Investigation and Damping a Moan Noise in a Passenger Car

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ABSTRACT

The common rail fuel injection system is normally designed to work over 1000 bar or 15000 psi fuel injection pressure in a passenger car (Diesel Engine) for better atomization of air-fuel mixture. As injection of fuel pressure increase, there is also an increase in the flow induced pressure pulsations. This flow induced pressure pulsations from the common rail can generate a moan noise in diesel engine and makes it more noticeable at driver's ear side during the vehicle running at idle condition and noise goes disappeared as engine speed increases further. The flow induced pressure pulsations magnitudes are also get amplified at ambient temperature below 0◦C due to fuel line material, stiffness properties and fuel density. This high magnitude of pressure pulsations can also lead to rough idle start at cold temperatures.

The current paper presents the different countermeasures to investigate and minimize a moan noise emanated from the common rail and Experiment Base Design approach (EBD) is used to achieve better NVH performance in a passenger car for damping a moan noise.

Keywords - Common Rail, Fuel Return Line, Moan Noise

I. INTRODUCTION

The diesel engine with common rail fuel injection system [6-7-11] includes High Pressure Pump, Injectors, Common Rail, Fuel Delivery Line and Return Line; Fuel Tank integrated with Fuel Pump, Fuel Filter and ECM etc. Refer Figure 1

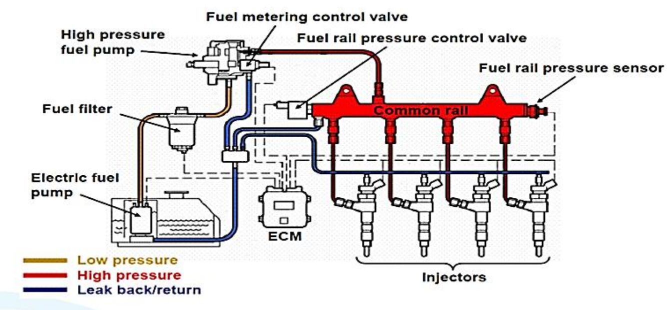

Figure 1. Common Rail Fuel Injection System

The paper briefly discusses the causes of a moan noise generated in diesel engine and countermeasure methodology taken to dampen the noise generated due to the high pressure pulsations.

The paper focuses on Experiment Base Design (EBD) [1] approach for solving the complex and unpredictable NVH problem by subjective feeling tests and objective data measurement in a short period of time. The flowchart is mentioned here with five phases and milestones to come out with an effective solution. Refer Figure 2.

The diesel engine specifications are given below. Refer Table 1

Table 1. Engine Specifications

Engine Type	4 Cylinders, 2 Valves/Cylinder
Displacement	Less than 1.5 L
Max. Power	Less than 90 bhp@4000 rpm
Fuel Injection System	Common Rail Injection
Valve Configuration	Double Overhead Camshaft

PROBLEM STATEMENT- Investigation and damping a moan noise in a passenger car that is heard in driver's side cabin when vehicle is running at IDLE rpm. This noise is generated due to the flow ripples and subsequently, pressure pulsation generated in common rail during the injector firing. Pressure pulsation magnitudes are increased due to deadheaded architecture of fuel system.

SOLUTION- There are different ways to dampen the pressure pulsations generated in common rail during the injector firing. One of the solutions is use of pulse damper integrated with the common rail [2-3]; another solution is to optimize the fuel lines with a suitable fuel line material with using the different sizes of expansion chamber [4-5] in the fuel return line to absorb the pressure pulsations due to change in flow rate.

