RT60: ITS USE AS AN OPTIMISER IN AUTOMOTIVE CABINS

A Bennetts Bay Systems Ltd, Westhay, Somerset, England
R Morris-Kirby HP Pelzer Uk (Lab 2000), Rugby, England

1 INTRODUCTION

Every human being will have a different impression of any given noise and this subjective perception [1] will change with age, experience, education and the person's general feeling of well being. The challenge for automotive engineers is that of fitting the "correct" sound trim materials to a vehicle that reinforce or confirm the expectations of the driver/buyer. As an example take a high-powered sports car and a 75-year-old grandmother. The engine noise and ride comfort preferred by the grandmother are unlikely to match those of typical purchasers of such a car. The sound trim needed to make the sports car "right" for the grandmother is going to make it potentially "wrong" for the target buyers who are attracted by its styling, horse power etc. The challenge for the automotive engineer is to ensure that the car's acoustic signature matches the expectations of those that will buy it and enjoy riding in it. The challenge is to do this for a range of power trains and suspension set-ups and to make it happen within a tight budget. The budget is defined in terms of package space available, weight of materials and finally the cost of the parts and labour required to fit them reliably.

The Reverberation Time (RT) is the echo or sustain time/period for an environment [2]. The time is usually specified for noise to decay from the initial level to one of -60dB. The global decay time in the vehicles cabin is not necessarily the same as the local one. The effect of this is that local materials used in the car cabin have both local and a global influence. This paper demonstrates how the RT60 reverberation time can be successfully used to quickly evaluate and benchmark a vehicle's acoustic performance. In addition the contribution in accuracy that detailed RT60 measurements can make to the calculation of Transmission Loss (TL) is demonstrated in the second part of the paper.

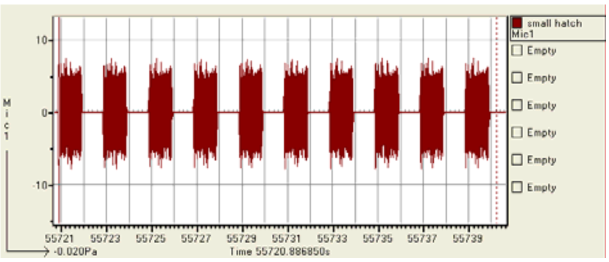
2 MEASUREMENT PROCEEDURES

2.1 Benchmarking & initial evaluation of the cabin acoustic

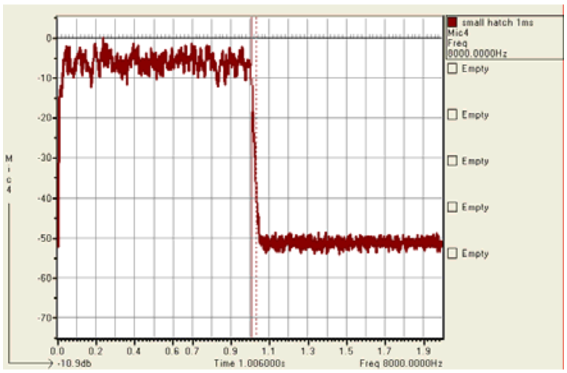
If the vehicle has already been trimmed, or a number of vehicles are to be used to form a benchmark, it is necessary to be able to measure the RT60 decay times throughout the vehicle(s) cabin. This is necessary, as the RT60 figure will always contain a "local" component superposed upon the average cabin figure. We are interested in the true average figure for the cabin, which can only be found by sampling the local RT60 values. The local RT60 values tell us how the local trim panels are performing. ISO 3382 recommends using at least three source positions and six microphone locations when measuring Sound Propagation Transfer Functions (SPTF) to effectively average out local effects. We are however interested in the local as well as the global behavior and so a larger number of microphone positions is required, approximately twenty; i.e. a total of sixty RT60 measurements. Making and analyzing these measurements for 6 -12 vehicles is tedious and with tedium can come mistakes. Complete automation of this process although attractive is not possible for, as in almost any other measurement and analysis task, blind acceptance of automatically computed output would invariably lead to the incorporation of bad results. The approach adopted was to excite the cabin with broadband white noise, pulsed on and off in one second bursts, over twenty cycles. The RT60 time for each of these bursts was calculated automatically over the ISO 354 recommended -5dB to -35dB decrement and over a range of other decrements, as RT60 values in a car cabin are short the reversed time sequence method was employed. The individual RT60 estimates were then averaged. The alternative decrements were selected after manual examination of specimen data, suggested sets are offered as defaults by the program. It should be noted that the early decay rates are deemed more reliable indicators of the correct RT60 for the low frequencies (60-500Hz). However for a vehicle cabin the fundamental cavity resonances, typically found between 70 – 140 Hz make any result under 200Hz unreliable. The best results will be achieved by taking the decrement from 0dB to –20dB for the lower frequencies rather than the –5dB to –35dB decrement figure suggested in the ISO 354 recommendation using 1msecond steps. The higher frequencies, above 500Hz, are affected less and so the standard –5 to –35dB decrement may be used with confidence. The software optionally will also search for and then uses the best decrement available. The final output from the software is an averaged best estimate. Typical RT 60 measurements made in a vehicle cabin are shown, figure 1 and Table 1. In Table 1 the 315Hz result was not stable and is recorded as not found.

