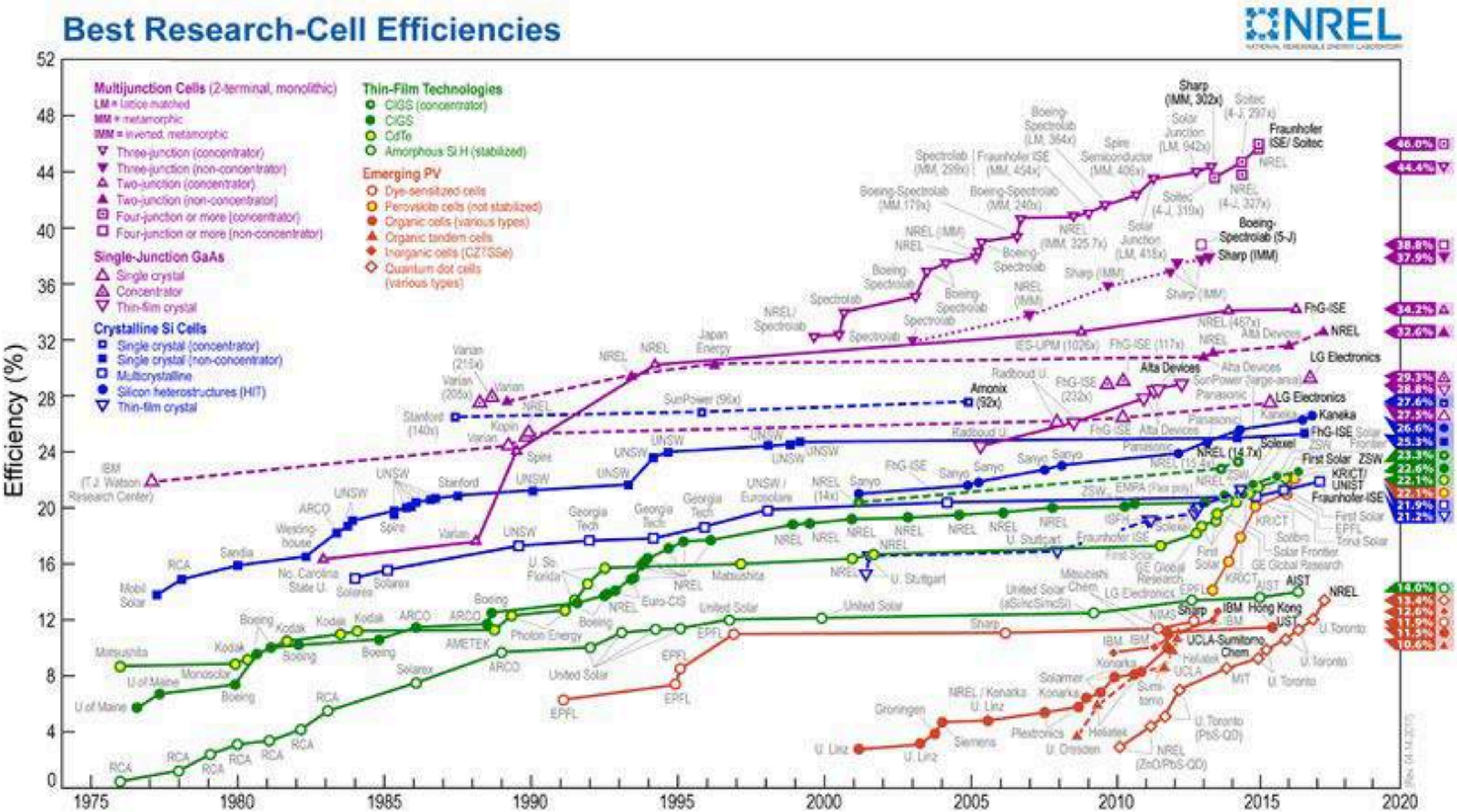
- Bulk Si-based PVs, made from layers of doped crystalline Silicon. These are still the most common form of PV panel. The costs have reduced substantially owing to huge increases in Chinese manufacture. This in turn has reduced the economic incentive to develop/scale thin film PV, and emerging PV technology.
- Second generation thinfilm PV have focused mostly on reducing the manufacturing complexity cf bulk Si or on creating flexible PV for retrofit.

Second generation thinfilm PV technologies

- Amorphous silicon
  - There are various ways of producing thin film Si-based PVs. The most common is plasma-enhanced chemical vapor deposition, which creates a layer of silicon ~1micron thick onto a substrate. There are various mechanisms that reduce the efficiency compared to standard Si PVs – these can be tackled with changes to device architecture, but there is usually a trade-off between manufacturing complexity and device performance.
- Cadmium telluride
  - About 5% of the PV market, accounts for ~50% of the thin film market. Some people are concerned about the toxicity of Cadmium. A more important concern is the rarity of Tellurium, which will potentially prevent this technology from scaling up much further.
- CIGS
  - An important manufacturer of this technology (Solyndra) went bankrupt in 2014. There are manufacturing challenges with this material – traditionally expensive processes such as vacuum deposition or sputtering are used. Again, there are issues with the availability of the key materials.

Potential of perovskites

- The key determinant of the the efficiency of a solar cell is the bandgap. Large bandgaps give rise to higher open-circuit voltages, and hence greater power generation, but can absorb a smaller fraction of the solar spectrum. The bandgap is determined by the properties of the material and usually you have to take what you get.
  - Perovskites have a tunable bandgap (it is controlled by the halide content), so they can be optimally matched to the solar spectrum.
- The mobility of charges is also very important. In inorganic bulk PV, the binding energy between the excited electron in the conduction band and the resultant hole in the valance band is very low – essentially the charges can be moved freely. However, in second and third generation PV this is not always the case. For organic PV materials (this includes DSSCs) and small molecules the charges are often bound together as excitons and must be separated (e.g. by the use of heterojunctions). This usually leads to more complicated device architecture, or a reduction in overall efficiency as some portion of the excitons recombine rather than separating. Recent research suggests that in Perovskites the binding energy of the exciton is low, and at room temperature the charges are essentially free. This suggests that Perovskites may give you the best of both worlds – the manufacturing potential of solution processable thin films, with the optimal band gap and free charges found in silicon.


Best Research-Cell Efficiencies
NREL
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells (various types)
Efficiency (%)
52
48
44
40
36
32
28
24
20
16
12
8
4
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020

Source: NREL

Demonstration projects: Thin Film PV

- Thin film PV (such as Polysolar's technology) has advantages over bulk PV for the sort of applications The Ray is considering. In particular, they can be adapted to many different geometries, and are lightweight. This should make them good candidates for both retrofitting and as stand alone barriers.
- The downside to thin film technologies is that they are more costly than bulk PV. (Note – this is because China has flooded the market with bulk PV, rather than because of an inherent difficulty in manufacturing thin film technologies). However we might expect the cost of thin film to come down over time.
- There may be a case for building a demonstration project with a current thin film technology, even if it is currently not the most economic option, and using it to show that a more efficient film-based technology (e.g. perovskite) will be economically viable and scalable in the next 5-10 years.

Technology Options For Solar Noise Barriers

- There are four main technology options for noise barriers that also generate solar power:
  - **Retrofitting** – this involves fitting standard poly/monocrystalline solar panels on to the noise barrier. There are various configurations with different efficiencies for power generation and implications for the level of noise shielding.
  - **Amorphous Silicon Panel noise barrier** – this is Polysolar's technology, which is most efficient in low light situations. It can be reinforced with toughened glass panels to form a noise barrier.
  - **LSC solar noise barrier** – this is Heijmans technology which uses fluorescent dyes to funnel light towards solar panels at the edge of the panels. It currently has lower efficiencies compared to other available technologies and is still in development.
  - **Bifacial polycrystalline solar panels** – this are most suited to N-S orientation. Can form a noise barrier in combination with toughened glass panels.

