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The Philosophy of Acoustic Design Practice: Why it’s OK to use the Sabine Equation

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ABSTRACT

Acoustic consultants routinely use a range of engineering approaches to provide ‘acoustic designs’ for projects in the built environment. However, the fundamental engineering design methodology that engineers adopt in approaching their work is rarely formally taught, and is often not well defined or understood by engineers themselves. Koen’s *Discussion of the Method* is used to explore ‘what is design’ and how it is that engineers go about designing things. The engineering design process is reviewed using the context of an acoustic consultant designing absorptive treatment for a railway tunnel environment. The use and limitations of Sabine’s equation for reverberation time (RT) in relation to alternative formulations and contemporary computer modelling approaches is reviewed. It is concluded that, in accordance with Koen’s *Method*, it is always reasonable for an engineer to use the Sabine equation as a part of the acoustic design process to understand the reverberation time characteristics of a space, provided the limitations are understood.

1 INTRODUCTION

Acoustic engineers and consultants are now integral in teams undertaking projects in the built environment, including transport infrastructure, buildings and industrial facilities. Acousticians are tasked with solving a range of practical problems, usually aimed at achieving design or contractual requirements and criteria related to noise and vibration – and most often tasked with making things quieter. However, the fundamental engineering design methodology that is adopted by acousticians to approach the problem solving necessary to undertake major projects is rarely formally taught. Indeed, in the authors’ experience, only a few of the things we were taught at university hinted at the design process itself. Much of the design approach and problem solving skills are left to be learnt ‘on the job’.

Nevertheless, there seems to be a renewed interest in understanding the design process itself – to try and seek out ways of improving the way we design things with a view to creating more satisfying, efficient, and ‘delightful’ design outcomes. Most engineers will have undertaken a teambuilding exercise where they are forced to construct some engineering edifice out of simple materials – usually it involves something like making a bridge or a tower out of spaghetti and marshmallows. The aim is usually to prove that your group’s design can span further or higher that everyone else’s, despite being constructed of lightweight, delicate materials that are prone to catastrophically fail when overloaded (or be eaten by your teammates, limiting their availability). The exercise forces the engineer to examine the design brief, the fundamental constraints to achieving it (for example the structural limitations and availability of the building materials), and to undertake some collaborative process where, as a group, the materials can be put together in the most efficient way.

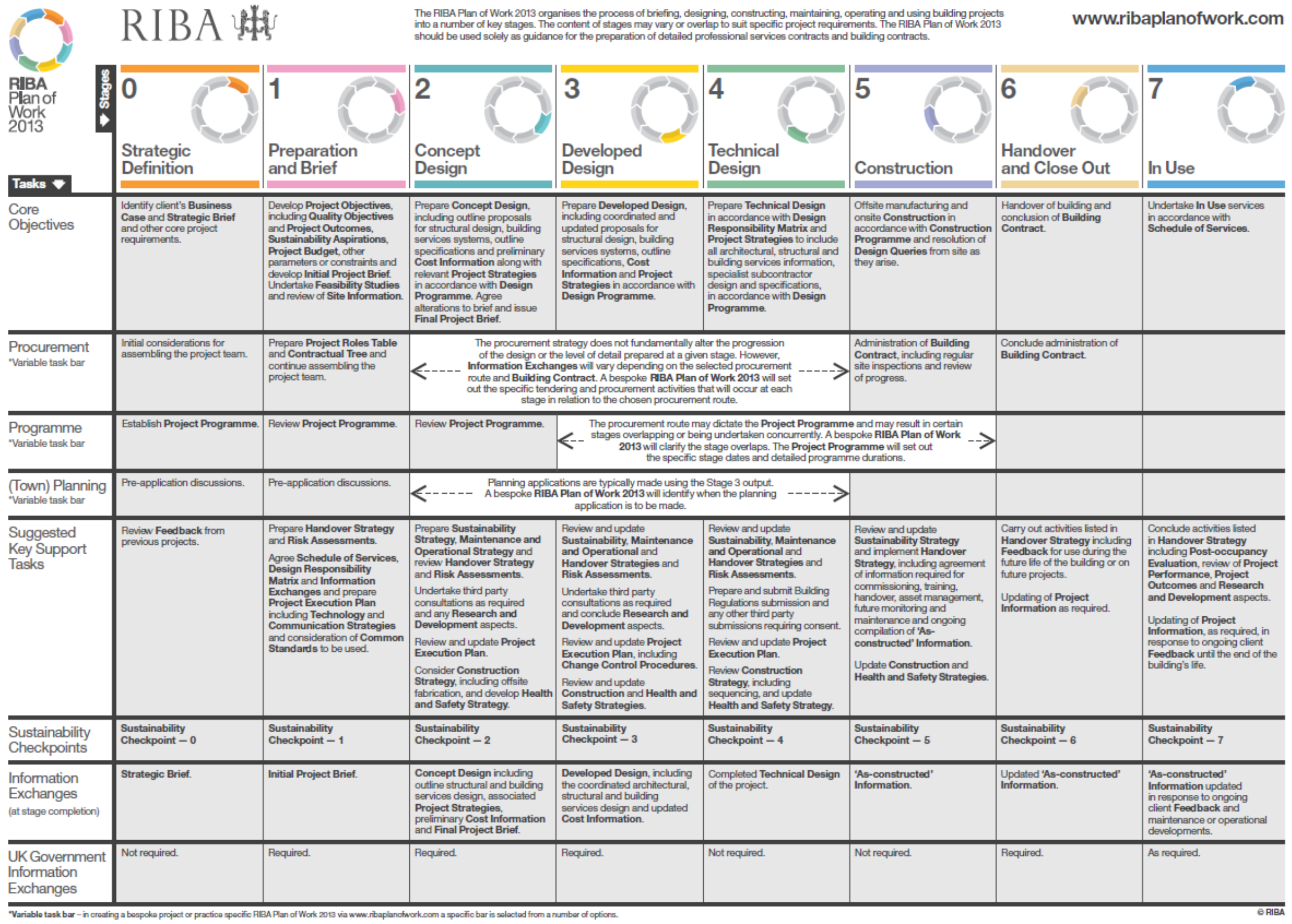
Amongst this backdrop, acoustic engineering is still sometimes referred to as a ‘black art’ by acoustics professionals and lay people alike, implying that the fundamental laws or rules for undertaking acoustic design or engineering are arcane and unknowable. However, there are a wide range of physical laws, and well established engineering approaches that acousticians apply to undertake acoustic designs for a diverse range of projects. The approach, or method, that is adopted by acoustic engineers to design things appears to be largely acquired by practice, and is rarely taught explicitly at university.