Figure 1. RT60 measurements in a car using a 1 millisecond step size.

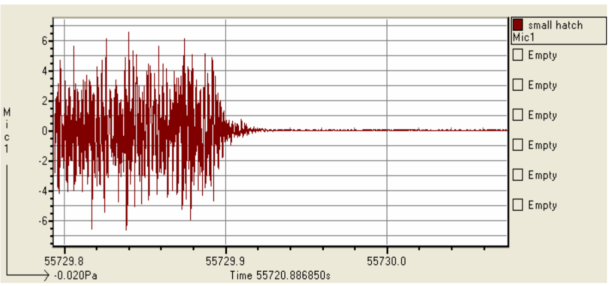
a) Sequence of white noise bursts.



c) Decay times per 1/3rd Octave band



b) The decay at the burst end.



Time – Grid lines spaced at 0.1 second intervals

Table 1. The best RT60 results obtained for this vehicle test. A correlation of >0.99 is desirable.

Best Results Correlation Threshold = -0.98000

Name	Filter	dB Range	Time Range(s)	RT60(ms)	DLF	Corr
RTAuto	250	(-8,-48)	(0.9820,1.0390)	81.1	0.10852	-0.980
Not Found	315	(0,0)	(0.0000,0.0000)	--	--	--
RT30(ms)	400	(-5,-35)	(0.9990,1.0240)	48.9	0.11254	-0.999
RTAuto	500	(-8,-48)	(1.0000,1.0350)	54.7	0.08045	-0.994
RTAuto	630	(-5,-50)	(1.0010,1.0450)	55.5	0.06290	-0.990
RTAuto	800	(-8,-48)	(1.0000,1.0450)	61.4	0.04481	-0.988
RTAuto	1000	(-8,-48)	(1.0050,1.0410)	50.0	0.04400	-0.981
RTAuto	1250	(-5,-50)	(0.9870,1.0470)	66.5	0.02646	-0.986
RTAuto	1600	(-5,-50)	(1.0020,1.0440)	54.9	0.02505	-0.998
RTAuto	2000	(-8,-48)	(1.0030,1.0360)	52.0	0.02117	-0.986
RTAuto	2500	(-8,-48)	(1.0060,1.0470)	54.8	0.01604	-0.992
RTAuto	3150	(-8,-48)	(0.9980,1.0410)	60.8	0.01149	-0.989
RTAuto	4000	(-5,-51)	(1.0060,1.0610)	64.8	0.00849	-0.993
RTAuto	5000	(-5,-51)	(1.0010,1.0510)	58.6	0.00751	-0.997
RTAuto	6300	(-8,-48)	(1.0110,1.0580)	64.4	0.00542	-0.996
RTAuto	8000	(-8,-48)	(1.0080,1.0550)	65.1	0.00422	-0.993

A correlation value of –1 means a perfect straight line, which we know from work done by Per V. Bruel [3] is an unrealistic expectation at low frequencies. The correlation should however not be below –0.98 and preferably –0.99 for frequencies above 500Hz.

To assess if a car's RT60 cabin values can be easily improved upon a simple "litmus test" can be engineered by forcing a large perturbation in the acoustic absorption coefficient for the cabin. This is achieved by placing a large acoustically absorbing foam block "calibrated absorber" on the rear seats of the car, but not covering the back window. If the car is already optimally fitted with absorbing materials the effect of the foam block will be minimal but if the car is less well optimized then there will be a significant change in the RT60 time. For quick benchmarking we may relax the need to make a complex measurement; a single loudspeaker position, in the passenger footwell, with four microphones situated at the head positions will suffice. This is by no means a rigorous approach but in less than 30 minutes the two sets of results can be obtained and the margin for potential improvement assessed. The results for two cars, one economy and the other luxury, are presented in Tables 2 & 3.

Table 2. RT60 decay time in milliseconds for economy and luxury cars with and without an additional foam block laid across the rear seats.

Centre Frequency of 1/3rd Octave Hz	Economy Car RT60 no foam	Economy Car RT60 With foam	Luxury car RT60 no foam	Luxury Car Rt60 with foam
160	128.6	80.8	111	73.9
200	173.3	111.6	68.8	68.5
250	101.2	98.7	51.4	53.8
315	178.1	109.7	67.8	72.2
400	107.6	77.8	90.5	41.3
500	109.9	62.2	70.6	44.4
630	102	54.3	68.9	47.5
800	75.2	68.8	52.6	55.5
1000	96.1	113.4	43.5	59
1250	110.2	66.9	76.4	54.8
1600	100.6	62.7	60.3	53.6
2000	110.7	69.2	56.4	51.9
2500	76.6	64.6	55.3	56.8
3150	91.4	56.3	54.7	57.4
4000	65.4	53.4	58.5	59.6
5000	58.7	49.2	61.9	61.1
6000	54.1	52	62.6	62.6
8000	55.3	46.1	63.6	62
10000	50.9	40.4	62.8	61.5
12500	44.4	41.7	67.1	58.4
16000	41.2	34	50.3	59.6
Sum of RT60	1931.5	1413.8	1355	1215.4

Table 3. Averaged RT60 times for all frequencies.

