EXHAUST SOUND QUALITY TUNING – THE INFLUENCE OF VEHICLE CABIN ACOUSTIC TRANSFER FUNCTIONS IN THE EXHAUST DEVELOPMENT PROCESS

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1 INTRODUCTION

In considering the importance of Airborne Acoustic Transfer Functions (ATFs) between the exhaust tailpipe and a vehicle's occupants an example of an engine sound quality strategy for a vehicle is first given, including the targeted contribution from the exhaust to the overall sound. The prototype vehicles used in automotive sound development are then outlined, including the relative merits of each. Noise Path Analysis (NPA) is used in the main part of the work to review the influence of exhaust ATFs across prototype phases. Trends in the results are outlined and explanations offered.

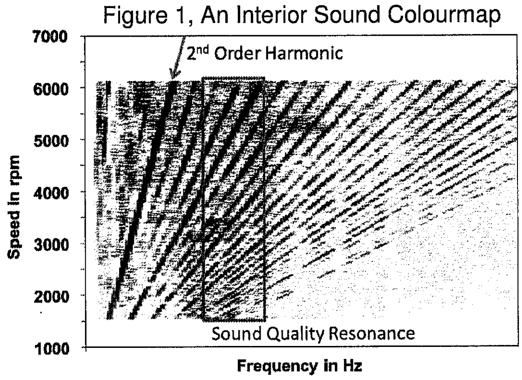
2 BACKGROUND

2.1 Engine Sound Quality

How the engine sounds in a vehicle has the potential to 'surprise and delight' a customer[1]. It is an area which receives specific attention by J. D. Power and Associates, who specialise in consumer research. In the Automotive Performance, Execution and Layout (APEAL) Study[2] the customer is asked to rate the 'Sound of engine/exhaust during rapid acceleration'.

In developing a sound subjectively pleasing to a customer, the objectively quantifiable parts of a sound which pleases must be defined. Figure 1 shows a colourmap of a fast acceleration in a Range Rover Evoque, which scores well amongst its peers in the 2012 APEAL study[2]. Frequency is on the x-axis, engine speed on the y-axis and Sound Pressure Level (SPL) in dB(A) on the z-axis. The harmonics of the engine sound are the diagonal lines in the plot. The four cylinders in the engine fire over two rotations of the crankshaft, this gives the fundamental 2[nd] engine order harmonic.

Figure 1, An Interior Sound Colourmap



In the case of this vehicle a strong 2[nd] order profile is engineered to bring a solid and 'sporty' base to the sound, this builds in level with engine speed. This is complimented by a 'Sound Quality Resonance' which highlights half order harmonics across the speed range; this brings an edge and excitement to the sound. It also brings modulation to the sound which off-sets the potential "heaviness" of a strong 2[nd] order profile. In development, the two aspects are tuned for an optimal balance.

2.2 Contribution of the Exhaust System

The exhaust plays an important role in achieving the strong 2[nd] order content in the mid-speed range (2000 to 4500 rpm) in the Range Rover Evoque. The 'Sound Quality Resonance' is from another sound source which in a secondary role also takes over from the exhaust in the high engine speed range for reasons which will become apparent. The 2[nd] order profile targeted for the driver from the exhaust is the focus of this paper and is influenced by two main factors; firstly the sound at the exhaust tailpipes and secondly how that is filtered through the exhaust ATFs between the tailpipes and the driver and passenger ears.

3 THE DESIGN AND DEVELOPMENT PROCESS

3.1 Target Setting

When developing a new vehicle it would be typical to generate a target sound for a fast acceleration. This could be achieved by filtering the sound of an existing vehicle. The sound would be positioned against sounds from competitor vehicles and input taken from the product marketing team and senior vehicle assessors. A cascade to individual system and component contributions to the sound can be generated from the overall sound, Noise Path Analysis (NPA) methods can be used to do this. Where detailed knowledge exists on the performance of sub-systems, this can be used to validate the cascade at an early stage in the development process. Where this is not the case a working assumption will need to be made. This is the case for Exhaust ATFs where ATFs from an existing vehicle could be used in the first instance. This enables targets for the sound at the exhaust tailpipes to be generated and consequently the total exhaust contribution to the interior sound to be defined.