This paper provides a philosophical investigation of acoustic engineering by exploring the fundamental ways that engineers approach design problems, based on Koen’s *Discussion of the Method* (2003). The ‘engineering method’ is illustrated using the engineer’s approach to predicting reverberation time, and a case study of the need to design acoustically absorptive linings for railway tunnels to control sound levels inside railway carriages.

By exploring and unpacking the way it is that we as acoustic engineers design things, the aim of the paper is to improve the way that we as a profession view (and review) the work of others, communicate our work to clients, and manage technical risk on projects.

2 WHAT IS ‘DESIGN’ AND THE ‘DESIGN PROCESS’?

Many engineers will be familiar with the common stages of building design and construction processes adopted by architects which are largely based around those first developed by the Royal Institute of British Architects (RIBA) in 1963 (see Figure 1).



RIBA

The RIBA Plan of Work 2013 organises the process of briefing, designing, constructing, maintaining, operating and using building projects into a number of key stages. The content of stages may vary or overlap to suit specific project requirements. The RIBA Plan of Work 2013 should be used solely as guidance for the preparation of detailed professional services contracts and building contracts.

www.ribaplanofwork.com

RIBA Plan of Work 2013

Stages ▶ Tasks ▼	0 Strategic Definition	1 Preparation and Brief	2 Concept Design	3 Developed Design	4 Technical Design	5 Construction	6 Handover and Close Out	7 In Use
Core Objectives	Identify client's **Business Case** and **Strategic Brief** and other core project requirements.	Develop **Project Objectives**, including **Quality Objectives** and **Project Outcomes**, **Sustainability Aspirations**, **Project Budget**, other parameters or constraints and develop **Initial Project Brief**. Undertake **Feasibility Studies** and review of **Site Information**.	Prepare **Concept Design**, including outline proposals for structural design, building services systems, outline specifications and preliminary **Cost Information** along with relevant **Project Strategies** in accordance with **Design Programme**. Agree alterations to brief and issue **Final Project Brief**.	Prepare **Developed Design**, including coordinated and updated proposals for structural design, building services systems, outline specifications, **Cost Information** and **Project Strategies** in accordance with **Design Programme**.	Prepare **Technical Design** in accordance with **Design Responsibility Matrix** and **Project Strategies** to include all architectural, structural and building services information, specialist subcontractor design and specifications, in accordance with **Design Programme**.	Offsite manufacturing and onsite **Construction** in accordance with **Construction Programme** and resolution of **Design Queries** from site as they arise.	Handover of building and conclusion of **Building Contract**.	Undertake **In Use** services in accordance with **Schedule of Services**.
Procurement *Variable task bar	Initial considerations for assembling the project team.	Prepare **Project Roles Table** and **Contractual Tree** and continue assembling the project team.	←---- The procurement strategy does not fundamentally alter the progression of the design or the level of detail prepared at a given stage. However, **Information Exchanges** will vary depending on the selected procurement route and **Building Contract**. A bespoke **RIBA Plan of Work 2013** will set out the specific tendering and procurement activities that will occur at each stage in relation to the chosen procurement route. ----→			Administration of **Building Contract**, including regular site inspections and review of progress.	Conclude administration of **Building Contract**.	
Programme *Variable task bar	Establish **Project Programme**.	Review **Project Programme**.	Review **Project Programme**.	←-- The procurement route may dictate the **Project Programme** and may result in certain stages overlapping or being undertaken concurrently. A bespoke **RIBA Plan of Work 2013** will clarify the stage overlaps. The **Project Programme** will set out the specific stage dates and detailed programme durations. --→				
(Town) Planning *Variable task bar	Pre-application discussions.	Pre-application discussions.	←------ Planning applications are typically made using the Stage 3 output. A bespoke **RIBA Plan of Work 2013** will identify when the planning application is to be made. ------→					
Suggested Key Support Tasks	Review **Feedback** from previous projects.	Prepare **Handover Strategy** and **Risk Assessments**. Agree **Schedule of Services**, **Design Responsibility Matrix** and **Information Exchanges** and prepare **Project Execution Plan** including **Technology** and **Communication Strategies** and consideration of **Common Standards** to be used.	Prepare **Sustainability Strategy**, **Maintenance and Operational Strategy** and review **Handover Strategy** and **Risk Assessments**. Undertake third party consultations as required and any **Research and Development** aspects. Review and update **Project Execution Plan**. Consider **Construction Strategy**, including offsite fabrication, and develop **Health and Safety Strategy**.	Review and update **Sustainability**, **Maintenance and Operational** and **Handover Strategies** and **Risk Assessments**. Undertake third party consultations as required and conclude **Research and Development** aspects. Review and update **Project Execution Plan**, including **Change Control Procedures**. Review and update **Construction** and **Health and Safety Strategies**.	Review and update **Sustainability**, **Maintenance and Operational** and **Handover Strategies** and **Risk Assessments**. Prepare and submit Building Regulations submission and any other third party submissions requiring consent. Review and update **Project Execution Plan**. Review **Construction Strategy**, including sequencing, and update **Health and Safety Strategy**.	Review and update **Sustainability Strategy** and implement **Handover Strategy**, including agreement of information required for commissioning, training, handover, asset management, future monitoring and maintenance and ongoing compilation of **‘As-constructed’ Information**. Update **Construction** and **Health and Safety Strategies**.	Carry out activities listed in **Handover Strategy** including **Feedback** for use during the future life of the building or on future projects. Updating of **Project Information** as required.	Conclude activities listed in **Handover Strategy** including **Post-occupancy Evaluation**, review of **Project Performance**, **Project Outcomes** and **Research and Development** aspects. Updating of **Project Information**, as required, in response to ongoing client **Feedback** until the end of the building's life.
Sustainability Checkpoints	**Sustainability Checkpoint — 0**	**Sustainability Checkpoint — 1**	**Sustainability Checkpoint — 2**	**Sustainability Checkpoint — 3**	**Sustainability Checkpoint — 4**	**Sustainability Checkpoint — 5**	**Sustainability Checkpoint — 6**	**Sustainability Checkpoint — 7**
Information Exchanges (at stage completion)	**Strategic Brief**.	**Initial Project Brief**.	**Concept Design** including outline structural and building services design, associated **Project Strategies**, preliminary **Cost Information** and **Final Project Brief**.	**Developed Design**, including the coordinated architectural, structural and building services design and updated **Cost Information**.	Completed **Technical Design** of the project.	**‘As-constructed’ Information**.	Updated **‘As-constructed’ Information**.	**‘As-constructed’ Information** updated in response to ongoing client **Feedback** and maintenance or operational developments.
UK Government Information Exchanges	Not required.	Required.	Required.	Required.	Not required.	Not required.	Required.	As required.