Cabin Status	Economy	Luxury
No Foam	92 msecs	65 msecs
With Foam	67 msecs	58 msecs
Change in RT60	27%	11%

The results are markedly different and agree with a cursory visual inspection of the two vehicles with regard to trim quality i.e. depth of carpet/underlay, headliner and seat quality. In the case of the luxury vehicle the only hard surfaces exposed were the glazed areas. Carpet and perforated leather covered much of the other surfaces; there was no exposed metal. The economy car had very thin carpet and poorly fitted underlay with many exposed areas of bare metal. From this type of benchmark work a target figure for RT60 can be set but the tuning of the local values, required for example for speech intelligibility (Articulation Index) etc. still has to be done by using the SPTF to optimize the absorption of the trim.

2.2 Sound Propagation Transfer Function and Airborne Reciprocity.

Sound Propagation transfer functions (SPTF's) between sources and receivers are key parameters in the understanding of noise transmission throughout the cabin as well as that generated by external sound sources.

There are two methods of measuring these transfer functions. The first is to put a calibrated noise source at each input position (actual location of the operating source); sometimes a difficult procedure to facilitate and one that potentially changes the structure completely if it is necessary remove or uncouple major components. The alternative is to use reciprocity; this is popular because there is no decoupling to be done. The reciprocal approach requires that a sound field be generated in the vehicle cabin; ideally the calibrated noise source will be at the drivers/passengers/listeners head position, with the measurements taken at the engine mounts using accelerometers or at the exhaust, using microphones. However, for an acceptable signal to noise ratio to be achieved the calibrated noise source has to generate a very high noise level inside the cabin[4].

These levels are well above those found during normal vehicle operation and can excite resonant and non-linear responses in the trim materials that may cause reciprocity to "apparently" fail. It has been found that the values for airborne SPTF are not the same when taken directly and reciprocally and to be useful for interior noise prediction these anomalies need to be rectified. Even then there are some instances where it is unlikely that the system will react reciprocally to airborne sound transmission between systems (cabin, boot or exterior) due to sound field incident angles at the boundaries of sub-systems and the creation of diffuse versus modally coupled sound fields inside systems such as vehicle cabins. These effects need careful study before blindly using reciprocity as a "Law". If the aim is to predict interior cabin levels generated from a known airborne sound power source then the direct SPTF is required. The use of reciprocal SPTF's in this case should be used with caution.

To determine whether reciprocity is holding, or not, the SPTF must measure the total energy at the source and compare it to the total energy at the receiver position. Normal SPTF's use power / pressure or volume velocity / pressure so these need to be converted to power / power or effective transmission loss before any statement about reciprocity can be made.

When placing an experimental sound source into a cabin, the cabin environment itself will affect the sound power coupling of the system depending on the distribution of cavity modes. A supposed "free field" or "semi-anechoic" calibration of the experimental sound source will change by at least a few dB due to the proximity of surfaces[3]. As an example let us look at the SPTF (power/pressure) between cabin and boot space both taken directly and reciprocally, figure 2. In this case the direct path is assumed to be from the boot to the cabin as in most cases airborne sound energy flows in this direction.

Figure 2 depicts the "raw" SPTF (power/pressure) result of the experiment and whilst the responses are not that different they show various anomalies in the low and high frequency ranges, which require further investigation. The graph for boot to cabin (direct) SPTF follows the expected shape for transmission across a two "room" interface, whilst the reciprocal cabin to boot shows a peak around 500Hz and a steep kick up after 4000Hz. To investigate why this occurs, the effect of the cabin on the power balance created by the experimental sound source was established by comparing the "free field" calibrated power with that estimated inside the cabin using spatially averaged SPL and RT60, these are shown on figure 3.

Figure 2 SPTF for cabin to boot in dashed black and boot to cabin in solid purple.