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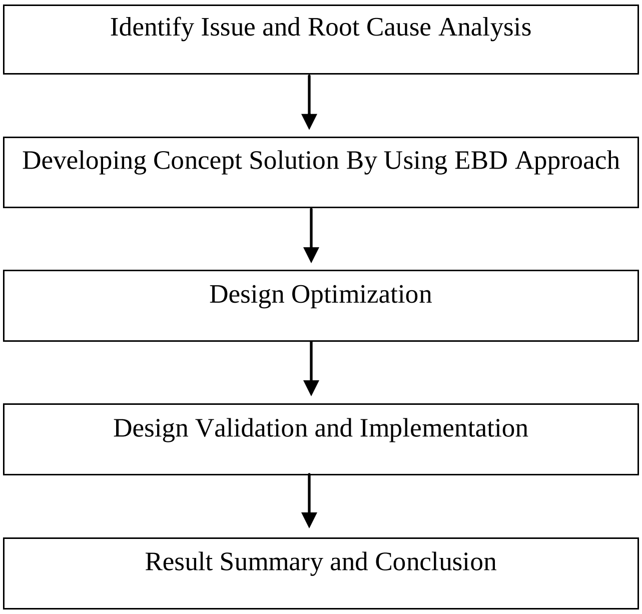


Figure 2. Flowchart Describing Phases and Milestones

II. IDENTIFY ISSUE AND ROOT CAUSE ANALYSIS

Subjective Evaluation- An abnormal noise was heard inside the passenger cabin during the engine idling condition and as the engine speed increases the noise disappears. The vehicle rating for subjective evaluation of NVH was done by jury. Table 2 illustrates subjective scale [8] used for the jury appraisals.

Table 2. Rating Scale for Subjective Jury Appraisals

1 2 3 4	5 6 7	8 9 10
Unacceptable	Fair	Acceptable

In conclusion, it is observed that subjective rating given by jury was between the scale of 1 to 4 and that was not acceptable from the customer point of view.

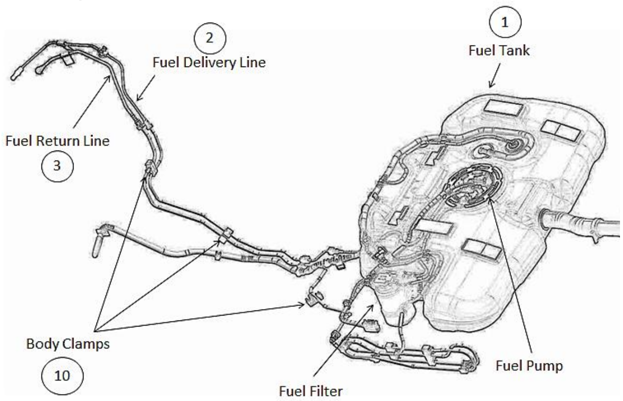
During initial investing of the noise source, source of the noise was unknown. The following swapping activities were carried out in the fuel system [10] as during the engine idle condition, fuel system works and it is concluded that noise source is from the common rail system after replacing the part (Refer Table 3). The common rail was generating high pressure pulsations during the operation of injector and that sudden pressure pulsations or pressure wave propagates from injection pulse to common rail to fuel return line. This pulsation noise was being transferred from the engine compartment to inside the passenger cabin.

FUEL INJECTION PULSE > COMMON RAIL > FUEL RETURN LINE > ENGINE COMPARTMENT > PASSENGER CABIN

Table 3. Swapping activities of Fuel System

Sr No	Swapping Activity of Fuel System Sequentially	Observation (Subjective Noise Rating)
1	Change of Fuel Tank	No Change
2	Change of Fuel Delivery Line	No Change
3	Change of Fuel Return Pipe	No Change
4	Change of High Pressure (HP) Fuel Pump	No Change
5	Change of Hose-HP Pump to Separator	No Change
6	Change of Hose-Rail to Separator	No Change
7	Change of Pipe-HP Pump to Rail	No Change
8	Change of Hose-Injectors to Separator	No Change
9	Change of Separator Part	No Change
10	Isolated Fuel Lines by Removing Body Mounting Clips	No Change
11	Change of Common Rail	Change in Noise Rating. Noise follows with Common Rail

This swapping activity was done and noise was being transferred after swapping a common rail.
Refer Figure 3