***Variable task bar** – in creating a bespoke project or practice specific RIBA Plan of Work 2013 via www.ribaplanofwork.com a specific bar is selected from a number of options.

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(RIBA, 2013)

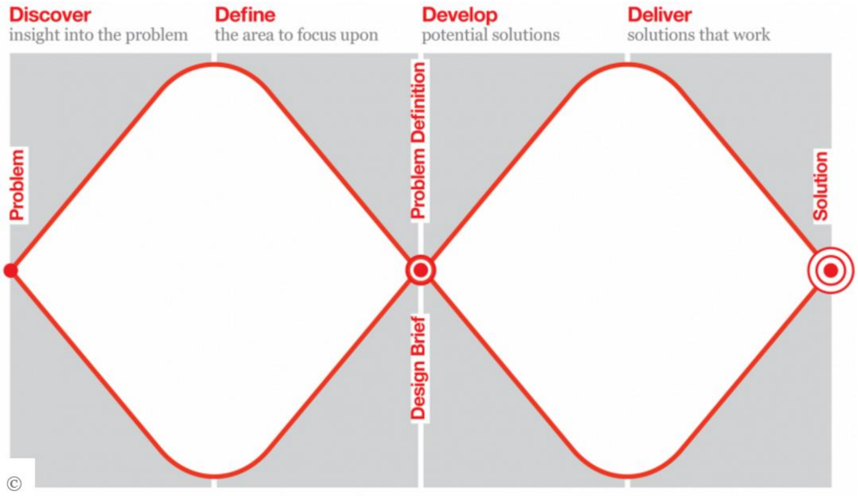
Figure 1: RIBA Plan of Work 2013.

The RIBA work stages provide an overview of the common design process adopted by architects, which includes the phases of Strategic Definition, Briefing, Concept Design, Developed Design and Technical Design prior to the construction itself. But while this provides an outline of a common design journey, it doesn’t really help to define the design activity itself.

‘Design’ is clearly difficult to completely or satisfactorily define, since it brings together the somewhat disparate threads of creativity, aesthetics, analytics and functionality. As a consequence, most dictionary definitions of ‘design’ are largely unsatisfying.

Nevertheless, a lot of attention is being applied to understanding ‘design’ and ‘the design process’ itself by a wide range of practitioners, including engineers, but also by other ‘creative’ or ‘design focussed’ professionals such as architects, industrial and graphic designers, artists etc.

Part of the current focus is an attempt to ‘redesign design’ – to try and unpick the design process itself and make it better understood, more efficient, and more responsive to clients’ and the wider community’s needs. The UK Design Council’s ‘Double Diamond’ process (2015) is one contemporary approach to defining design. The key being that it precedes the usual design development processes with *discovery* and *problem definition* phases. Only once the problem space is satisfactorily explored, and the ‘right’ problem identified, are the usual range of possible design solutions considered using a process of ‘divergent thinking’ (sometimes called ‘ideation’) prior to refining the solution to the most optimum with ‘convergent thinking’.



(UK Design Council, 2015)
Figure 2: UK Design Council’s ‘Double Diamond’ design process.

The IT industry and the associated ‘dot-com’ and ‘startup’ boom have made significant contributions to thinking about design, as they strive to create new products at unprecedented speed that are tailored very specifically to users’ needs. The IT industry also has a significant advantage over typical ‘bricks and mortar’ design, since it is much easier to iterate software designs and to test prototypes than it is with buildings and roads.

Another key approach adopted in these new descriptions of design is ‘user-centeredness’ – putting the ultimate user at the centre of the design process - so the outcome is completely targeted at their satisfaction. These design approaches are typically referred to as Design Thinking, Human Centred Design (HCD) and User-experience (UX) design.

3 HOW DO ENGINEERS DESIGN THINGS?

So what is the approach, or method, that engineers (including acoustic engineers!) actually use to design things? There is surprisingly little discussion of ‘the engineering method’ in the literature.

Pioneering US acoustic engineer Ted Schultz provided an apt description of the process in his book *Community Noise Rating* (Schultz, 1982):

> *By its nature, the work of a consultant involves them in daily practical noise control problems. In many* cases *there is no clear cut approach and no widely accepted solution to the problem (if there were, the consultants would, in all probability, not have been called in!). In these cases the consultant draws upon their knowledge of existing acoustical theory, their past experience, and their intuition, apply these, perhaps, on a trial-and-error basis, to come up with a “state of the art” solution consistent with their clients time-schedule and budget. In this approach there is seldom time, or money, for carefully documented research. Nevertheless, after years of experience with a number of similar problems, a pattern begins to emerge and the consultant can, with some confidence, assemble their rules-of-thumb and case-histories into a consistent scheme for assessing a particular noise problem, for predicting the probable subjective response, for establishing how much noise control will be required and for proceeding to a practical solution. Such a procedure, once published, acquires a certain tutorial status and is likely to be copied by other consultants, thus, at least establishing a common vocabulary and promoting uniformity of approach to the problem.*

This approach will no doubt be familiar to many consulting acoustic engineers.