3.2 Design Validation

As development progresses components and sub-systems will be validated and modifications made to the design, as required. Three main iterations of prototype vehicle would typically be built in this process, critically there is the potential for the exhaust ATFs to have different properties across these prototypes and this directly impacts on how the exhaust tailpipe sound is tuned and the ultimate scope to achieve an acceptable sound in the vehicle. Significant changes to the exhaust system become more expensive and less feasible as the program progresses.

3.3 Prototype Vehicles

3.3.1 Early Prototypes

An *Early Prototype* would typically have an existing vehicle body but a prototype engine. They have the advantage of the robust fit and finish of the interior and sealing of the body structure. The disadvantages are that the cabin dimensions and exhaust configuration, size and shape may not be representative of the future vehicle. An indication of the character of a new engine can be obtained with this prototype and initial exhaust concepts can be developed. Work can also begin to correlate virtual exhaust models. With a rolling road test cell some exhaust designs can be tested which would not fit a road-going vehicle.

3.3.2 Mid-Program Prototypes

A *Mid-Program Prototype* has a 'design-representative' under-floor structure, along with the latest engine. The advantage at this stage is that design and package feasible exhaust systems can be driven and assessed. The external dimensions of the exhaust are frozen by this time however, allowing only tuning of the exhaust internals and pipe diameters. A key feature of *Mid-Program Prototypes* is that the top of the vehicle and the interior are made of surrogate parts from existing vehicles or using custom-made parts. The parts are modified to fit the design representative understructure. Achieving robust sealing and trim fitment is a challenge and this can have a significant influence on the exhaust ATFs and consequently how the exhaust is tuned.

3.3.3 Confirmation prototypes

When the full vehicle design is in place *Confirmation Prototypes* will be built. They have a representative body structure, engine and exhaust layout. The trim is representative in shape although it may not be at full-scale production standards for fit and finish. This level of prototype gives the best indication of the exhaust transfer functions that will be seen in production but by this time only minor changes can be made to the exhaust without incurring significant cost.

3.4 Vehicle ATF Sensitivities

How ATFs vary between the front and rear seating positions is also important. This is significant where a strong 2nd order profile is sought in the front seats, a side effect is that the sound in the rear seats can be too strong, a compromise must be found in this case. Where the compromise falls will depend on the marketing position of the vehicle. There can also be differences between vehicle specifications for example three and five door derivatives. The spread of ATFs across a given sample size of vehicles is also worthy of consideration but is outside the scope of this paper.

4 INVESTIGATION APPROACH

4.1 Noise Path Analysis

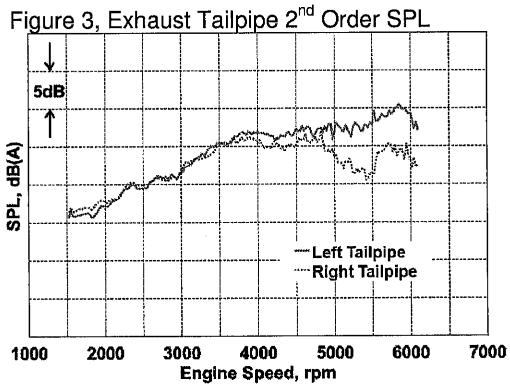
In surveying the influence of exhaust ATFs on the interior sound a Noise Path Analysis (NPA) approach is used. This uses three main sources of data: firstly a measure of the sound of each exhaust tailpipe under acceleration; at a set distance from the tailpipe. Secondly, a local ATF measure between the exhaust measurement position and the end of the tailpipe, for each tailpipe. In this approach each exhaust tailpipe can characterised as a point source of a known strength, independent of the measurement environment. The third data set and the variable in this investigation is the ATFs between the exhaust tailpipes and the occupant ear positions. With NPA the contribution of each tailpipe and the phase interaction between them can be considered. Details of Noise Path Analysis techniques can be found in recent publications[3].

4.2 Exhaust Tailpipe Sound

The Range Rover Evoque featured in this study and shown in Figure 2 has two tailpipes, one on each side of the vehicle. Figure 3 shows the measured 2nd order profile at each of the exhaust tailpipes. The sound is relatively symmetric across the tailpipes up to 4000 rpm, after this the right tailpipe levels are lower, this is partly due an asymmetric pipe layout relating to off-road capability. This orifice sound will remain constant through the NPA, only the exhaust ATFs are changed.