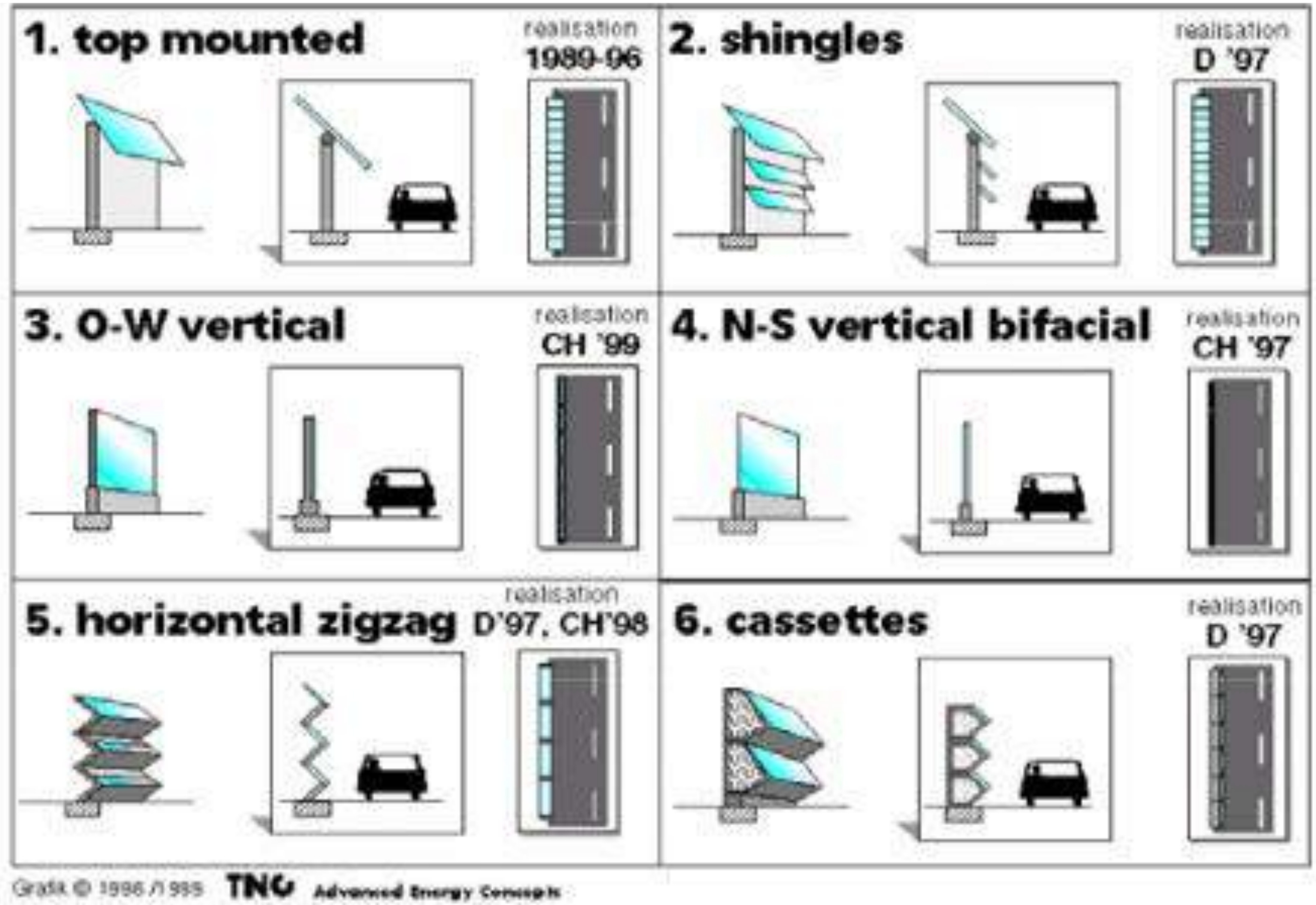
Summary of Technology Options

Technology	Companies	Summary
Standard noise barrier plus standard solar panels separate from barrier		Base case to compare other options to.
Standard noise barrier retrofitted with standard solar panels	Kotech/Ramboll/Nuwatt/ SSM	
Si-A solar panel noise barrier	Polysolar	Works best under low light/shading
LSC solar panel noise barrier	Heijmans/Eindhoven University	Trial indicated efficiencies are too low – back in lab for further development
Bifacial standard solar panels with toughened glass noise barrier	Kohlhauer, Ertex Solar, TNC Energie	Trialed along with LSC in Netherlands – met targets but best suited to N-S orientation.

Design options for solar barriers

- Solar PV technologies
- Barrier designs and materials

Solar panel placement for retrofit



Source: http://www.tvenergy.org/content/files/publications/photovoltaic-noise-barriers-1334753493.pdf

Solar panel placement for retrofit

- Cassette type (retrofit)
  - Installation in Munich, Germany with a peak power of 9.9 kW
  - Design is highly integrated into the existing noise barrier and is easily mountable.
  - The performance ratio (PV module energy output vs. theoretical maximum) was between 0.55 (July) and 0.79 (February).
  - The main reason for poor performance in the summer was inefficient heat dissipation – the module operating temperature became too high.
  - Self shading effects caused by the upper module on the lower module were also an issue.
  - Panels were also damaged due to vandalism (graffiti) which reduced efficiency.

Solar panel placement for retrofit

- Shingles type (retrofit)
  - Installation in Germany with peak power of 9.1kW.
  - Design is compact and aims to maximize energy output per m of road. Performance ration varied between 0.59 (Jan) and 0.7 (May). Operating temperature remains moderate due to air convection
  - Self shading reduces lower module outputs. Loss due to shading is ~4%.

Solar panel placement for retrofit

- Zig-Zag type (retrofit)
  - PV modules are stacked in alternating planes of PV panels and noise absorbing surface. The PV panels are tilted at an angle of 75• compared to an optimum angle of 35•. This reduces the energy output significantly.
  - The performance index varied between 0.69 (July) to 0.79 (Feb).
- The zig-zag and cassette orientation of retrofitted solar panels give best sound protection. The shingle and bifacial orientations act as sound reflecting modules.

Design Type	Height of module	Insertion Loss at 1.5m height(dB)**	Insertion Loss at 5m height(dB)**
Cassettes	3.2m	13.7	9.7
Shingles	3.0m	11.7	3.8
Zigzag	3.9	14.1	4.3

Metal Noise Barriers

- Metal noise barriers do exist, but are rarely used compared to concrete barriers or earth berms because:
  - They are higher cost per unit area [1], often around twice the cost of a concrete barrier of the same size
  - They can suffer from corrosion and have lower lifetimes [2] – this makes stainless steel the most common material choice, but the panels need to be thicker than standard sheeting and often have to custom made and corrugated [3].
  - They are reflective rather than absorptive and can increase noise levels in the area they face e.g. the other side of a highway [3]. One option to overcome this is to cover an absorptive material with metal sheets, but this is also higher cost than concrete [4].