Schultz's description provides a good overview and is helpfully focussed on acoustic consultants in particular, However, Koen has undertaken a much more detailed examination of methods used by engineers, more broadly, to approach problems in his *Discussion of the Method: Conducting the Engineer's Approach to Problem Solving* (1988). In his work, Koen seeks to develop a fundamental understanding of the approach and methods used by engineers to solve problems which provides valuable insight for practising engineers.

Koen begins by defining the 'engineering method' as:

> *the strategy for causing the best change in a poorly understood situation within the available resources.*

He notes that the Engineering Method is fundamentally different to the Scientific Method – which has also been more widely studied (for example, Thomas Kuhn's *The Structure of Scientific Revolutions*, (1970), or Descartes' *Discours de la Methode* (1637)). Physicist and aerospace engineer Theodore Von Karman summed up the primary difference between scientists and engineers as: *'Scientists discover the world that exists; engineers create the world that never was'*.

Going further, Koen states that, unlike the Scientific Method, the Engineering Method is not associated with a specific morphology (that is, a specific form or structure), and does not follow a strict set of steps. Koen says that 'the essence of engineering is not captured in the commands: analyse, synthesise and evaluate'. Importantly, as Karl Willenbrock, an esteemed US engineering professor and former IEEE president stated:

> '*Their [engineers'] designs must satisfy scientific as well as non-scientific criteria such as manufacturability, maintainability, risk-minimisation, and cost-effectiveness*'.

All engineering designs are subject to design constraints. Koen highlights a few such as, physical, economic, political and artistic constraints, and highlights that the engineer therefore always seeks the best change within the available resources. The question then is 'What is best?', and what are 'the available resources'?.

With regard to 'what is best?', engineers seek optimum solutions against a range of evaluation criteria. The process of balancing an improvement in one criterion against a worsening of another is a 'trade off'.

The 'available resources' define and limit any engineering problem. Past experience with similar problems usually produces a better design. Past experience with similar problems should, therefore, be considered as a resource – and the use of precedents is strongly supported by both Koen and Schultz's observations.

Overall, Keon notes that:

> *The engineer's best solution to a problem is found by trade-offs in a multivariant space in which criteria and weighting coefficients are the context that determines the optimal solution. There is never an implication that a true, rational answer even exists. The answer the engineer gives is never the answer to a problem, but is their engineering best answer to the problem they are given – all things considered.*

3.1 Heuristics as the basis for Engineering Design

Developing his definition of Engineering Design, Koen embraces heuristics, or 'engineering rules of thumb', as the best way of understanding how engineers design things, and he redefines the Engineering Method as:

> *the use of heuristics to cause the best change in a poorly understood situation within the available resources.*

In general, heuristics are broadly defined as:

> *experience-based techniques for problem solving, learning, and discovery that find a solution which is not guaranteed to be optimal, but good enough for a given set of goals.*

In the context of engineering design, Koen goes on to define a heuristic as:

> *… anything that provides a plausible aid or direction in the solution of a problem but is in the final analysis, unjustified, incapable of justification, and potentially fallible*.

In identifying heuristics, Koen goes on to say that:

> *A scientist considers ambiguity in knowing if an answer to a question has been found a fatal weakness. She seeks procedures, strategies, and algorithms that give predictable results known to be true. Uncertainty about a solution's validity is a sure mark of the use of a heuristic. Unlike scientific theories, two heuristics may contradict or give different answers to the same question and still be useful*.

He then identifies the following four characteristics of a heuristic:

a) It does not guarantee a solution
b) It may contradict other heuristics
c) It reduces the search time to solve a problem
d) Its acceptance depends on the immediate context rather than an absolute standard.

Hungarian mathematician George Pólya, in his 1945 book on approaches to mathematical problems *How to Solve It* says:

> *Heuristic reasoning is reasoning not regarded as final or strict but as provisional and plausible only, whose purpose is to discover the solution to the present problem… We shall attain complete certainty when we shall have obtained the complete solution, but before obtaining certainty we must often be satisfied with a more or less plausible guess.*

3.2 What heuristics do engineers use?

A group of heuristics is usually required to solve most engineering design problems. Koen's work identifies 59 heuristics from general engineering practice, which fall into the following broad categories:

1. Rules of thumb and orders of magnitude
2. Factors of safety
3. Quantify variables
4. Always give an answer
5. Risk controlling heuristics
    a. make small changes to the state of the art,
    b. always give yourself a chance to retreat,
    c. use feedback to stabilize engineering design.

Three key heuristics adopted by engineers as part of the engineering method are:

1. Allocate resources as long as the cost of not knowing exceeds the cost of finding out
2. Allocate sufficient resources to the weak link, and
3. Solve problems by successive approximations.

4 AN ENGINEER'S APPROACH TO DETERMINING REVERBERATION TIME (T_{60})

At this stage, it is helpful to review a key heuristic used in everyday practice by acoustic engineers as an example. There are literally hundreds of possible heuristics that are used by acoustic engineers that could be explored ranging from very simple approximations to very complex design calculations. These include, for example, Sharpe or Davy's methods for calculating Transmission Loss, Makekawa's or Degout's methods for calculating noise barrier attenuation, and approximations for source sound power levels of transformers, generators or industrial fans, just to name a few.

For the purpose of this paper, an acoustic engineer's approach to determining Reverberation Time (T60) will be examined, as it is critical to the project example that follows. The Reverberation Time of a space is the critical measure of the time it takes for sound to decay, and is one of the key parameters (and sometimes, unfortunately, the only parameter) we as acoustic engineers use to define the 'acoustics' of a space.