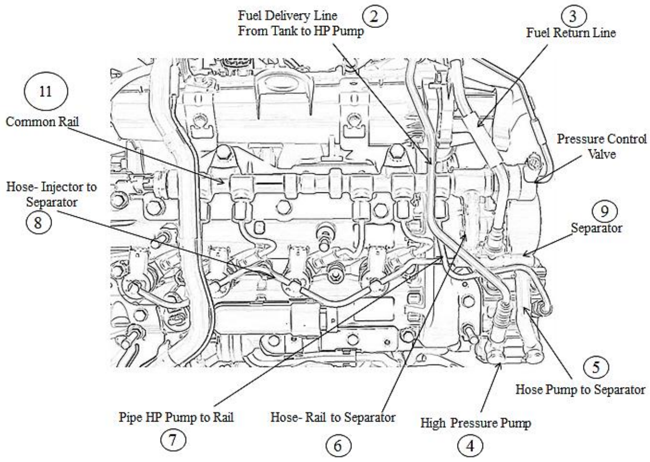


Figure 3. Fuel System Layout in the vehicle (Underbody and Engine compartment)

Objective Evaluation- The subjective evaluation was done and it is observed that noise source is from the common rail. In order to validate the above hypothesis, objective data of noise and vibration measured [9] by using tri-axial accelerometers from Bruel & Kjaer and free field microphone. The accelerometers were located at different positions in the engine compartment near to common rail, separator, hose-rail to separator, hose- pump to separator. The microphone was positioned inside the passenger cabin-driver side. Refer Figure 4

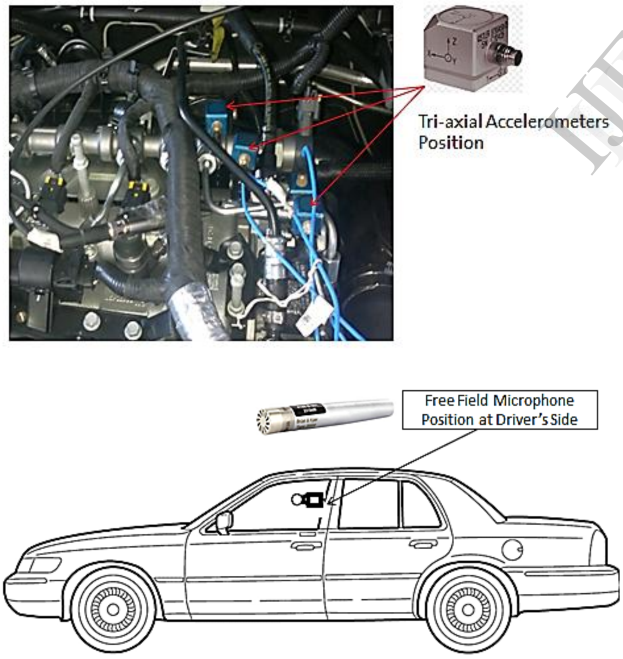


Figure 4. Accelerometers and Microphone Position

From N & V data measurement at idle condition to further rpm , the moan noise frequency found around 300 to 500 Hz (centre around 400 Hz) near to the common rail, high pressure, low pressure fuel lines. Refer Figure 5

The similar frequency range 300 to 600 Hz found inside the passenger cabin. Refer Figure 6