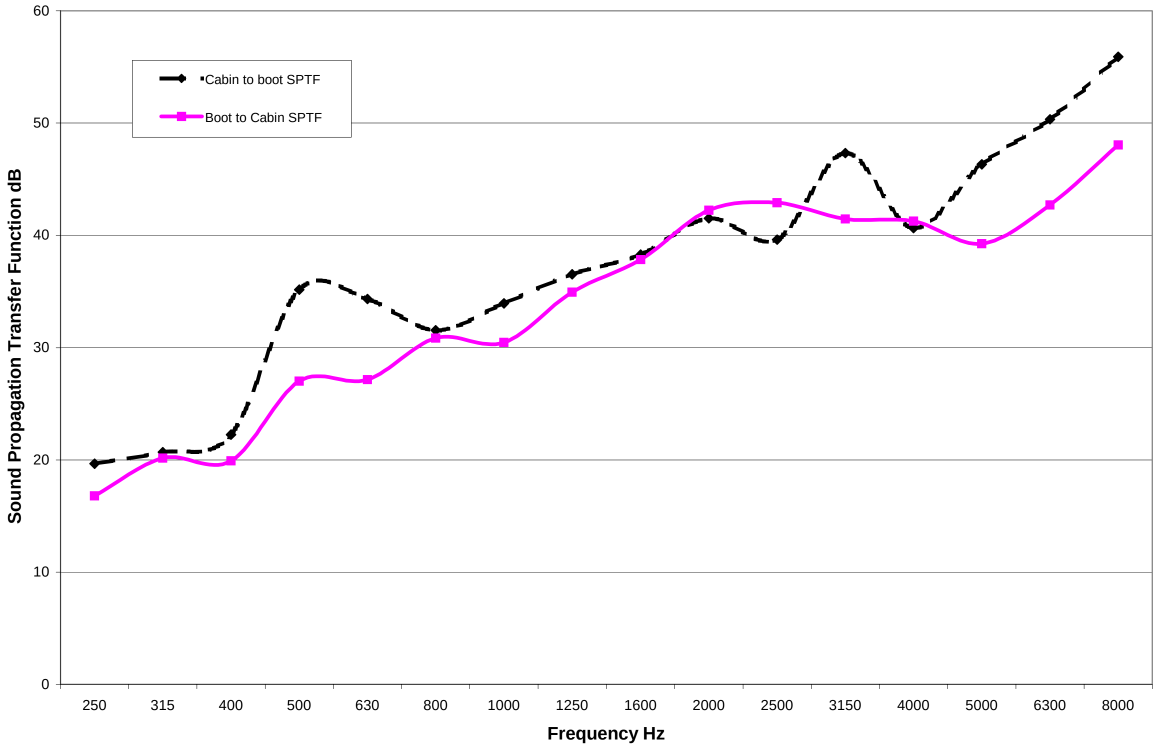
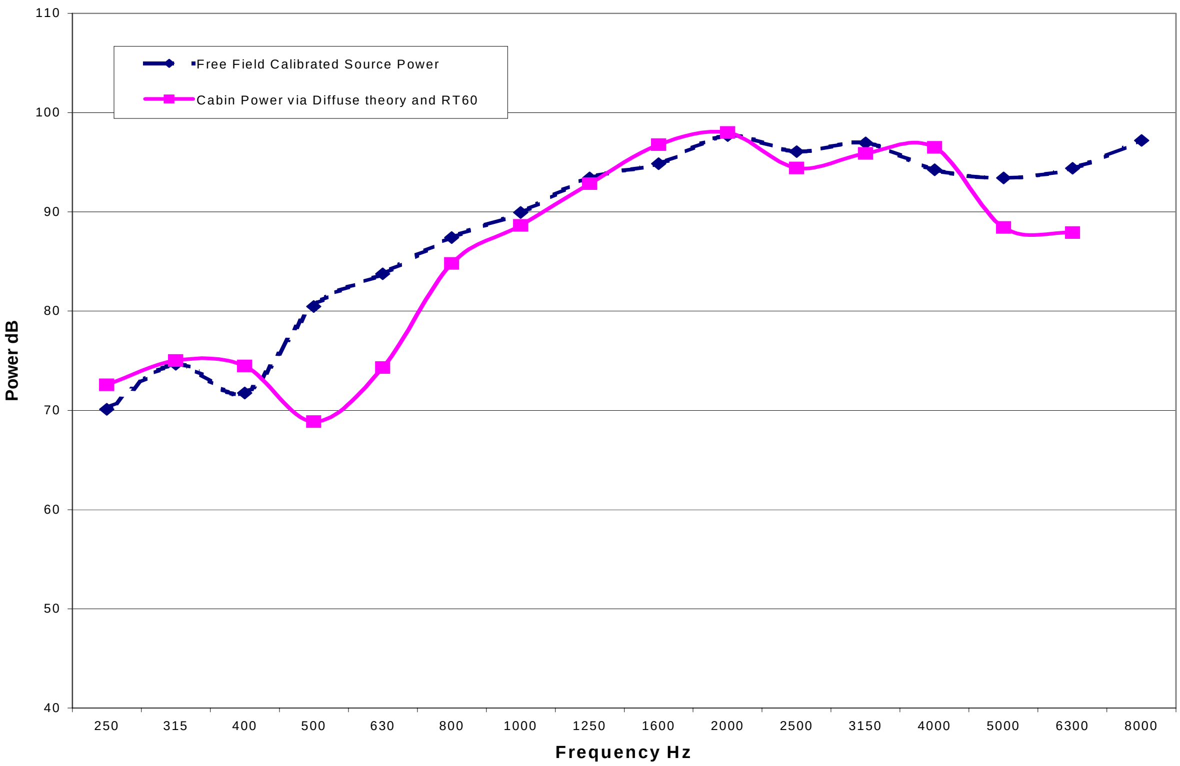
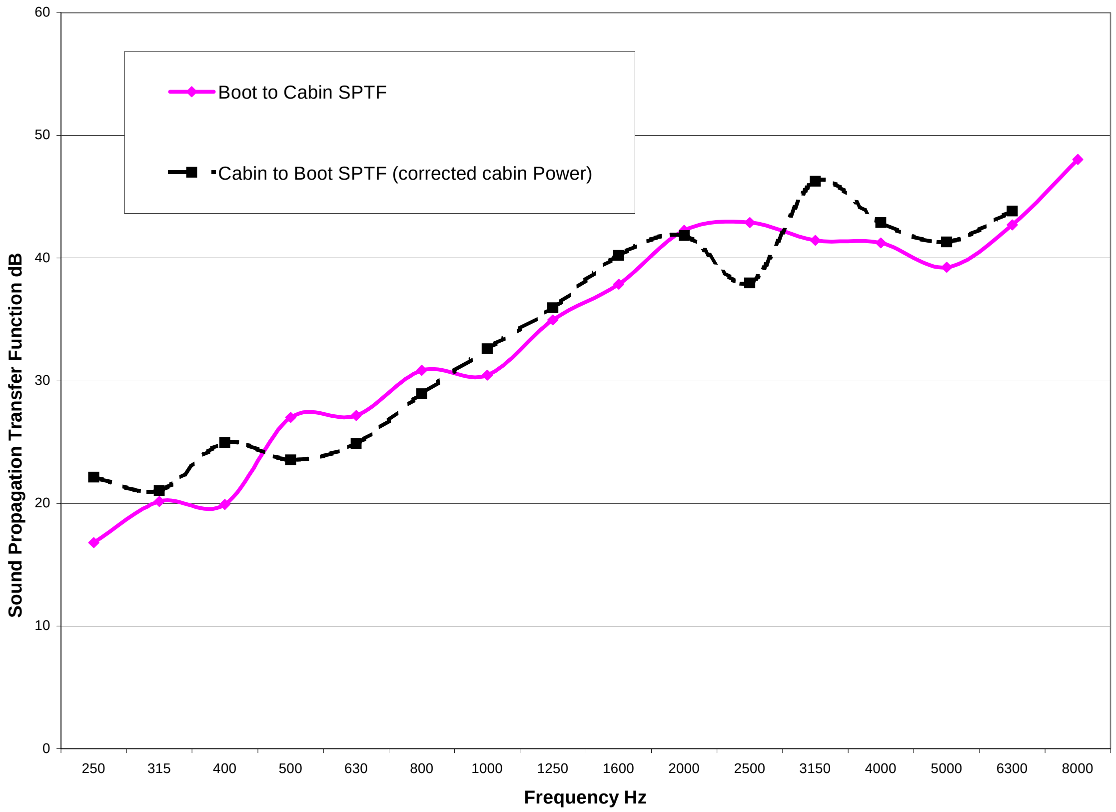