4.1 Sabine's Equation

The primary heuristic that acoustic engineers use to determine Reverberation Time is the Sabine Equation:

$$T_{60} = 0.161\,\frac{V}{S\bar{\alpha}} = \frac{55.25}{c}\,\frac{V}{S\bar{\alpha}} \tag{1}$$

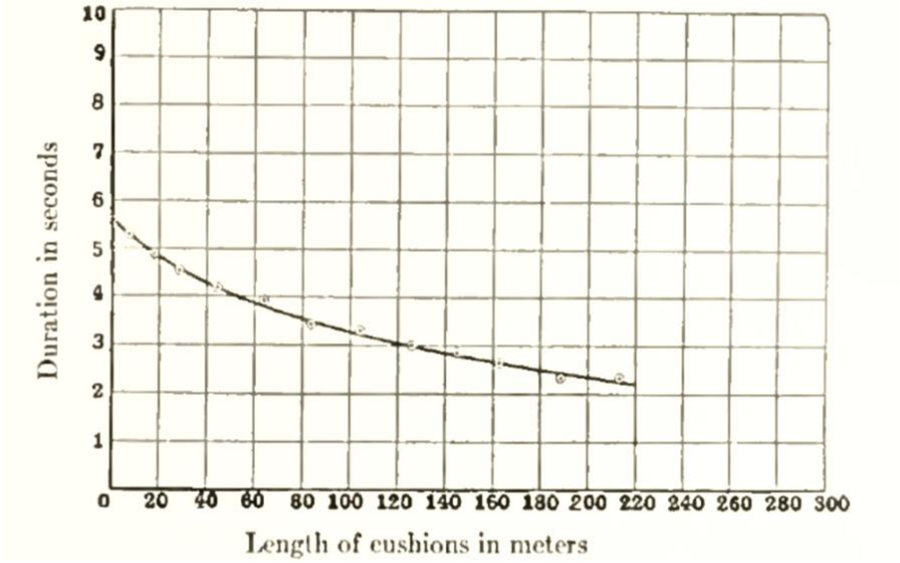
Where T_{60} is the reverberation time with a decay of 60 dB, V is the room volume (m^3), S is the room surface area (m^2) and $\bar{\alpha}$ is Sabine's average absorption coefficient for the room finishes.

The relationship, which relates the reverberation time to the ratio of the room volume to the amount of absorptive material in the space was determined empirically by Wallace Clement Sabine in the 1890s based on measurements in several rooms at Harvard University (Sabine, 1922). It was based on his observation that 'Broadly considered, there are two, and only two, variables in a room – shape including size, and materials including furnishings'.

As part of his investigation of acoustic problems with the lecture theatre in the Fogg Art Museum at Harvard University (which had a 5-second RT!), Sabine undertook measurements to determine the relative absorbing power of various 'substances'. Using an organ pipe as a constant source of sound, Sabine and his assistants timed the duration of audibility of the decay. He then gradually added absorptive material – firstly using the strongly-absorbent cushions from the seats in the nearby Sanders Theatre, before testing the absorbing power of other materials, people and furnishings.

While his analysis was directed at the practical problem at the Fogg Art Museum, Sabine stated that he sought a quantitative (rather than qualitative) solution as a predictive tool, so that 'its application can precede, not follow, the construction of the building'. In this respect, he was explicitly establishing his research and resulting equation as an engineering heuristic, that would aid in the *design process*.

The results of his measurements of reverberation duration in relation to the *length* of cushions from the Saunders Theatre are shown in Figure 3 below.



(Sabine, 1922)
Figure 3: Sabine's relationship between reverberation duration (T_{60}) and *length* of sound absorbent cushions installed in the space (m).

Further measurements in other spaces and on a range of materials were focussed on enabling him to express the results 'in some more permanent, more universally available, and if possible, more absolute unit than the cushions', and allowed him to determine 'the absorbing power of wall-surfaces, and a law according to which the reverberation of a room depends on its volume'. (Note that Sabine actually derived experimentally a constant value of 0.164, rather than 0.161 which is more universally adopted today.)

However, the Sabine equation, as we now know it, is a relatively simple empirical equation that does not allow for the aspect ratio or shape of the room, or effects like air absorption losses. Furthermore, Sabine observed that;

> '*The efficiency of an absorbent in reducing the duration of the residual sound is, under ordinary circumstances, nearly independent of its position'*.

In particular, Sabine’s equation applies for diffuse sound fields (i.e. sound is distributed uniformly), and for relatively reverberant (or ‘live’) rooms. In practice, of course, this rarely holds. We note here that, in a Koenian sense, these limitations of Sabine’s equation are completely expected of any engineering heuristic, and sit comfortably with Koen’s broad definitions (*experience based, not guaranteed to be optimal, good enough, potentially fallible*) described in Section 3.1 above.

4.2 Eyring, Fitzroy and other alternative formulations

Nevertheless, the limits on its application have led researchers to seek adjustments or alternatives to Sabine’s equation in an effort to improve the prediction. This has led to the development of other alternative empirical equations to determine RT, which provide better results than Sabine’s original equation in certain circumstances.

For example, Eyring (1930) adjusted Sabine’s approach for a ‘live’ room based on the mean-free-path within the volume, so created a more general formula that provides better results in more acoustically ‘dead’ spaces, as provided in Equation 2:

$$T_{60} = 0.161 \frac{V}{-S\ln(1-\bar{\alpha})} \tag{2}$$

Eyring’s formulation therefore provides better results where there is a lot of absorption. Further researchers tackled other limitations of Sabine’s approach. Probably the most well-known is Fitzroy (1959), who investigated the geometrical aspects of the sound field, and whose approach allows the consideration of absorption normal to the three major room axis. There are a wide range of further alternative formulations for Reverberation Time in rooms, including those by Millington-Sette (1932), Tohyama (1986), Arau-Puchades (1988) and Neubauer (2001).

More recently, Beranek (2006) discussed the use of various classical equations which are used to calculate reverberation time. His analysis investigates at some length the premise of there being a single “correct” equation for calculating reverberation time. Beranek concludes, essentially, that it is not possible to do so and essentially describes that each is a model with different assumptions. It is demonstrated that no single equation can ‘correctly’ predict the reverberation time of a space, and particularly that:

> *The premise of this paper is that if a particular reverberation equation (transfer function) is used and the reverberation time is held constant, the calculated absorption coefficient for the absorbing material will vary as it is moved around or made larger or smaller. Alternatively, if one requires that the absorption coefficient must remain the same regardless of its position or size, there is no single equation (transfer function) that will calculate the correct reverberation times. To explore this premise, this paper concentrates on the absorption of sound by a seated audience in concert halls.*

4.3 Computer room-acoustic models

More recently, computer room-acoustic models have also been used to estimate reverberation time. Dance and Shield (1999) provide a historical review of reverberation time prediction using classical theory, numerical simulations and physical scale models for performance spaces, including the work undertaken by Sabine, Eyring, Fitzroy, Kuttruff, and others, and particularly concentrating on the alternative Millington formulation. The results of predictions using the ‘classical’ theory are compared to those from three of the early computer numerical models (REDIR RT, CISM and RAMSETE). All models were found to produce results within 14% of the values calculated by the Eyring formula, with the results of the numerical simulations improved somewhat if the Millington based absorption coefficients were used.