Figure 2, The Range Rover Evoque

Figure 3, Exhaust Tailpipe 2nd Order SPL



4.3 Exhaust ATFs

The following ATFs from four prototypes are used in the NPA investigation which follows, they account for the main phases of development and also for two derivatives of the product.

1.) Early prototype
2.) Mid-program prototype
3.) Confirmation prototype – 5 door derivative
4.) Confirmation prototype – 3 door derivative

5 RESULTS

5.1 Total Exhaust Contribution

5.1.1 Front Seat

In the results that follow the total exhaust contribution to the interior sound is compared; when using each ATF set. The Front Left Outer Ear position is considered then the Rear Left Outer Ear position. In the sections which follow the Front position is explored in more detail, starting with the tailpipe contributions for each prototype and then the phasing of the ATFs. The results are plotted against engine speed for the 2nd order harmonic, for 1000 to 7000 rpm this equates to 33 to 233Hz.

For the Front position, Figure 4, Sound Pressure Level (SPL) is shown in dB(A) on the y-axis. An early guideline for the targeted exhaust contribution is also shown. The prototypes can be taken in-turn and features identified. The noise contribution with the *Early Prototype* ATFs builds consistently then has a drop-out at around 4000rpm, the levels recover to an extent but remain relatively muted for the remainder of the speed range. The contribution in the *Mid-Program Prototype* builds more rapidly than the *Early Prototype* and is upwards of 5dB stronger at 3500rpm. The contribution then also drops-out; but later at close to 4500rpm. For the *5 Door Confirmation Prototype* there are some peaks in the low speed contribution at 2400rpm and 2600rpm after this the level and profile is similar to the *Early Prototype*. There are not the same drop-outs in the *Confirmation Prototypes* though. The contributions do fade from 4000rpm however and then follow the trends of the other prototypes. The *3 Door Prototype* shows a similar profile to the *5 Door*, albeit with slightly more muted levels.

Figure 4, 2nd Order Exhaust Contribution - Front

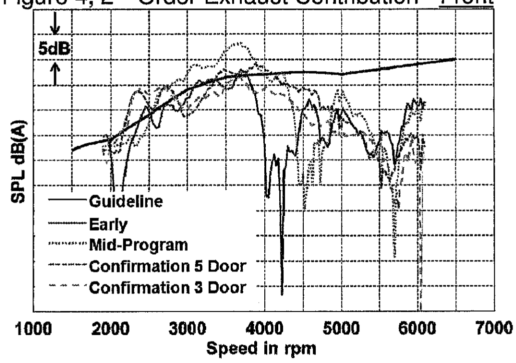
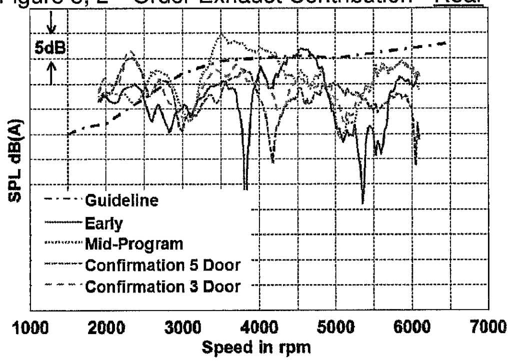


Figure 5, 2nd Order Exhaust Contribution - Rear



5.1.2 Rear Seat

In a driver focused vehicle the sound in the front seat naturally receives more focus than the rear seat. The rear must be at an acceptable level though and Figure 5 illustrates one of the challenges in exhaust tuning. The contribution to the rear sound below 2500 rpm is relatively strong in comparison to the same engine speed in the Front, Figure 4; the figures are on the same scales. This is of particular note for the *Confirmation Prototypes*, as an increase is seen at 2400rpm in comparison to the *Early* and *Mid-Program* prototypes. The peak in the sound has the potential to manifest itself as a "heaviness" in the car, it essentially brings a limit to how loud the exhaust can be tuned which impacts on the sound at the front seat. Given that much of the exhaust design has been frozen by the stage, this highlights the challenge of tuning a strong exhaust sound while being subject to the changing characteristics of prototypes. The *Mid-Program Prototype* shows strong levels at 3500rpm for the rear, in a similar way to the strong levels seen in the front. The risk here is to design too much attenuation in the exhaust. In this application a Helmholtz resonator was designed to soften the mid-speed levels based on *Mid-Program* work; to then be removed later.
The Rear seat does not show the same drop-outs as the front seat for the *Early* and *Mid-program* prototypes. There is a drop in the levels at 5000rpm though.