References

1. https://www.soundfighter.com/metal-vs-absorptive-sound-barriers/
2. https://www.ohioturnpike.org/wp-content/uploads/2013/05/Summary_Report_Full_Compressed.pdf
3. https://www.fhwa.dot.gov/ENVIRonment/noise/noise_barriers/design_construction/design/design05.cfm
4. Sinha, Kumares C., and Samuel Labi. *Transportation decision making: Principles of project evaluation and programming*. John Wiley & Sons, 2011.

Companies providing solar noise barriers

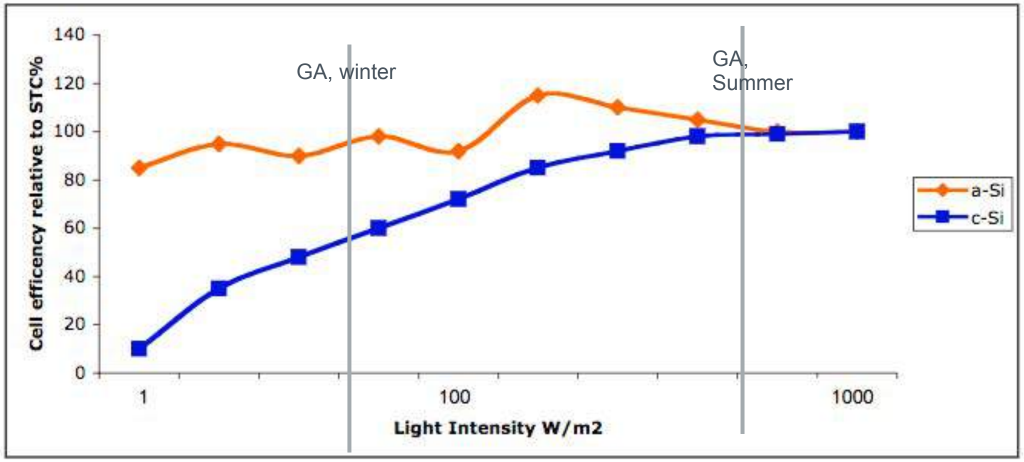
Companies providing solar noise barriers

Innovia researched the following list of companies who have capabilities in the production and installation of solar noise barriers.

- Polysolar
- Heijmans
- TV Energy
- TNC Switzerland
- Ertex Solar, Austria
- NuWatt Energy, U.S. (retrofitting)
- Kohlhauer, Germany
- Schott Solar
- ECN and SEAC

Polysolar

- Thin film technology with partially transparent (20% transmission) panels designed for integration into buildings in the place of traditional glazing.
- Can produce clear panels.
- Power can go to battery storage or to an inverter for feeding back to the grid or local uses. Traditional solar panel wiring.
- Available in two panel sizes:
    - 1200mm (4ft) x 600mm (2ft)
    - 1400mm (4.5ft) x 1100mm (4ft)
- The glass is triple laminate to meet safety requirements with colored laminate in between the glass. The laminate is safety glass and heat treated. This is then bonded to a metal back bar or metal frame and stand.
- Only more efficient that standard crystalline silicon technology (c-Si) in low light intensity. In Georgia, this means the area would have to be significantly shaded to get significant gains vs. conventional solar panels. Grey lines on the chart show light intensity in Atlanta, GA for a vertical N-S panel in summer and winter. In this range, a-Si has a small advantage



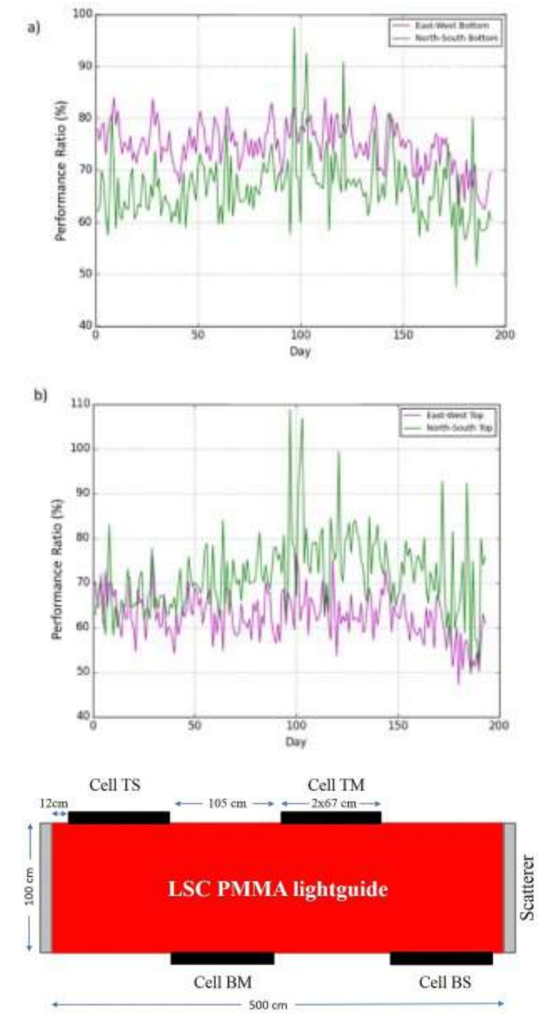
Source: Polysolar

Heijmans

- Technology is based on luminescent solar concentrator (LSC) technology.
    - This consists of a polymer plate filled with fluorescent molecules that absorb the incident sunlight and re-emit the light at a longer wavelength, some of which is trapped by in the polymer plate.
    - The trapped light is then directed towards the narrow edges of the plate, where long, thin PV cells are placed to convert the light into electricity.
    - The technology has been at lab-scale since the 1970s, but it suffered from issues with light-to-electricity conversion efficiencies which can be low due to restricted absorption ranges, losses from dye emitted light directed outside the angles needed for TIR, absorption of light by the polymer that makes up the light guide and most crucially the reabsorption of the dye emitted light.
- There is currently a trial installation on the A2 highway near Den Bosch in the Netherlands of two 5m by 4.5m panels. These are aiming to show that 1km of energy generating noise barriers could produce enough electricity to power 50 households for a year. The solar panels were bifacial modules an on an east-west orientation. Heijmans were responsible for the installation of the panels that were produced by Evonik GmbH.
- Results of the project indicated that the yield of the LSC modules was lower than expected (by a factor of nearly 10) and further work needs to be done to improve this. One of the key issues that reduced the yield was that the panels were covered in dirt and pollutant particles from the traffic exhaust and in graffiti. This reduced the incident light. There were also issues with self-shadowing.
- The same trial also tested bifacial Si-C solar panels covered with toughened glass to help with noise abatement. This did meet the energy generation target of the trial.
    - These panels were 4x5m^2 and 12mm thick. The glass on the bifacial Si-C panel was 8mm thick.

Heijmanns LSC panels: Technical details

- The test panels consisted of four cast PMMA plates 1x5x0.012m^3 . Two used the fluorescent dye Lumogen Orange240 and two used Lumogen Red305, both from BASF. The top and bottom edges of the panels were attached with two strips of series connected cells each containing 12x78mm^2 monocrystalline PV cells from SolTech. These were mounted on the sides or top and bottom of the plate.
- One set of two panels was placed facing N/S and the other E/W with inclinations of 15º to the N and E respectively.
- This performance did not meet the expected standard, so further work is being done on the LSC panels before more pilot tests.