5 IS IT OK TO USE SABINE’S EQUATION TO PREDICT RT IN A RAILWAY TUNNEL?

This section ties together the preceding discussion about the engineering design method, and the range of approaches to predicting reverberation time with a real-life, practical example. The example draws on our examination (undertaken as part of the resultant litigation) of the approach adopted by the project acoustic engineers for the design of in-tunnel and in-car noise for the Epping to Chatswood railway tunnel (ECRL). Our work centred on trying to answer the primary question of whether it was *reasonable to use Sabine’s equation to predict reverberation time in a railway tunnel*.

5.1 The Epping to Chatswood tunnel in-car noise issue

The issue of excessive in-car noise within the Epping to Chatswood railway tunnel in Sydney, when it first opened in 2009, is reasonably well documented (Coker & Anderson, 2010; Weber et al, 2012). The key reasons for excessive in-car noise were attributed to high source levels of wheel/rail noise radiation (due to both high rail roughness and low track stiffness), insufficient tunnel absorptive treatment and low vehicle sound insulation (due to the use of old, naturally ventilated rolling stock). The mitigation included track polishing and track dampers to control noise emissions from the wheel and rail, and the installation of additional in-tunnel sound absorptive treatments to control sound propagation within the tunnel.

Adverse media fallout from the high in-car noise levels in the Epping to Chatswood tunnel and the subsequent legal proceedings have combined to create a strong precedent for including absorptive material in railway tunnel projects in Australia, and they have been specified on several recent projects (eg Forrestfield, Sydney Metro, Melbourne Metro).

However, while absorptive tunnel linings have also been used on several older Australian railway tunnels including the Sydney Eastern Suburbs Line (ESL) and Melbourne Underground Rail Loop (MURL) (see Figure 4), there is actually little precedent for them, since they are not commonly installed on metropolitan railway tunnels internationally.

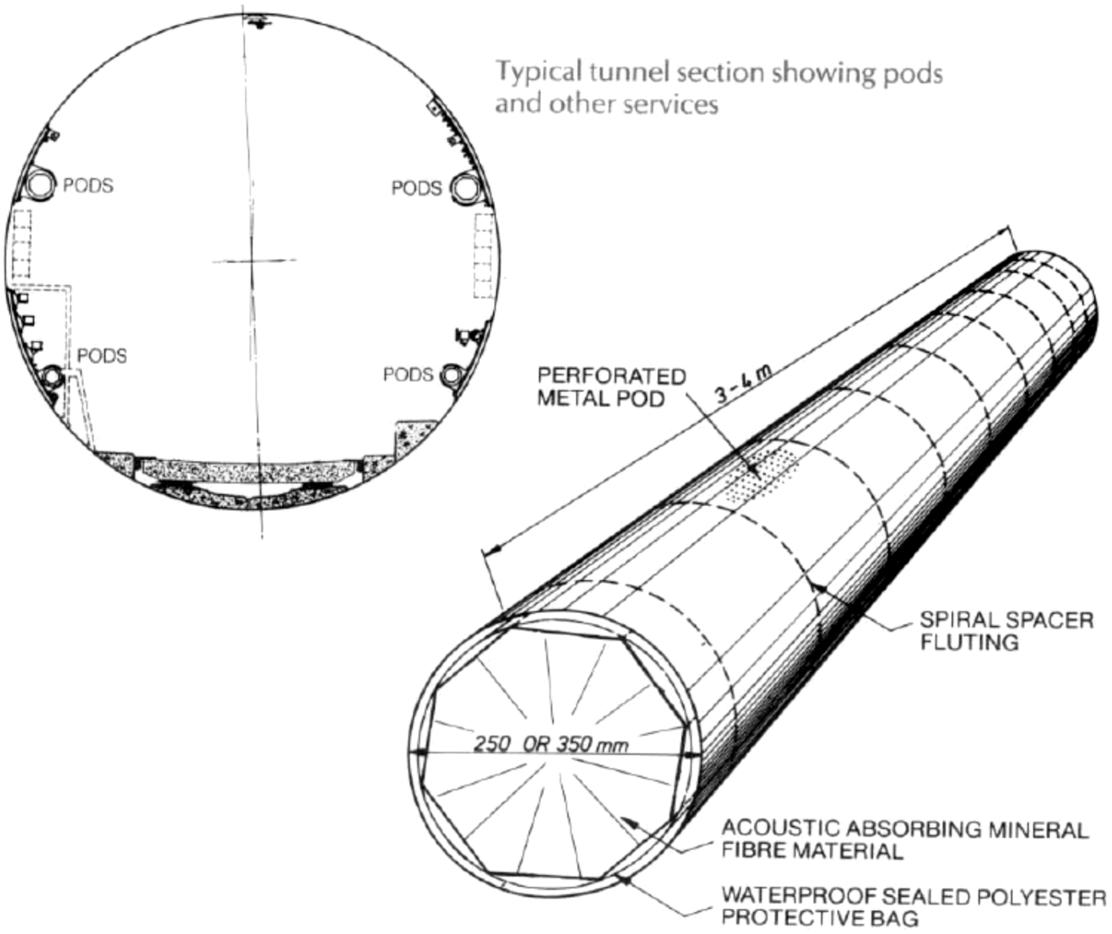


Figure 4: Melbourne Underground Rail Link absorptive pod detail and tunnel locations.

5.2 Approach to the acoustic design of the ECRL tunnel

The acoustic design work for the ECRL tunnel was undertaken during the tender and detailed design period. It is important to understand that while the desired outcome was clearly to limit the in-car noise levels, the project specification did not actually relate to in-car noise levels, but instead adopted a maximum reverberation time within the tunnel in octave bands, measured in accordance with AS2460. This ‘indirect’ approach to controlling in-car noise was apparently adopted because it allowed a clear separation between the responsibilities of the tunnelling and systems contractor, and the rolling stock operator (Sydney Trains).