5.2 Left and Right Tailpipe Contributions

In Figures 6 to 9 the total exhaust contribution to the 2nd order sound is repeated. The additional curves show the Left Hand (LH) and Right Hand (RH) tailpipe contributions. For the *Early Prototype*, Figure 6, the LH and RH tailpipe contributions add to give the total contribution up to 4000rpm. At 4000rpm the drop-out in the total contribution is seen, the individual tailpipe contributions continue to build though, this indicates cancellation of the contributions. After 4000rpm the asymmetry in the tailpipe source sound, seen in Figure 3, means that the LH tailpipe drives the total contribution for the remainder of the speed range. A similar trend is found when viewing the *Mid-Program Prototype* contribution in Figure 7, except the cancellation and drop-out occurs 500rpm later. In addition there is less symmetry between the tailpipe contributions in the mid-speed range. The same drop-out is not seen with the *Confirmation Prototypes*, Figure 8 and 9, although the RH tailpipe contribution does drop in this region meaning the total contribution is formed by the LH tailpipe. The *3 Door Prototype* shows less symmetry in the tailpipe contributions in the mid-speed range.

Figure 6, Early Prototype

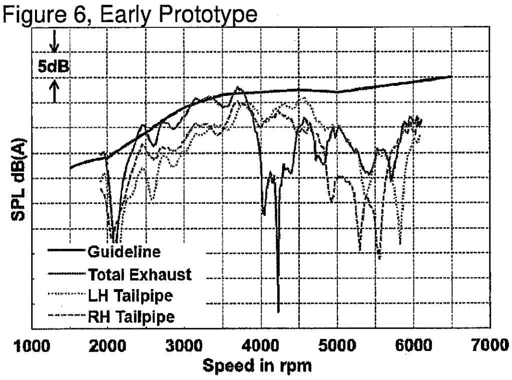


Figure 7, Mid-Program Prototype

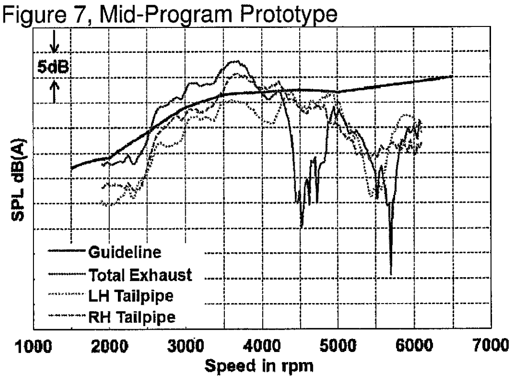


Figure 8, Confirmation Prototype – 5 Door

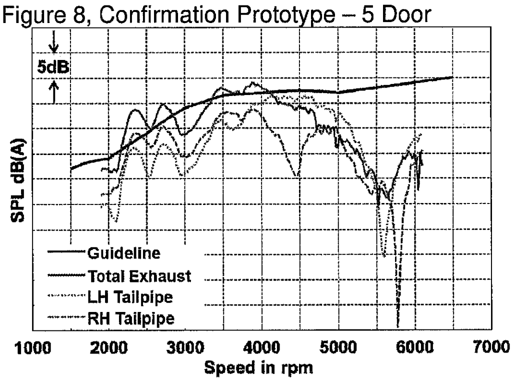
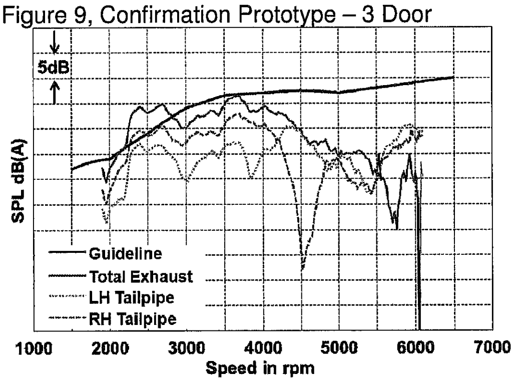