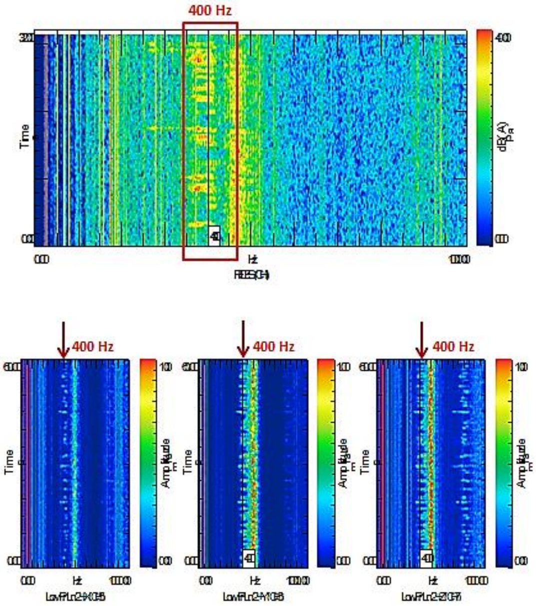


Figure 5. N & V Colour Plot in Engine Room

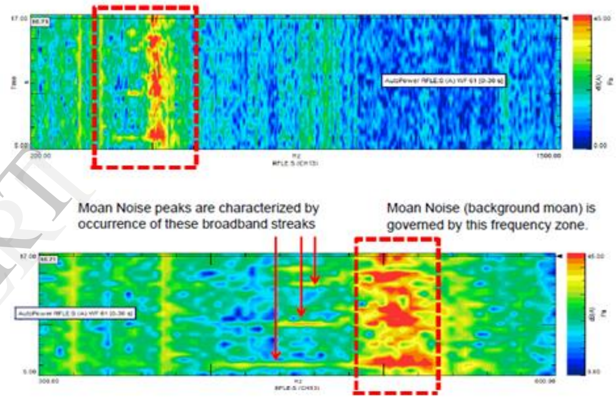


Figure 6. Noise at Driver's Ear Location on Issued Vehicle

The noise source was the common rail re-confirmed after objective data measurement and further investigation started to find the root cause in common rail pressure control valve (PCV) Refer Figure 7.

Also, further countermeasure study started to dampen the noise directly behind pressure control valve and find the feasible solution as earliest.

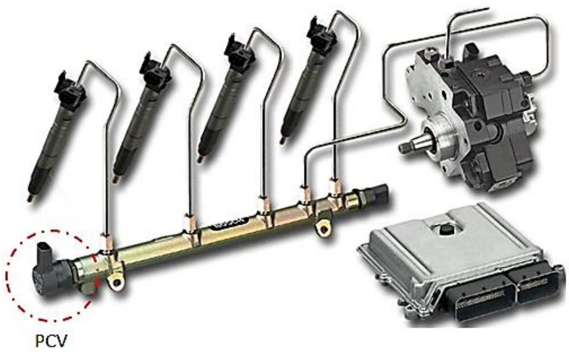


Figure 7. Pressure Control Valve in Common Rail

III. DEVELOPING CONCEPT SOLUTION BY USING EBD APPROACH

To find the root cause in PCV of Common Rail was tedious and time consuming activity. So it is decided to bring an alternative solution on table as earliest and some ideas were generated like

Concept 1: To disconnect the fuel return line from fuel bundle or separator as noise trace found in the fuel return line during the objective data measurement. A moan noise disappeared after removal of the fuel return line from the separator. Refer Figure 8

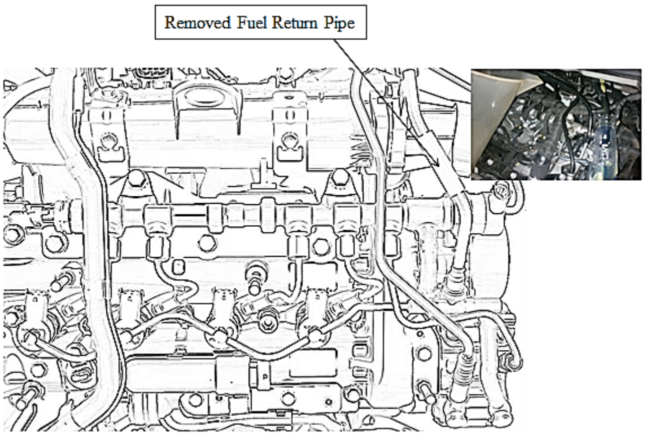


Figure 8. Disconnected Fuel Return Line

This is given a solution to use the fuel return line of a soft material like rubber hose instead of present nylon material to absorb the pressure pulsations.