Source: Heijmans

Kohlhauer Volta GmBH

- Kohlhauer are a German company that specialize in noise barriers. One of their products, the Volta, consists of solar panels attached to glass with a metal framework.
- A noise barrier 200m long and 4.5m high can support 60 4mx1.5m panels which produce a peak output of 18kW, which gives an annual power yield (in Germany) of 15,500kWh. The total cost for this is €299,000, with the standard noise barrier costing €248,400. This gives an additional cost of €50,600 for the solar panels, or 140€/m^2.
- There are three designs available: Bifacial (N-S) orientation using panels from TNC/Ertex, thin film modules from Schott Solar and transparent thin film using Schott Thin Film ASI Thru modules (10% transparency) with output of 220Wp per element. There is also a high power option using poly double glass modules from Schott Solar with between 230-300Wp per panel.

KOHLHAUER VOLTA® OPAK

KOHLHAUER VOLTA® THRU

KOHLHAUER VOLTA® BIFAC

KOHLHAUER VOLTA® POWER

Source: Kohlhauer Volta GmBH

Kohlhauer Volta GmbH

- Installed solar noise barrier (Kohlhauer Volta) in Munich in 2013. It consists of integrated PV modules with solar cells embedded between panes of toughed glass. Kohlhauer worked with an Austrian company, Ertex Solar, to develop the solar cells. Bauer-Energietechnik did connection and integration. The cells are arranged to make the barrier translucent to improve ambient light.
- It covers an area of $66m^2$ and generates 7.544 kW peak (defined under standard test conditions of 1,000 W/m^2.



Source: Kohlhauer Volta GmBH

TNC Energie Consulting GmbH

- Builds photovoltaic noise barriers consisting of bifacial polycrystalline silicon panels on concrete support structures on roads/rail or on median structures. Installed the first photovoltaic noise barrier in Switzerland in 1989. Since then it has installed 7 such barriers in Europe on both roads and railways.
- The Bifacial modules work best with a north-south orientation and in that position can get the same annual yield as a standard module in a south-facing position.
- The coverage of the PV modules can be varied to give different levels of light transmission through the barrier.
- The performance ratio of the module varies between 0.56-0.69.

Source: TNC Energie

TNC Energie example PV noise barrier

Figure 5, Italy's longest PV Noise barrier

Source: TV Energy http://www.tvenergy.org/content/files/publications/photovoltaic-noise-barriers-1334753493.pdf

Schott Solar

- Specialists in solar panel construction and toughened glass. They have been involved in many European PNB projects as a supplier of the barrier (they integrate solar panels manufactured by e.g. TNC Energie into a toughened glass structure).
- They are a key suppliers for photo-voltaic noise barriers in Europe.

ECN and SEAC

- There is a demonstration project in progress:
    - Demonstration of a 450 m long prototype noise barrier, 6 m high with 4 m high PV panels on both sides, along a north-south stretch of the A16 near Dordrecht. Target performance is 90% of time in use and output of 300 MWh/year based on full time performance during the 18-month testing period, yielding approximately 356 tonnes CO2 reduction in the demonstration period (based on solar energy produced);
    - Expected to achieve a cost reduction of 20% compared to PV added to existing noise barriers;

Ko-tech/Ramboll/Nuwatt/SSM

- This consortium is installing solar panel on an existing noise barrier in Lexington, Massachusetts.
- Aim to install 2,500 ft of solar panels (166 panels) along a stretch of Route 128 to produce 825,000 kW.
- Claims to be first solar noise barrier in U.S. Project was announced in October 2016.

Source: http://lexington.wickedlocal.com/news/20161026/lexington-could-take-advantage-of-new-solar-panel-technology,

Oxford PV

- Working on commercializing perovskite solar cell technology, which has a higher efficiency that current thin film technology but is too early stage for a demonstration on The Ray (TRL 1-2). The technology is probably 10 years away from large scale commercial deployment.

Source: http://www.oxfordpv.com/Research

What goes inside?

Early stage concepts

These ideas are the result of an initial brainstorm. None of these concepts have been vetted for feasibility, appropriateness or quality.

General theme and layout

Early stage ideas

Make it like a public garden

There could be a path round the barrier, to take you round a story / different features, benches, perhaps a central hub or 'mini bandstand' which could have video / lighting / music etc. to draw people in. Also provide a quiet space to think / read a book / rest for a while.

Make it like a science museum

Populate space with lots of mini demonstrators and 'try me' buttons etc. – make it an engaging learning experience, and appealing to younger generations too. Enable people to see the future. Could include an architectural model of a bigger solar noise barrier, and provide more information on the technology / applications.

Make it an entertainment space

For example, could you use the curved barrier shape to make a mini amphitheater, with a stage in the center? Could be used for talks, events, performance etc, and not be disrupted by the noise of traffic. The solar power could be used for microphones / speakers etc., with message at end "this event has been entirely powered by this solar noise barrier."

Ways to explicitly demonstrate noise reduction

Early stage ideas

Video

This could be integrated either as a plinth / viewpoint style object, or projected onto the glass. Could also work with speakers set along the barrier. Video could contain two main messages:

1. Barrier function/technology, made by the Ray
2. Who the Ray are, mission, other projects

Microphone on road side of barrier

Microphone records sound level from cars, and then may play this noise through speakers on inside of the barrier – people could push a button to switch noise on/off to hear comparison. Could also provide a noise meter reading, and highlight effects on wildlife / hearing etc. at different levels.

Openable windows in the barrier

People can open a hatch / single panel to let the traffic sound through, so you can compare with and without the barrier, and hear the effect.

Projected sound waves

At night, project the sound waves created by traffic onto the glass panels, so you can visually see what you would be hearing if the barrier wasn't there.

Ways to implicitly demonstrate noise reduction

Early stage ideas

Music speakers

Possibly you upload your 'Raylist' and it plays in the space. Idea is that the noise level is reduced so much that you can hear music. The barrier converts bad sound to good sound. Could it turn into a place for events / parties? People use it as they want.

Hammock / lounge furniture

There is so little noise, that people can have a snooze / rest. Maybe an outdoor chaise longue or a reclined seating area, implied that it is meant for resting.

Water feature to show ripples

Have a channel / pond of water that crosses from inside the barrier to the outside – the water on the road side of the barrier should be rippled, and the water behind the barrier should be calm.

Increase people's noise threshold

Decrease visual noise in the surroundings (e.g. shade, smooth objects, lower the contrast).

Ways to utilize solar power for benefit

Early stage ideas

Lighting

Particularly for night time, so it remains a safe place to go. Could be flood lit, or have lighting bollards. Maybe people can push a button / download an app to change mood lighting of the space.

Water feature

To emphasize the tranquillity of the space – make it super pleasant and relaxing. It may also be possible to create an energy storage water feature, to prevent need for large batteries / connecting to the grid.

Work bar

Could provide laptop / phone charging, and provide a place to make a phone call. Could also power a WiFi hotspot. Could have an interactive screen somewhere to learn about The Ray and their mission.

Outdoor vending machine

Provide refreshments for your journey – snacks, drinks, and healthy food e.g. grapes. Use the power to chill. Could even be an apple tree or raspberry bush..? Maybe the power could be used to automate growing process e.g. auto irrigation / sprinklers for grass.

Ways to utilize solar power for benefit (cont.)

Early stage ideas

Patio with gobo projection

Could project The Ray's logo, or a message about the barrier. Gobo could be mounted on the top edge of the barrier, and project onto a flat patio area.

Noise cancelling speakers

Increases the noise reducing effect of the barrier, by utilizing power from solar panels to power noise cancelling speakers – an active barrier. Noise reduction in more than one way – justifies having a solar noise barrier, and not just a standard noise barrier.

Self playing piano

Contributes to relaxing, pleasant environment, without having speakers.

Aquaponics

Power a pump for aquaponics.