Figure 9, Confirmation Prototype – 3 Door



5.3 Phasing of the Exhaust ATFs

To confirm the influence of the phasing of the exhaust ATFs the LH and RH tailpipe ATFs are shown in Figures 10 to 13 for each of the prototypes. The plots are still shown against rpm, rather than frequency, to enable direct comparison to the contributions. Amplitude is shown in the upper plot in dB and referenced to volume velocity, phase is in the plot below. At around 4000 rpm the *Early Prototype* ATFs are out of phase and a similar trend is seen for the *Mid-Program Prototype*, this explains the cancellation seen in the interior noise in the last section. The *5 Door Confirmation Prototype* shows a similar trend at 4500 rpm, in this way it has more in common with the *Early Prototype* than with the *Mid-Program Prototype*, this is also the case for the amplitudes. The *3 Door Confirmation Prototype* shows a different trend to the other prototypes, the ATFs remain in-phase until 5500 rpm. The amplitudes of the ATFs are generally lower than the *5 Door Prototype* though.

Figure 10, Early Prototype

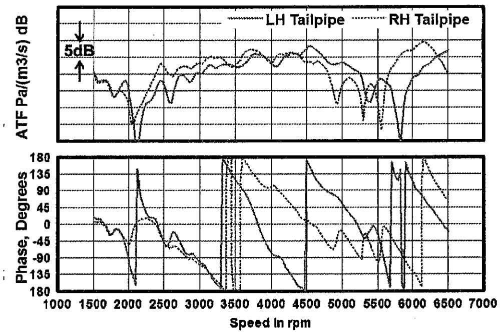


Figure 11, Mid-Program Prototype

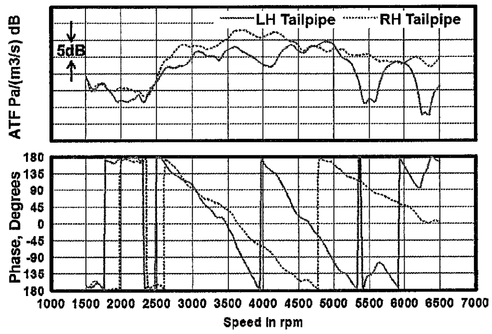


Figure 12, Confirmation Prototype – 5 Door

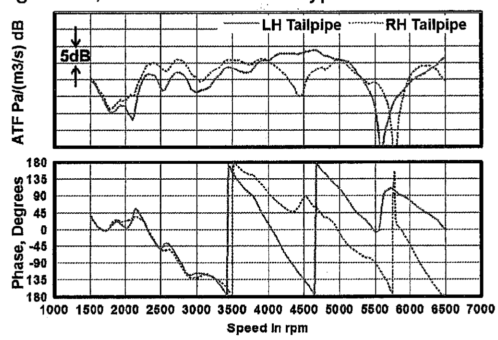
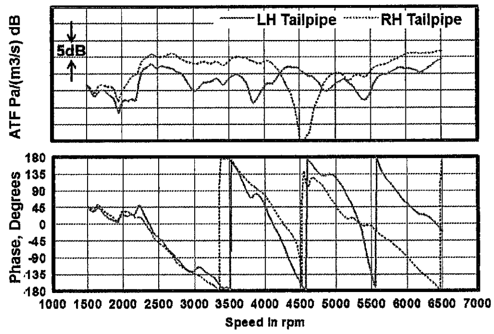