Concept 2: To use a non-braided rubber hose from separator to fuel bundle side instead of nylon fuel return pipe. The rubber hose length is used around 500 mm. A non-braided rubber is solved the purpose of damping the noise but it can't be used on the vehicle due to the durability concern, engine compartment temperature sustainability concern and packaging constraints. Refer Figure 9

Figure 9. Non-Braided Rubber Hose as Fuel Return Line

Concept 3: Try out with an expansion chamber of different sizes with a braided rubber hose in a fuel return line at different location as a noise reduction coefficient (NRC) of rubber hose is higher than a present nylon pipe. Refer Figure 10

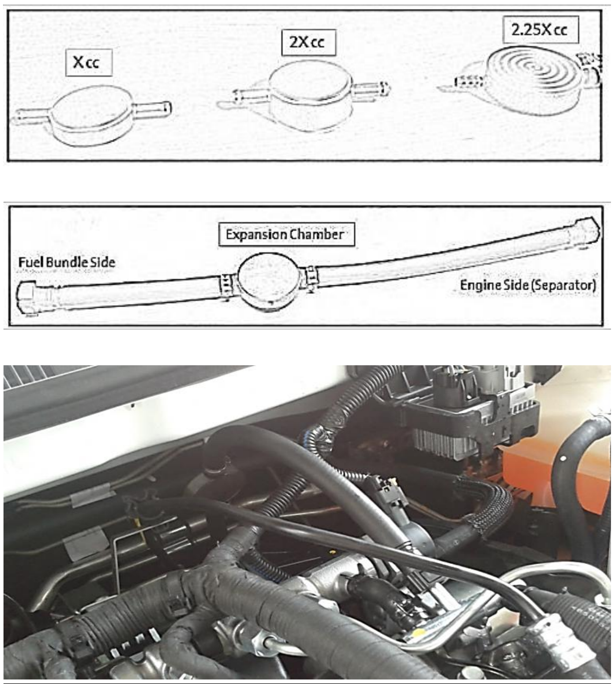


Figure 10. Different Sizes of Expansion Chamber with a Braided Rubber Hose

Trials were done on the vehicle by using the different sizes of expansion chamber (X cc, 2X cc, 2.25X cc) at different location in fuel return line according to vehicle packaging and 2X cc, 2.25X cc expansion chambers with a braided rubber hose found suitable for damping the pressure pulsation in fuel return line. This measurement was done subjectively and then objective data recorded by using the accelerometers near to common rail and fuel return line. The microphone placed in a passenger cabin at driver side. A moan noise is disappeared at frequency 300-500 Hz and a corresponding 12 dB (A) decrease in the noise level is noted in the front cabin. Refer Figure 11

The expansion chamber theory for noise damping in hydraulic fluid system works due to sudden change in flow rate and volume of fluid.

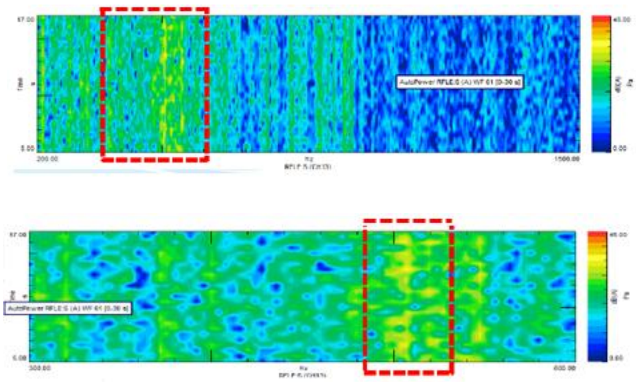


Figure 11. Noise at Driver's Ear Location with an Expansion Chamber on Issued Vehicle

The theoretical approach can be used for predicting the noise performance in fuel system by using an AMESim simulation model, but it's time consuming and tedious task as it requires complete fuel system including engine injection system combined with hydraulic and structural dynamic model. This requires several weeks to collect the needed data and create an AMESim simulation model. So Experiment Base Design (EBD) is a much quicker and direct approach than trying to do an AMESim Simulation. Also, a drawback of AMESim simulation model is that airborne or structure borne noise can't be assessed at all.