In our view, this approach was reasonable. However, the specification itself was poorly defined, with considerable scope for conflicting interpretation. In particular, it did not specify whether the measurements should be undertaken as T_{20} or T_{30} – this proved to be a key factor in determining compliance with the specification, and was the subject of much of the legal argument.

(It is conceded that choosing the right thing to specify, particularly in the Scope of Work and Technical Criteria for major projects is difficult, because it must balance the responsibility of construction contractor with their ability to control and influence the outcome, against the risk to the State. Nevertheless, in our opinion, large project contracts are increasingly focussed on trying to eliminate almost all risk for the State, and pass on unquantifiable and inappropriate risk back to the construction contractors and design teams.)

In response to the specification, the acoustic design included preliminary predictions of the reverberation time within the tunnel adopting Sabine’s equation, and by assuming a representative section of tunnel with completely absorptive ends. The model was used to estimate the broad extent of acoustically absorptive panel within the tunnel, and their required absorption coefficients, necessary to comply with the reverberation time specification. Importantly, the limitations of using Sabine’s equation in such a ‘non-Sabine’ environment were identified, and trials were recommended within the completed tunnel to confirm the extent of absorptive treatment required prior to final installation. This approach strongly reflects current IT design methods which strongly favour testing prototypes.

As it eventuated, the in-tunnel prototyping resulted in some additional absorptive panels being adopted. However, it was not until revenue-service had begun that the excessive in-car noise levels prompted further in-tunnel RT testing which suggested the Reverberation Time was above the specified requirements. Further in-tunnel absorptive linings were then installed during short night-time possessions, at considerable additional expense to the construction contractor, who subsequently sued the acoustic consultant for the cost of the additional absorptive panels and their installation.

5.3 Criticism of the ECRL design approach

As part of the litigation against the acoustic consultant, the contractor undertook an independent peer review of the design documentation. That review was particularly critical of the consultant’s use of the Sabine equation to undertake the preliminary design – describing it as ‘completely inappropriate’. The review suggested that alternative modelling methods, particularly the Kang-Orlowski method, for long spaces (Kang, 1997), as well as computer modelling in Odeon, should have been used instead.

However, even Kang’s approach should be understood as being an alternative heuristic, and there are, of course, several other more detailed approaches that provide even better results. For example, Li has developed a ‘coherent’ model which accounts for phase interactions and considers grazing incidence sound absorption coefficients (Li and Lam, 2005; Lai and Li, 2007). The reverberation time predicted using Li’s model is directly compared to Kang’s model (which assumes incoherent sound addition and more generalised random incidence absorption coefficients) and measurements undertaken in the Western Harbor Tunnel in Hong Kong and a long corridor in the Department of Mechanical Engineering at the Hong Kong Polytechnic University.

The results of both comparisons are shown in Figures 5 and 6 below, and indicate that Li’s ‘coherent’ model systematically predicts more accurate reverberation times than Kang’s model.

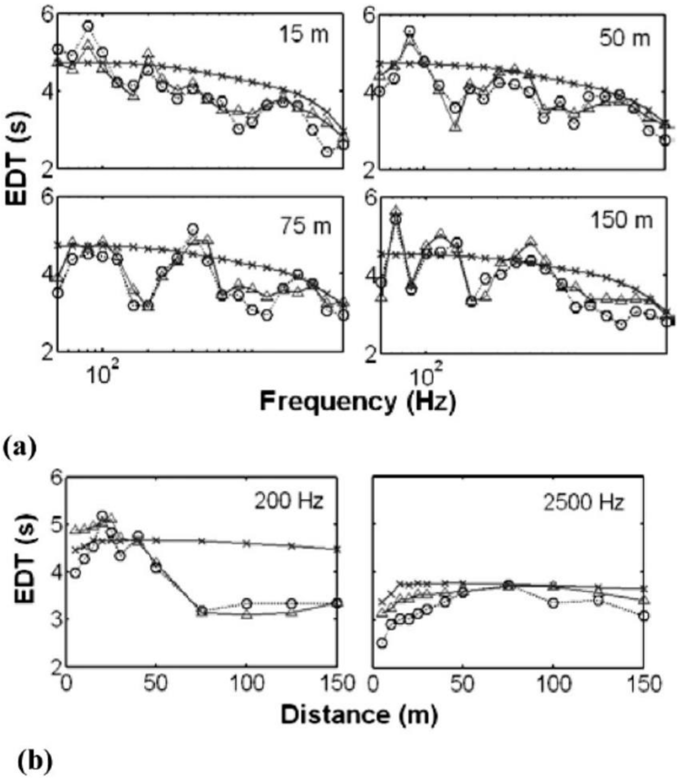
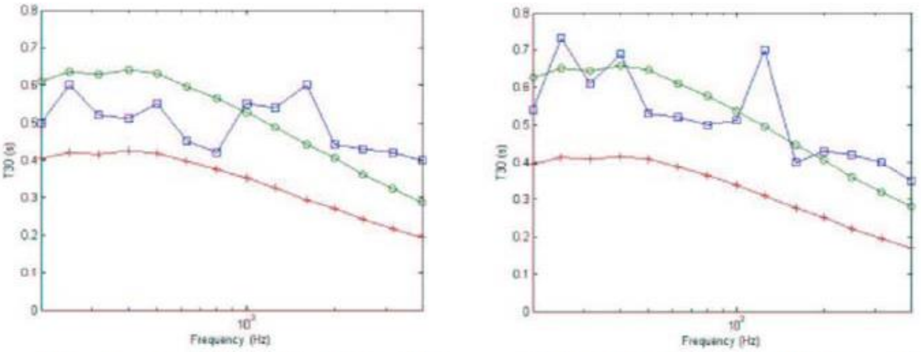
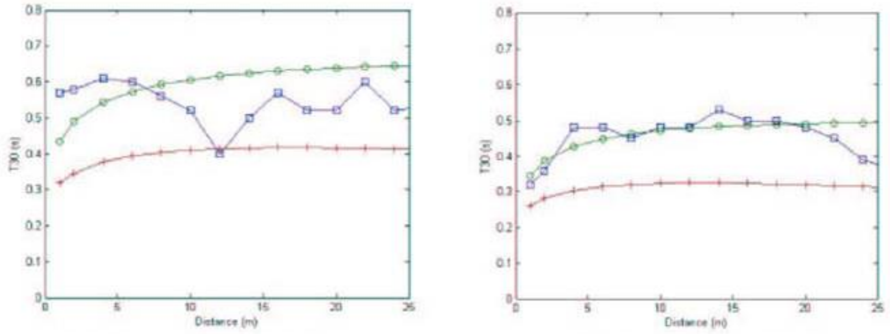


Figure 5: Comparison of measured and predicted Early Decay Time (EDT) in the tunnel.
○ = Measurement, ∆ = coherent prediction (Li), x = incoherent prediction (Kang). Ref. Fig. 4, Li and Lam, 2005.