Figure 13, Confirmation Prototype – 3 Door

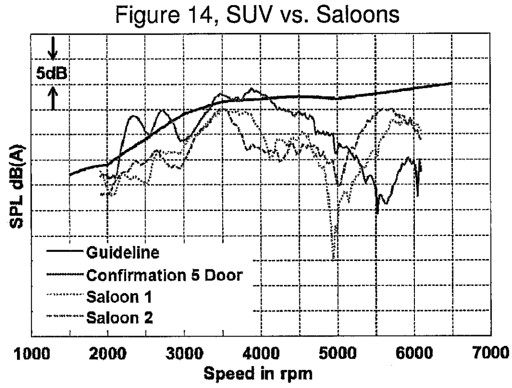


6 DISCUSSION

6.1 High Speed 2nd Order

A feature seen in the prototype vehicles in the Results section is a drop in 2nd order content at higher engine speeds. The total effect seen can be explained by two factors; firstly the modal influence of the cabin which can create spatial variation in both amplitude and phase and secondly by phase interference effects caused by having two sound sources with different propagation characteristics. This is seen most clearly for the *Early Prototype*, in Figure 6 at 4500 rpm the individual tailpipe contributions are strong and of a similar level but interfere to give a drop-out, this is confirmed by the phase in Figure 10. Later in the speed range the amplitude of the ATFs drop-out at around 5500rpm, features in the phase indicate a modal response of the cabin. The prototypes used in this investigation have similar fundamental Sports Utility Vehicle (SUV) cabin shapes. The NPA technique gives the ability to substitute ATFs from another vehicle type. Figure 14 shows the outcome when ATFs from two saloon vehicles are substituted into the NPA, the outcome is compared with the *5 Door Confirmation Prototype*. The difference between the saloons is the position of the tailpipes and this will be covered in Section 6.3. The saloon contribution is lower in the mid-speed range but the content remains relatively strong in the high speed range where the SUV content fades. One explanation for the softening of the 2nd order content above 5000 rpm in the SUV prototypes is the fundamental modal response of the cabin.

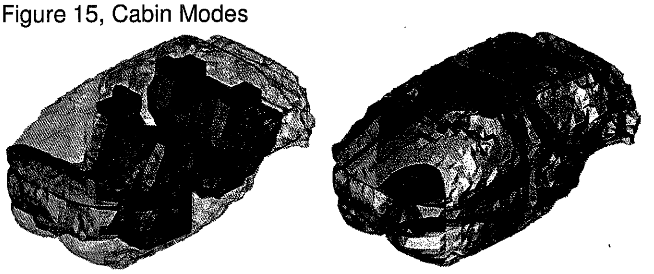
Figure 14, SUV vs. Saloons



6.2 Cabin Modes

In considering the cabin response, a virtual model of the cabin can be viewed. Figure 15 shows an outline of the Evoque cabin to the left of the figure, the four seats can be seen in the figure along with the dashboard. One of the higher frequency cabin modes is shown to the right of the figure. This particular mode is across the cabin. In this case sound at each tailpipe can couple with a given ear position with different effects. This could explain a feature seen in the *3 Door Confirmation Prototype* in Figure 13, where an amplitude drop-out is seen at 4500 rpm for the LH ATF but not the RH. This does have the advantage that if one tailpipe has a weak coupling and therefore contribution the other may remain strong and keep the total contribution to a target level.

Figure 15, Cabin Modes



6.3 ATF Phasing

A feature seen in the *Early* and *Mid-Program Prototypes* is the cancellation of the LH and RH exhaust tailpipe contributions at around 4000 rpm due to the phasing of the ATFs. The effect is also present on the *5 Door Confirmation Prototype* but to a lesser degree, due to a drop-out in the amplitude of the RH tailpipe amplitude. The *3 Door Confirmation Prototype* sees a phase shift later in the speed range at 5500rpm.

In influencing the phasing between the tailpipe ATFs the position of the tailpipes can be considered. The principle will be visited using the exhaust ATFs from the saloon vehicles considered in Section 6.2. The amplitude and phase for the exhaust ATFs are shown in Figures 16 and 17, where the former is a saloon with outboard tailpipes i.e. at the extremities of the vehicle, similar to Evoque. The latter has the tailpipes positioned closer together, otherwise the vehicles are similar. In this case the phasing of the tailpipes remains closer, this will be due to the propagation paths to the ear position being more closely aligned than the outboard tailpipe configuration. While the phase is better aligned there is still the effect of cabin modes on the ATFs, so although there is some benefit in the higher speed range the full benefit of aligning the phase is not seen. Having demonstrated the concept it would be interesting to move the tailpipes closer together on a vehicle similar to the *Early Prototype* and validate the principle on this vehicle.