Transmission loss between Nylon Pipe and Rubber Hose with Expansion chamber can be calculated by using transmission loss formula, speed of sound and frequency of noise but this is not going to discuss in here in depth as EBD is a better and practical approach for all fuel line noise development. Here, theory of expansion change and design parameters discussed in a short.
The simplest kind of reactive muffler is the expansion chamber [5], where the duct opens into a large volume, creating an abrupt change in cross-sectional area at each end of the volume. Refer Figure 12

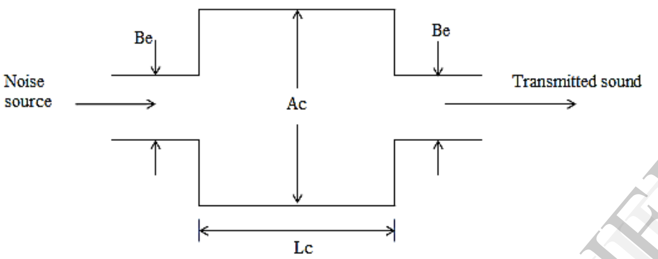


Figure 12. Geometry of Expansion Chamber

Expansion chambers operate most efficiently in applications involving discrete frequencies rather than broad band noise. The length of the chamber is adjusted so that the reflected waves cancel the incident waves. The transmission loss through an expansion chamber is defined as the difference in sound pressure level of the incident sound wave and the transmitted sound pressure level. It may be estimated from:

$$TL = 10 \log \left[1 + \frac{1}{4}\left[\frac{Ac}{Be} - \frac{Be}{Ac}\right]^2 \sin^2 \frac{2\pi Lc}{\lambda}\right]$$

Where TL is Transmission Loss, dB
Ac is the cross-sectional area of the chamber, m^2
Be is the cross-sectional area of the inlet to the chamber, m^2
Lc is the length of the chamber, m
λ is the wavelength of sound, m

The above equation is valid for the cross-sectional dimension less than one wavelength for the frequency of sound interest. Note that when the length of the expansion chamber is equal to λ/2, 3λ/2 … etc the transmission loss will be zero.
The following rules apply for the design of expansion chamber

- The greater the area ratio of Ac to Be, the greater the TL.
- The length of chamber controls the frequency at which there is maximum attenuation.
- Large chamber walls should be avoided because they tend to vibrate and radiate noise.
- When a number of discrete frequencies must be attenuated, several expansion chambers can be placed in series, each tuned to a particular wavelength.

IV. DESIGN OPTIMIZATION

After different trials on the vehicle, 2X cc expansion chamber with a braided hose selected for noise reduction. So in design optimization stage; the feasibility of the final solution according to vehicle engine compartment layout was studied.
The vehicle packaging study was done with this solution considering engine pitching/rocking in Y direction (engine roll evaluation) and minimum required clearance with the surrounding parts were maintained. Refer Figure 13