Figure 3. Effect of the cabin on the Power from the Experimental Sound Source. Free field power radiated is shown in dashed blue. Effective Cabin power was calculated via diffuse theory and the full and detailed RT60 measurement is shown in solid purple.



Figures 2 and 3 show that the actual power established inside the cabin is deficient at the frequencies where the direct and reciprocal SPTF also deviate.
To determine whether reciprocity is valid the SPTF (power/pressure) need to be converted into SPTF (power/power) or "Transmission loss", and this requires that the power in both the source system and the receiving system be calculated.
For transmission through a boundary between systems it is the impinging sound power on the boundary that determines noise transmission, so the coupling effect of the cabin has to be accounted for in a SPTF measurement. Thus the next stage is to modify the reciprocal SPTF for the actual sound power established in the cabin by the experimental sound source; this is shown in figure 4. Once the actual power inside the cabin is calculated the direct and reciprocal SPTF take on a similar shape and level. To do this requires a high density of RT60 and SPL measurements to be made and the RT60 module easily carries this out.

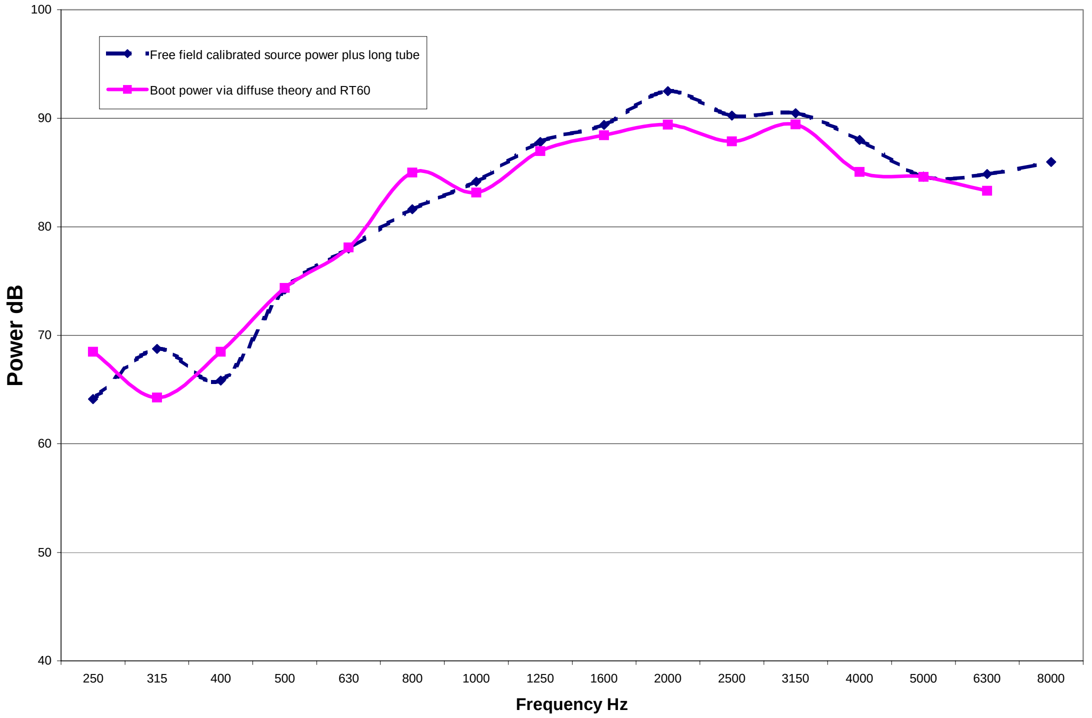
Figure 4. SPTF corrected for the cabins effect on the power