Figure 16, Saloon 1 – Outboard Tailpipes

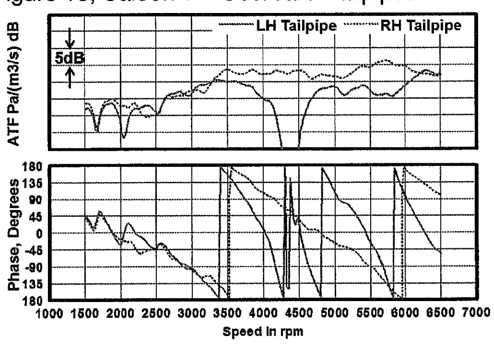
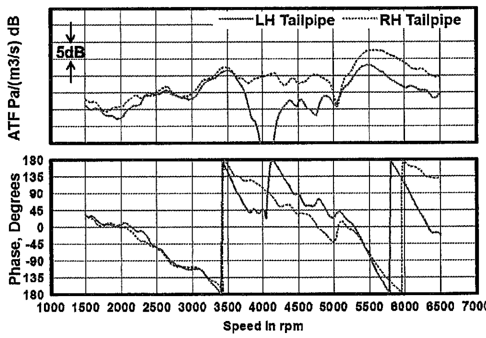


Figure 17, Saloon 2 – Inboard Tailpipes



6.4 Prototype Integrity

The results in Figure 4 showed the *5 Door Confirmation Prototype* to have more in common with the *Early Prototype* than with the *Mid-Program Prototype* in the early to mid-speed range; certainly in terms of ATF level and the total exhaust contribution. The example shown reflects one prototype, on one vehicle program, it is not necessarily characteristic of all *Mid-Program Prototypes.* The higher amplitude ATFs in the prototype are explained by the challenges in fitting a surrogate upper structure to the design-intent lower structure and ensuring the robust fitment of trim and body panels. An alternative scenario is to make more use of *Early Prototypes* but carry-out additional light modifications in order to fit a design-intent exhaust layout. As these prototypes are based on existing vehicles ensuring robust fit and finish of trim and panels presents less of a challenge. If a prototype engine is required this does bring a significant cost and can present a limiting factor in using additional *Early Prototypes.* Even with representative ATF levels there is still the challenge to preempt features arising from the cabin dimensions and modal response of a new vehicle.

7 CONCLUSION

The link between the sound of a vehicle under acceleration and the contribution of the exhaust to the 2^{nd} order profile has been shown. In defining the exhaust contribution an assumption is required for the exhaust ATFs; this allows the sound at the exhaust tailpipes to be tuned accordingly. In developing a vehicle prototypes are built to validate the design. It has been shown practically that exhaust ATFs can vary across prototype phases. The *Mid-Program Prototype* presents the greatest challenge in gaining a representative indication of the exhaust ATFs in the production vehicle. This is explained by the fit and finish of the vehicles and the measures required to match the upper and lower structures. An alternative proposition is to lightly modify *Early Prototypes,* purely for exhaust development. This enables development of an exhaust system to the correct dimensions but also to robust ATF levels. The shape and modal characteristics of the new vehicle cabin remain unaccounted for though and this is where virtual modelling techniques can be developed further.

In explaining the trends in the results the drop in the 2^{nd} order at high engine speeds is accounted for by modal characteristics of the cabin and also cancelation of the tailpipe contributions; due to the phase relationship of different propagation paths from each tailpipe. It has been seen in discussing the results that moving the tailpipes closer together offers potential in modifying the phase relationship between the exhaust tailpipe ATFs and in doing so minimise the potential for drop-outs in the exhaust content due to cancellation. In reviewing a cabin mode example it was shown an advantage can be had with outboard tailpipes where a cross-vehicle mode is seen. In practice a compromise can be made between the effects, how they are used will depend on the vehicle.

For the Range Rover Evoque the exhaust content was maximised within the limits of rear seat acceptability. The fundamental challenge of a drop in 2^{nd} order content at high speed was overcome by using another sound source to maintain the high speed 2^{nd} order profile. The result is a solid and consistent 2^{nd} order base to the sound which builds with engine speed. When balanced with the higher frequency Sound Quality Resonance this has given a total sound with both depth and modulation and one which has been received well by customers.

8 REFERENCES

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