Ways to utilize solar power for benefit (cont.)

Early stage ideas

Cool people on a hot sunny day

Either run fans, run a water mister or power an ice maker (for BYO picnic drinks)

Ways to enhance barrier aesthetics

Early stage ideas

Change tint colors of the glass

Perhaps showing lots of different colors, to demonstrate the aesthetics possibilities of the panels for architects etc.

Substitute concrete base and pillars for alternative material

Could the pillars be wooden? Or they could be made thinner / have a smooth profile to improve the aesthetics. Should it be made to look crash worthy (i.e. with concrete base) or made to looks as good as possible?

Opaque + transparent glass

Use smart glass / electricity to switch glass from being transparent to opaque – perhaps people could switch this themselves, so they can play around with the aesthetic of the barrier, or provide themselves with some shade.

Alter the physical form of barrier

For example, the barrier could be tilted towards the sun, made to look like a ribbon, concave / convex effects by altering form of the pillars (glass panels must still be flat, but they don't all need to be on the same plane). This would demonstrate the freedoms of the aesthetics to architects etc. Could glass panels be staggered?

Features to make it a pleasant environment

Early stage ideas

Plants, ponds, fish and wildlife

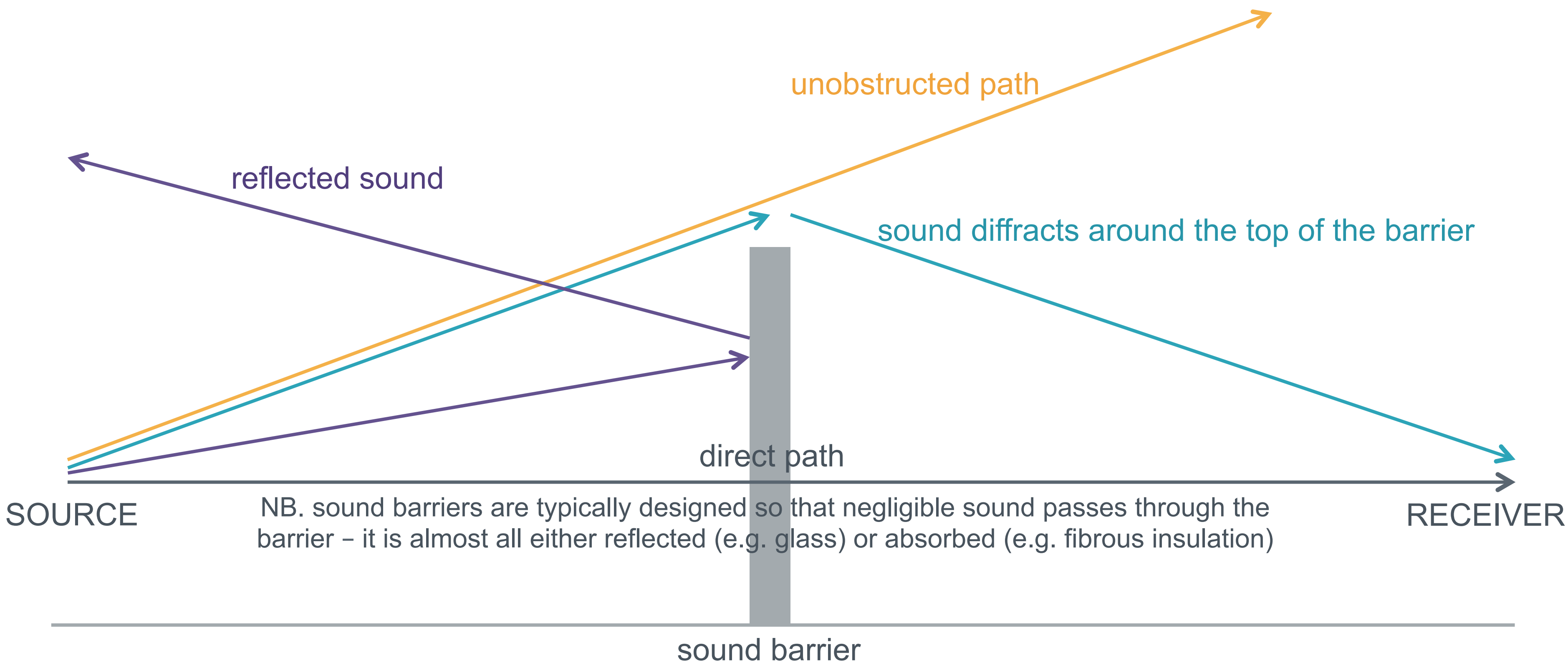
Attractions to draw people to the space and learn about the barrier function. Beautiful flowers etc. or could have hedgehog homes. Could place attractors for wildlife e.g. flowers for bees, berries for small animals. This would link how noise pollution can affect animal habitats.

Swings

Just for fun – but also an attraction for children, so that they are drawn to the space and learn about new technology / The Ray.