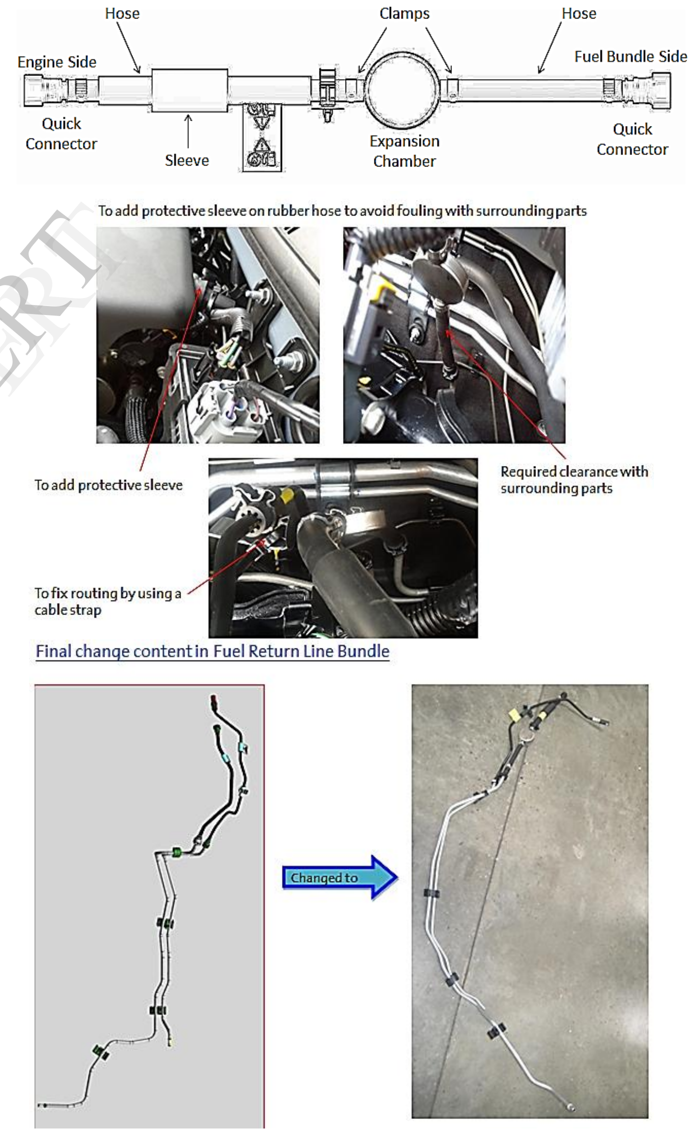


Figure 13. Fuel Return Line Routing Study in Vehicle

V. DESIGN VALIDATION AND IMPLEMENTATION

In design validation stage, fuel return line with 2X cc expansion chamber validated for different tests to meet the vehicle environment condition. The following component level testing was done on the fuel return line with 2X cc expansion chamber to validate the part in terms of durability and performance. The major tests covered in this paper are

- Leakage test
- Internal Cleanness
- Burst test
- Pressure cycle test
- Pull of load test for quick connector

VI. RESULT SUMMARY AND CONCLUSION

The final result summary of all design proposals tried out on the vehicle for pulsation noise suppression can be summarized as follows. Refer Table 4

Table 4. Summary of Different Proposals

Sr No	Iteration	Result
1	A Non Braided Rubber Hose as Fuel Return Line	Not Good
2	A Braided Rubber Hose with X cc Expansion Chamber	Not Good
3	A Braided Rubber Hose with 2X cc Expansion Chamber	Acceptable
4	A Braided Rubber Hose with 2.25X cc Expansion Chamber	Acceptable
5	A Braided Rubber Hose with 2X cc Expansion Chamber- Design Validation Tests	Passed

The current work describes the approach towards solving the NVH related problems in a passenger car by using Experiment Base Design (EBD) approach on the vehicle. This can reduce the time to solve the problem. All other design criterion like durability, performance and safety aspects must be taken care while recommending such design modifications. The future scope of work involves

- Further deep drive in common rail pressure control valve (PCV) root causing and countermeasure to damp moan noise at common rail itself.
- Study to make a stream lined flow in fuel low pressure circuit by working on the fuel return separator assy.

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DEFINITIONS/ABBREVIATIONS

EBD	Experiment Base Design
PCV	Pressure Control Valve
ECM	Electronic Control Module
NRC	Noise Reduction Coefficient
TL	Transmission Loss, dB
EPDM	Ethylene Propylene Diene Monomer