(a) source-receiver distance: 16m (b) source-receiver distance: 28m



(c) frequency: 500 Hz (d) frequency: 2 kHz

Figure 2: Comparison of measured and predicted T30 in the corridor.
□ = measurements, ○ = Li simplified model, + = incoherent prediction (Kang). Ref. Fig. 4, Li and Lam, 2005.

More recently, Ridley and Sperritt undertook predictions and measurements of the reverberation time within the Sydney Harbour Tunnel for the purposes of assessing the speech intelligibility index (STI) of the emergency public address systems. This includes a comparison of the RT measurements to predictions using Kang's (2002) method implemented numerically by calculating up to 400 image-sources (reflections) at the receiver. A key finding is that both measurement and modelling of the tunnel reverberation time is difficult. The model implemented using Kang's method obtained fairly significant deviation from the measured values, by up to three times or more at distances down the tunnel of more than 15.6 m. Kang's method was shown to underestimate the reverberation time compared to measurements. It was also noted that particular difficulty in both measurement and prediction occurred for frequencies below 500 Hz.

5.4 A Koenian response to the criticism

The important relationship between Koen's work and the absorption design for the ECRL is the understanding that the engineer's approach, despite adopting the relatively simplistic Sabine equation, still followed a reasonable engineering method, particularly in its application of engineering heuristics.

For example, the use of Sabine's equation to determine the Reverberation Time, is better understood as the use of a engineering heuristic which relates the reverberation time in a space to its geometry (particularly the volume) and the extent of absorption in the space. Kang's approach is also a heuristic (arguably a better one, but a heuristic nonetheless) that relates the Reverberation Time in a space to its geometry and the extent of absorption in the space.

The engineer also applied the heuristic: Solve problems by successive approximations, by undertaking testing of existing tunnel conditions in the Eastern Suburbs Line to further refine their calculations, and then undertaking the testing of the trial section in the ECRL.

6 CAN ENGINEERS' DESIGNS BE WRONG?

The preceding analysis prompts an interesting question – when considered in the context of Koen's Engineering Method, is it possible for an engineering design to be wrong? In particular, where projects have had technical problems which have resulted in litigation, lawyers and expert witnesses are usually very keen to assign blame, and identify errors or mistakes in the engineering design.

While lawyers and laypeople (and some engineers themselves) may be comforted by the notion that an engineering design can be classified as either "right" or "wrong" in a binary sense, we think that Koen's consideration of engineering design clearly suggests that such a simple analysis is not possible. This view is also supported by Asimov's enlightening and entertaining essay *The Relativity of Wrong* (1988), where he expresses the notion that "right" and "wrong" are actually fuzzy concepts, rather than absolute, and in particular, that 'everything that isn't perfectly and completely right, is not totally and equally wrong'.

Our view, based on consideration of both Koen's and Asimov's work, is that engineering design is never (or, at least, very rarely) 'wrong' - although perhaps, sometimes, it is not as right as it could be. In this respect, the 'level of rightness' depends entirely upon the state-of-the-art adopted by the engineer (Koen abbreviates this as the s.o.t.a) – noting that every engineer's s.o.t.a. will be different, and dependant on the context of their cumulative experience and of the design being undertaken.

While this viewpoint may be difficult to fully accept – we believe it provides a valuable context within which to frame project risk for clients and to undertake peer reviews.

7 CONCLUSIONS

Koen provides a compelling view of the fundamental engineering design process adopted by consultants. Our hope is that by shedding light on Koen's work, and providing a practical example of its use, we can help acoustic engineers to understand their work better, and therefore provide better design solutions to their clients.

In regards to the design approach, our key conclusion is that each of Sabine, Eyring, Fitzroy – and more recently – Kang and Li's models are best understood as being engineering heuristics that provide an estimation of the reverberation time within a physical space with a particular geometrical arrangement (notably volume and length), and extent of absorptive material. Each model has a range of limitations which affect their accuracy in being applied to a particular scenario, and while Kang's model may be more suited to the prediction of Reverberation Time in long spaces than Sabine's model, it is still equally an estimation that is subject to engineering constraints, and there are other models that apparently provide better estimations. That does not mean that Kang's model is 'wrong', in the same way that we argue that the Sabine model is not 'wrong' either, but there are spaces which will behave more as 'Sabine spaces', and there are other spaces that will behave as 'Fitzroy spaces' or 'Kang spaces' – and it is knowing under which circumstances to apply a heuristic that is crucial.

As discussed in Asimov's work (Asimov, 1988), it is important not to assume 'that which isn't perfectly and completely right, is totally and equally wrong'. Most of us are able to accept that no criteria, or guideline, or assessment technique, or RT prediction is ever perfect. They are always the result of compromise and an attempt to provide the best possible solution to the problem within the available resources. So, we take guidance from Dr. Asimov who concludes 'theories are not so much wrong, as incomplete'.

In our view, it is always acceptable to adopt the Sabine Equation to provide a preliminary estimate of reverberation time within a space – and more than that, the calculation is so simple, it should always be the first port of call of any acoustic engineer evaluating the reverberation time of a space, whether it is a conference room, a seminar space, a band rehearsal room, a concert hall or opera house, or a railway tunnel. This is not to say that it is acceptable to *solely* rely on the Sabine equation, because clearly the limitations inherent in its application (and there are many) need to be carefully understood by the acoustic engineer. It would be usual to employ other risk-controlling heuristics to progress the design process.

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