The same modification also has to be applied to the boot coupling although as this space is far smaller and has less natural absorption the effect is likely to be much smaller, see figure 5. Also the spatial sampling criteria and microphone spacing in such a small space makes calculating power using diffuse assumptions difficult so care has to be taken.

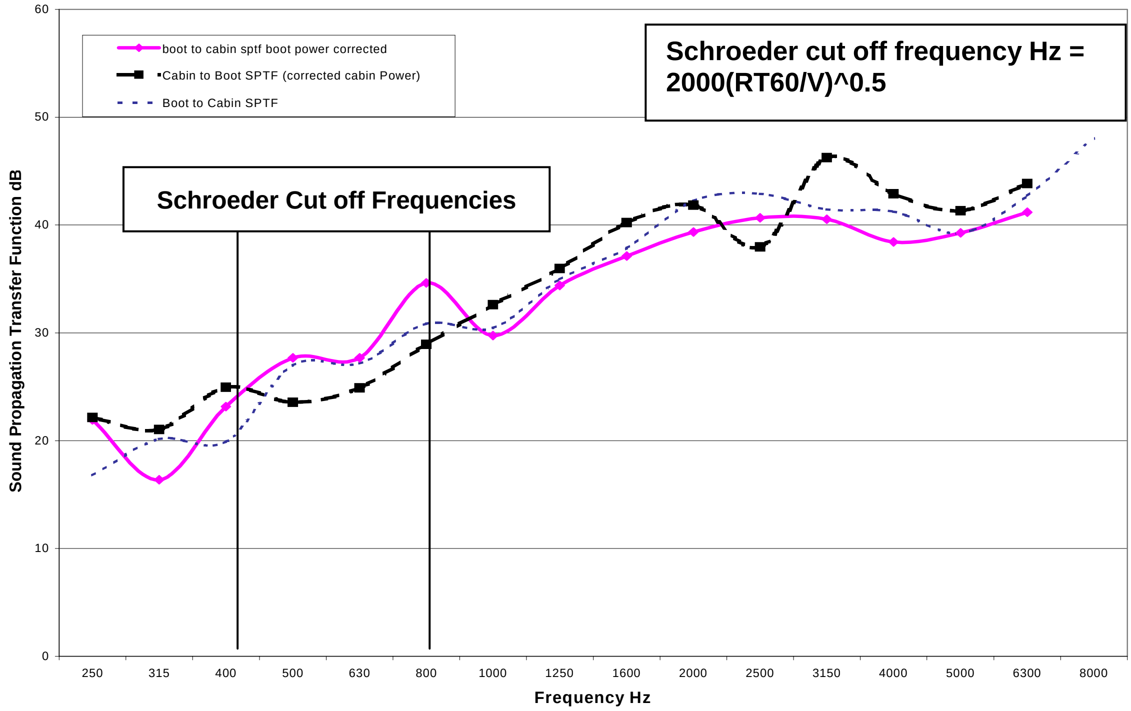
Both these modifications to the SPTF seem to be leading to the conclusion that reciprocity is holding in this example, but two other parameters have to be accounted for before the SPTF can be accepted as accurate. These are the low "cut-off" frequencies above which diffuse theory operates. For the cabin this low cut off or "Schroeder" frequency was estimated at 400Hz for the cabin and 800Hz for the boot. Below the Schroeder frequency the assumption of a diffuse field from which power was calculated does not hold very well.

Figure 5. Effect of the boot space on the radiated power of the experimental sound source Free field power shown in dashed black. Boot power via diffuse theory and RT60 in purple.