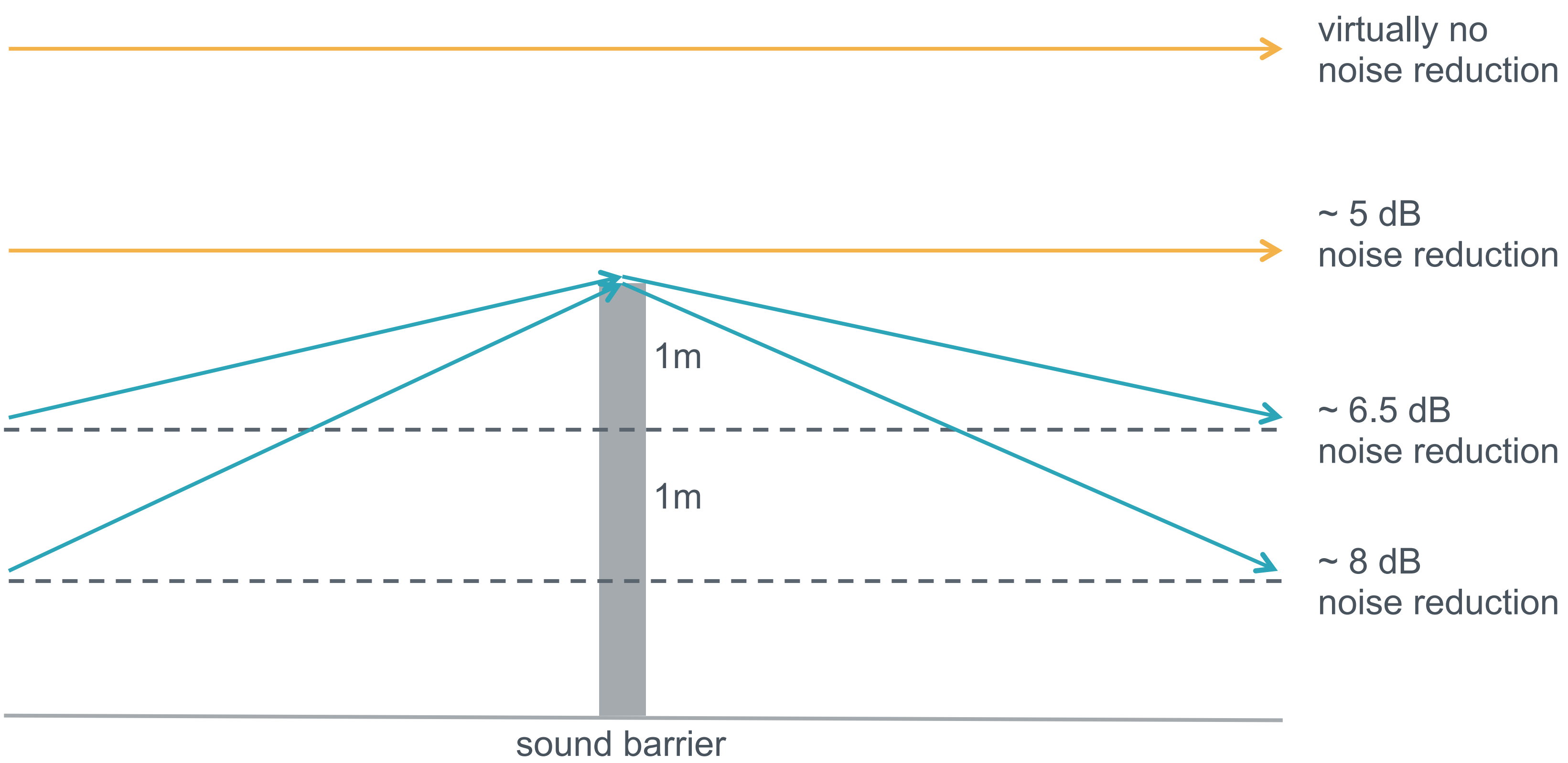
Calculating noise reduction

It's all about diffraction – sound bending round the top of the barrier



Assuming the direct path is blocked, the noise at the receiver is dominated by sound diffracted round the top of the barrier

Rules of thumb…



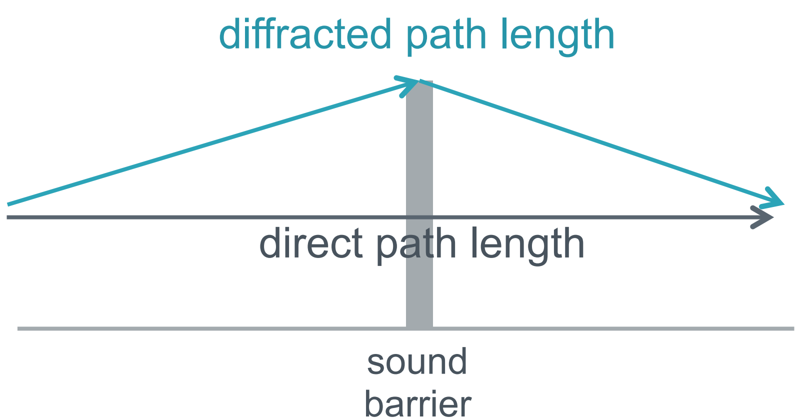
5dB reduction for sound that just grazes the top of the barrier, and 1.5 dB reduction for each additional meter of barrier height

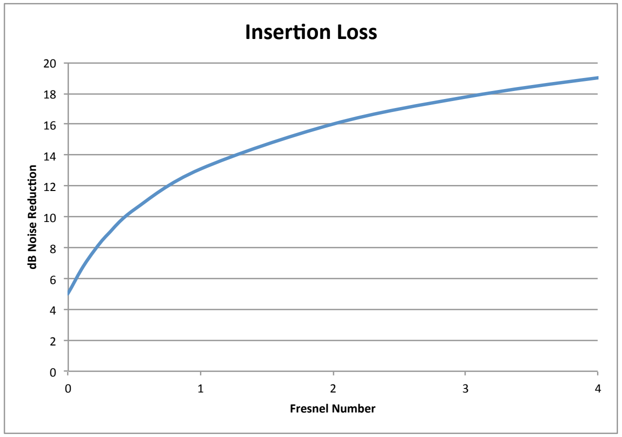
More accurately....

Fresnel number = the number of extra wavelengths that the sound has to travel to get around the barrier.

= the difference between the diffracted path length, and the direct path length, in wavelengths.

The graph below then shows the **Insertion Loss**, which is the reduction in sound after inserting the barrier.





$$\text{Insertion Loss} = 5dB + 20\log\left[\frac{\sqrt{2\pi N}}{\tanh\sqrt{2N}}\right]dB \quad \text{up to N} = 12.5$$

$$\text{Insertion Loss} = 20\text{dB} \quad \text{for } N > 12.5$$

N = Fresnel Number = Number of additional wavelengths the sound must travel around the barrier

Highway traffic noise has a peak around 1000Hz, with a wavelength of about 1 foot

What’s achievable?

- 5dB is relatively easy to obtain
- 10 dB is obtainable using barriers of significant size
- 15 dB is difficult to obtain
- 20 dB is practically normally impossible to maintain

- http://www.ucprc.ucdavis.edu/pdf/UCPRC-RP-2010-04.pdf
- Page 19

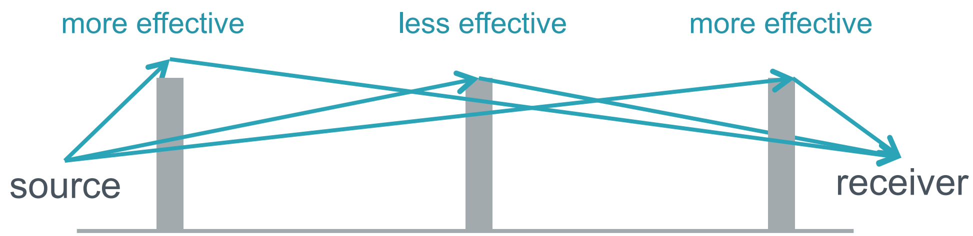
Assessment of the Troup County High School site

How noisy is it at the school?

- The line of sight from the highway (or maybe the Google StreetView camera) to the school ground level just intersects the existing berm, and this may be delivering 5dB of sound reduction already
- The school is about 600 ft from the highway. “Traffic noise is not usually a serious problem for people who live more than 500 feet from heavily traveled freeways”
  - http://www.nonoise.org/library/highway/traffic/traffic.htm
- Key question: is noise at the school currently a problem?

Would a noise barrier be effective?

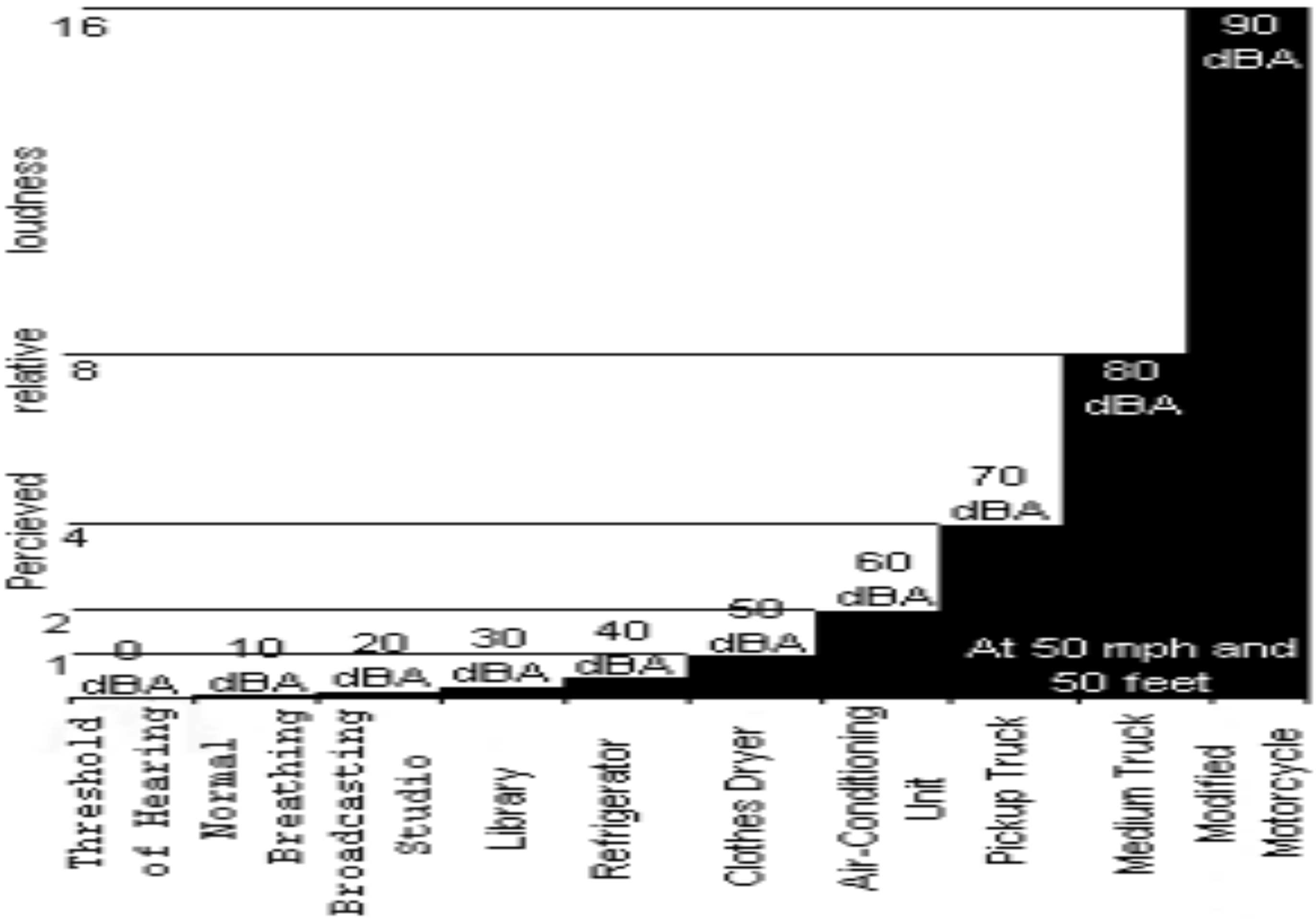
- A noise barrier is most effective is it’s positioned near the source or receiver:



- The berm is ~110m from the school and ~82m from the I-85 – we very roughly estimate a 3m high barrier would deliver a ~4-8dB reduction at the school

Highway noise and DOT guidelines

How loud is a highway?



Source: http://www.nonoise.org/library/highway/traffic/traffic.htm

EPA Noise Pollution Rules

- The EPA has set a maximum noise level of 80db at 50ft from the centreline of travel for heavy and medium sized trucks.
- The noise levels are descried using 2 terms Leq and L10. The former corresponds to the equivalent noise level throughout the day whereas the latter corresponds to the noise level exceeded 10% of the time in the noisiest hour of the day. The different noise abatement levels can be defined as:

Activity	L_{eq} (dB)	L_{10} (dB)
Category A: Lands on which serenity and quiet are of extraordinary significance and serve an important public need.	57	60
Category B: Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries and hospitals.	67	70
Category C: Developed lands, properties or activities not included in categories A or B.	72	75
Category E: Interior of: residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals and auditoriums	52	55

- Levels of highway noise for busy traffic typically range from 70-80 dB.

Source: Federal Highways Agency http://www.fhwa.dot.gov/environment/noise/regulations_and_guidance/probresp.cfm

Noise Survey

- Noise surveys are done at potential sites for noise barriers to assess the individual case for a noise barrier.
- An ambient sound level survey, or baseline survey as they're sometimes called, collects all the sounds associated with a given environment to give you a "baseline" sound level for that specific location. Most municipalities require an ambient survey of at least 24hrs with some being as long as 72hrs. Measurements must be conducted only under appropriate environmental conditions (temperature between 32 and 110 degrees F, relative humidity between 5 and 90%, winds less than 12 mph, no precipitation, dry roads, etc.)
- In this case, as an existing highway is the dominant noise source, there should be a noise model for the highway, and any new noise survey needs to be checked against the noise model for validation. The key metric for determining whether noise abatement is needed is the L10, the noise level exceeded 10% of the time in the noisiest hour of the day. This would need to be above 70 dB at the impacted location to justify noise abatement measurements.
- Any noise barrier must achieve a reduction of at least 5 dB at the point of impact to be considered beneficial.

US DOT Noise Barrier Design Guidelines

Acoustic Considerations

- Barrier Panel should weigh at least 20 kg/sq.m for sound loss of 10dB. Barrier height should be enough to ensure only a small part of the sound gets diffracted over the edges.

Types of noise barrier

- Noise Berm: Not Aesthetic, needs adequate drainage requirement, accessibility around noise berm to be considered.
- Post and Panel Wall: Possibility of sound transmission leaks between stacked panel and panel to post connection. Special considerations for wind loading.
- Free standing Pre cast concrete: Issues with construction since pre cast requires transportation and traffic implications.
- Noise Wall: The noise wall structures are usually placed with noise berm and are made up of concrete, wood, plastic, glass, metal and composites.

Aesthetic considerations

- Landscaping, Alignment changes, sloping of panels, drainage should be considered.

Drainage and utility considerations

- Proper water drainage should be considered. Care should be taken in placing road signsnear noise barriers. Also overhead and underground utility components shall be checked.

US DOT Noise Barrier Design Guidelines

Structural Considerations

- Panel expansion and contraction shall not be constricted. Proper loading data for wind, snow shall be considered. Proper design of barrier footing.

Safety Considerations

- **Fire Safety** of the barriers should be considered. Also provisions for emergency access shall be considered. Glare properties of the noise barriers shall be checked.
- **Traffic Protection and Detours:** The cost of traffic protection/detours may increase barrier installation cost. The contractor may charge a higher unit cost for barrier construction performed close to traffic as compared to construction in a less restricted area.

Noise barrier design

- The best configuration appears to be T-shaped with the shielding element on the top inclined at 60˚ to the vertical. This minimizes reflection to the other side of the road, which might be more of a concern in urban areas.
- Most studies find it hard to quantify the benefits of the noise barrier as they are mainly ecological. Some use analysis of preferences of residence and translate this into willingness to pay via hedonic pricing method. It can also be quantified in terms of the cost of houses land in the area using a noise sensitivity depreciation index.

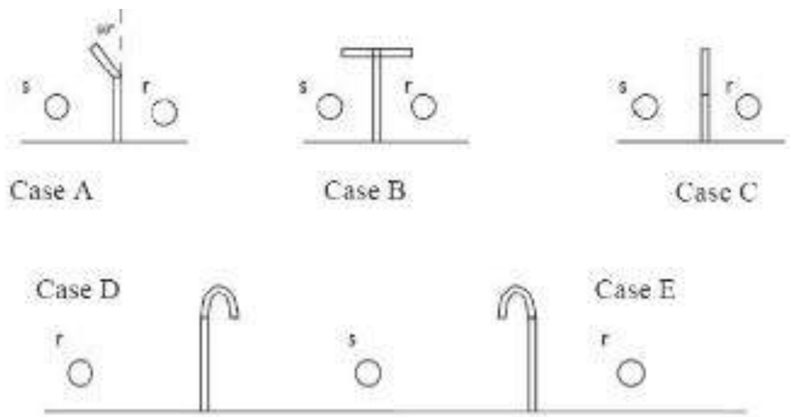


Fig. 1. Several diffractors used to compare the acoustic and energetic characteristics.