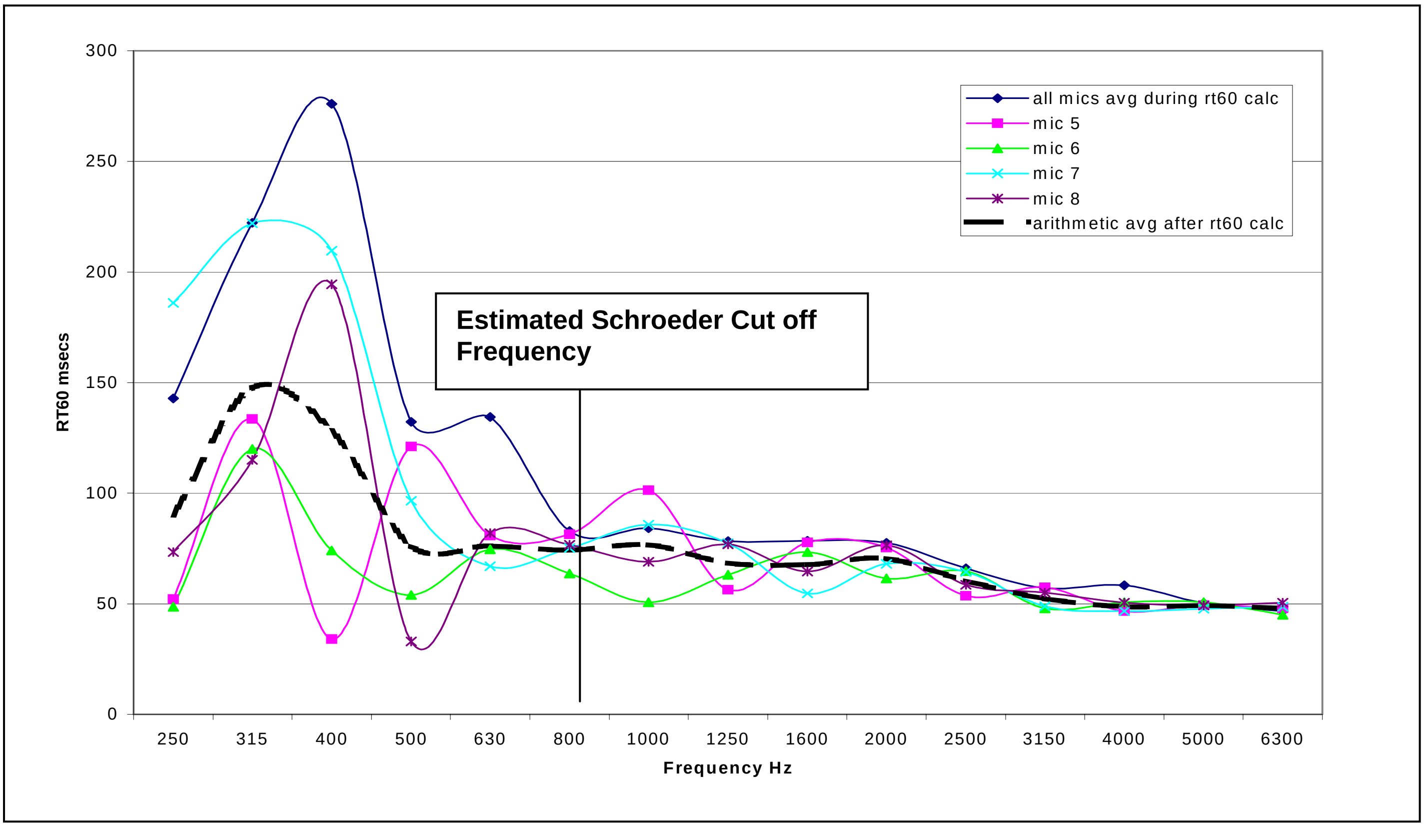
In figure 6 we show both SPTF modifications and the position of estimated Schroeder cut off frequencies.