Source: De Schepper, Ellen, et al. "Combining photovoltaics and sound barriers–A feasibility study." Renewable energy 46 (2012): 297-303.

Safety Concerns for Solar Noise Barriers

- Key concerns with solar noise barriers:
  - Glint and glare might distract motorists. Evidence from a UK trial found no significant differences in driver behavior before and after installation of the PVNB.
  - Noise reflection – noise barriers protect properties situated behind them but slightly increase noise on the other side of the road due to reflection. Trees and shrubs behind the noise barrier can help absorb reflected noise.
- Need to avoid shading by structures such as trees, poles etc.
- Needs to be ”safe” if a car crashes into it.
- Most solar panel/glass construction reflects noise, which does mean it acts as a noise barrier for structures behind it, but can increase local noise in front of it. Is this an issue?

Sources

Sources

- Metal Noise Barriers
  - https://www.soundfighter.com/metal-vs-absorptive-sound-barriers/
  - https://www.ohioturnpike.org/wp-content/uploads/2013/05/Summary_Report_Full_Compressed.pdf
  - https://www.fhwa.dot.gov/ENVIRonment/noise/noise_barriers/design_construction/design/design05.cfm
  - Sinha, Kumares C., and Samuel Labi. *Transportation decision making: Principles of project evaluation and programming*. John Wiley & Sons, 2011.
- Polysolar
  - http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/13874.txt
  - http://www.polysolar.co.uk/_literature_138380/2015_Guide_to_BIPV
  - http://www.bpva.org.uk/media/88136/uk_solar_pv_strategy_part_2.pdf
- Heijmans
  - http://www.techtimes.com/articles/68439/20150713/colorful-dutch-roadside-noise-barriers-generate-solar-power.htm
  - Debije, Michael. "Renewable energy: Better luminescent solar panels in prospect." *Nature* 519.7543 (2015): 298-299. http://www.nature.com/nature/journal/v519/n7543/full/519298a.html
  - https://www.seac.cc/en/conclusions-on-solar-noise-barriers-sonob-project/
  - https://www.seac.cc/en/graffiti-on-solar-noise-barriers/
  - https://www.seac.cc/wp-content/uploads/2017/03/SONOB-RVO-eindrapport-openbaar.pdf
  - https://www.heijmans.nl/en/news/unique-field-test-started-solar-noise-barriers/
  - Kanellis, Michalis, et al. "The solar noise barrier project: 1. Effect of incident light orientation on the performance of a large-scale luminescent solar concentrator noise barrier." *Renewable Energy* 103 (2017): 647-652. http://www.sciencedirect.com/science/article/pii/S0960148116309557
  - https://www.nature.com/nature/journal/v519/n7543/full/519298a.html

Sources

- Kohlhauer Volta
  - http://www.gnf.eu/wp-content/uploads/2015/09/GNF-KOHLHAUER-VOLTA-en.pdf
  - https://www.kohlhauer.com/en/noise-barriers
  - https://www.kohlhauer.com/en/blog/photovoltaic-noise-barrier-in-munich
  - http://www.ertex-solar.at/en/news/news-archive/256-photovoltaic-noise-barrier-in-munich
- TNC Energie
  - http://www.tnc.ch/en/power-instead-noise-photovoltaic-noise-barriers-1
  - http://www.tnc.ch/en/bifacial-cells-%E2%80%93-double-sided-photovoltaic-systems
  - http://pvdatabase.org/projects_view_details.php?ID=376
  - http://www.autobrennero.it/en/the-motorway-network/sustainable-development/noise-protection-wall-/
- Schott Solar
  - http://www.schott.com/english/applications/energy_environment.html?highlighted_text=solar+panels

Sources

- Noise Barrier Design
    - http://www.nonoise.org/library/highway/traffic/traffic.htm
    - http://www.fhwa.dot.gov/environment/noise/regulations_and_guidance/probresp.cfm
    - http://ac.els-cdn.com/S1876610215025576/1-s2.0-S1876610215025576-main.pdf?_tid=788706da-30ab-11e7-a799-00000aab0f6b&acdnat=1493890047_afe0263785f50ac363545ff3de2b09a5
    - De Schepper, Ellen, et al. "Combining photovoltaics and sound barriers–A feasibility study." Renewable energy 46 (2012): 297-303.
    - http://ac.els-cdn.com/S1876610215025576/1-s2.0-S1876610215025576-main.pdf?_tid=ce88b054-358f-11e7-a6fd-00000aab0f6c&acdnat=1494427922_9397584acacf74380af2f641bdc1eec6 Vallati, A., et al. "Photovoltaics noise barrier: acoustic and energetic study." *Energy Procedia* 82 (2015): 716-723.
    - http://www.dot.state.mn.us/environment/noise/pdf/mndot-2015-noise-policy.pdf
    - http://www.dot.ga.gov/BuildSmart/Projects/Documents/I285SR400/Environmental/Final%20Noise%20Abatement%20Policy.pdf
    - https://www.fhwa.dot.gov/environment/noise/noise_barriers/design_construction/design/design17.cfm
    - https://www.fhwa.dot.gov/environment/noise/regulations_and_guidance/probresp.cfm
    - http://www.highways.gov.uk/knowledge_compendium/DA144AAA7CCD4D47984453C11EE7FE6D.aspx
    - Can, Arnaud, et al. "Traffic noise spectrum analysis: Dynamic modeling vs. experimental observations." *Applied Acoustics* 71.8 (2010): 764-770. https://hal.inria.fr/hal-00506615/document
    - Pilkington Noise Control with Glass: Technical Bulletin http://assetmanager-ws.pilkington.com/fileserver.aspx?cmd=get_file&ref=8221&cd=cd.

Sources

- ECN and SEAC
  - http://solarhighways.eu/over-solar-highways/partners
- Ko-tech/Ramboll/Nuwatt/SSM
  - http://lexington.wickedlocal.com/news/20161026/lexington-could-take-advantage-of-new-solar-panel-technology, http://www.nuwattenergy.com/innovative-solar-us-pv-noise-barriers/
- Retrofitting
  - Nordmann, Th, et al. "Integrated PV noise barriers: six innovative 10 kWp testing facilities, a German/Swiss technological and economical success story!." *2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, Austria*. 1998. https://www.researchgate.net/publication/282692701_INTEGRATED_PV_NOISE_BARRIERES_SIX_INNOVATIVE_10_KWp_TESTING_FACTLITIES
  - http://www.tvenergy.org/content/files/publications/photovoltaic-noise-barriers-1334753493.pdf
  - http://www.appropedia.org/index.php?title=PV_deployed_on_noise_barriers_literature_review

Sources

- Carbon neutral concrete
  - A. Samarin (7 September 1999), "Wastes in Concrete :Converting Liabilities into Assests", in Ravindra K. Dhir; Trevor G. Jappy, Exploiting wastes in concrete: proceedings of the international seminar held at the University of Dundee, Scotland, UK, Thomas Telford, p. 8
  - https://www.theguardian.com/sustainable-business/2016/dec/13/sequester-carbon-blue-planet-climate-change
- Solar power in the USA
  - http://www.sciencedirect.com/science/article/pii/S1364032117308584
  - https://www.eia.gov/totalenergy/data/monthly/pdf/sec7_3.pdf

MAKE IT HAPPEN

Innovia Technology Limited,
St Andrew's House, St Andrew's Road,
Cambridge, CB4 1DL, UK