Figure 6. SPTF's Modified for Boot and Cabin Power Coupling Effects



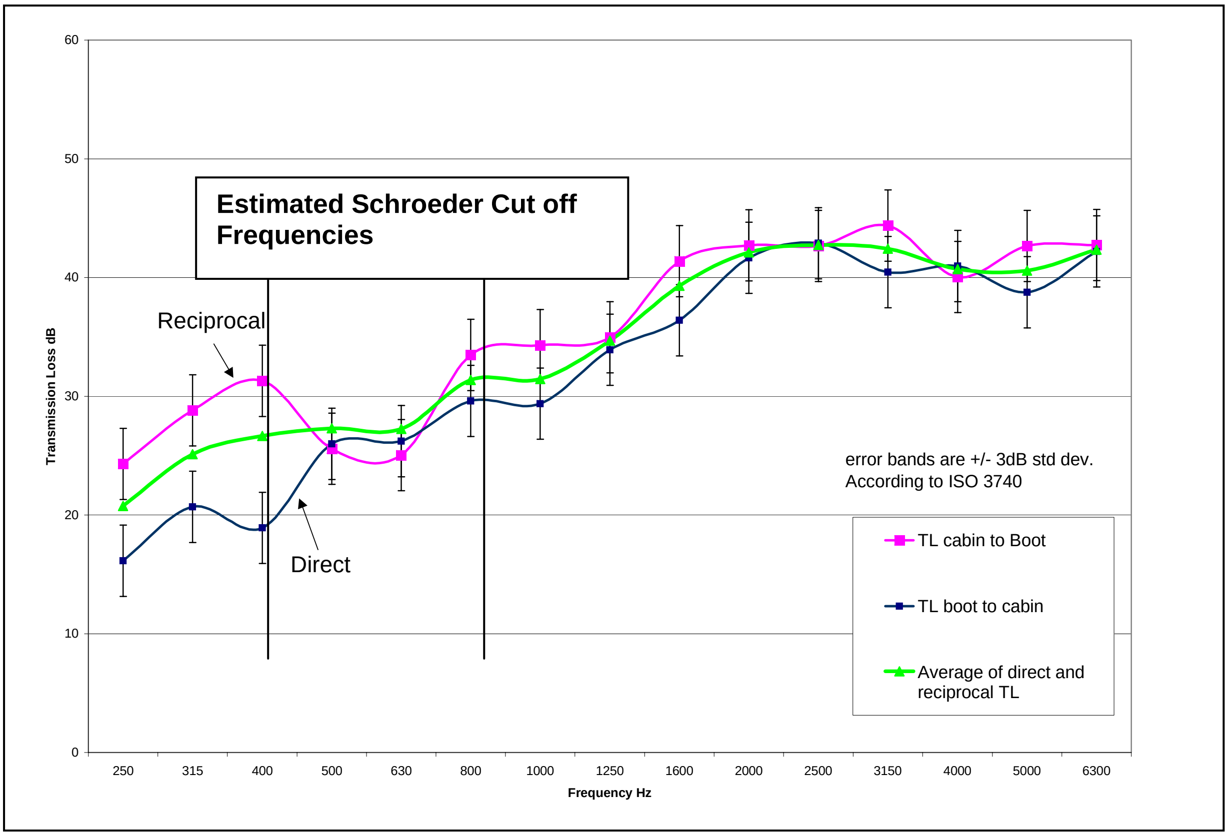
The results so far show that the SPTF levels between cabin and boot directly and reciprocally have to be modified for excitation power before reciprocity is observed. Converting SPTF to Transmission Loss (TL) incurs a further modification; that of calculating receiving power via diffuses field theory. As there is an uncertainty involved each time power is computed from diffuse fields the error in calculating the TL is likely to be worse than for the SPTF. The International Standard ISO 3740 identifies the standard deviation of uncertainty of estimating sound power in a reverberant environment as around 3dB. Thus any calculation of TL using in-situ measurements should have a 3dB deviation applied. Also ISO 3740 identifies measurement uncertainty even for a large chamber laboratory test as 2.5 dB at 250 Hz and 1.5 dB from 500Hz to 4 kHz. The main concern with measuring the received sound power is similar to that of excitation power, namely the spatial variation of SPL and RT60 in each "room". The usual microphone positions i.e. situated at each passenger head position is unlikely to provide sufficient sampling density for accurate results and ISO 3382 recommends that at least six microphone positions are used and that power injection should be applied to at least three locations for the determination of environmental parameters. RT60 inside the boot was measured using a four-point power injection method. Four microphones were placed in each corner of the boot to measure the decay. The RT60 that was then calculated over the entire decay curve using the automatic curve fitting correlation software module described in 2.1 of this paper. All the microphone signals were combined as one average response prior to RT60 computation. Figure 7 shows that below Schroeder cut-off the calculated RT60's have a wide spatial variation and that combining all signals prior to RT60 calculation produces an RT60 time far higher than a simple average of each microphone after RT60 calculation.

Figure 7. Boot RT60 and spatial variability



The transmission loss between the two systems can now be calculated including the error bars necessary to account for the uncertainties in this procedure, figure 8. So does reciprocity hold for airborne transmission in this instance? It would appear that for frequencies above the cabin's cut off frequency the reciprocal and directly calculated Transmission loss follows either side of an average value within the +/- error bands associated with the test standards. Below the cut off frequency this deviation becomes extreme. So for higher frequencies the cabin and boot are responding in a reciprocal manner. However, this does not mean that SPTF's taken reciprocally can be used in their raw state for interior noise level prediction. It is recommended that, where possible, airborne SPTF should be taken directly so as to remove the necessity of considerable extra processing of the raw reciprocal data.

Figure 8. Direct and Reciprocal Transmission Loss calculated using Modified SPTF' s



3. CONCLUSIONS.

An accurate and quick method of determining multi-channel RT60, using the time reversal technique has been demonstrated. It allows vehicles to be easily bench marked and their sensitivity to large perturbations in trim absorption examined by the addition of the "calibrated absorber".
If reciprocally measured SPTF are to be used for cabin interior noise level prediction from an exterior source or coupled sub-system then they have to replicate those measured directly. The second part discusses the use of direct and reciprocal SPTF's and the need for their modification using spatially sampled RT60 in order to compensate for the effect that the local acoustic environment inside vehicle cabins has on sound transmission between sub-systems.

4. ACKNOWLEDGEMENTS

Dr Paul Stringer, who in collaboration with HP Pelzer engineers, created and validated many of the unique features available in the RT60 module.

5. REFERENCES.

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