

Transient Thermodynamic Performance and Passby Noise from the Silencer of a Modern Diesel Engine in an Actual Vehicle

P A Lakshminarayanan

ABSTRACT

The passby noise is the net effect of the noise from the engine, tires, vehicle panels, the fan and the exhaust silencer. Exhaust noise is probably the loudest component of the passby noise in diesel trucks. The passby noise is measured when the vehicle is in transient condition according to the standards. A technique is developed to simulate the transient noise from the exhaust using 1-d simulation software AVL-Boost. It considers thermodynamics of combustion in the engine including the turbocharger, inertia of the engine and the vehicle. The technique helps in optimizing exhaust silencer, acceleration and in-cylinder parameters in transient conditions and the turbocharger fatigue.

A 165 kW 6-cylinder turbocharged and intercooled engine is simulated. The transient performance of the engine in the vehicle is validated by comparing the predicted results with the observed fuel consumption on road, time to accelerate to 60 km h⁻¹ and the fluctuations in the turbocharger speed. The Linear Acoustics model of the silencer in conjunction with this transient model of the engine is used to predict the insertion loss of the silencer and the vehicle passby noise. In the first step, the silencer model is validated with test results by measuring the insertion loss in an actual vehicle. In the second step, the vehicle is modeled with the silencer by using load signals, fuelling and injection timing maps. The predicted noise is compared with the experimentally measured passby noise and the results are encouraging.

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INTRODUCTION

Limits to noise emission are laid down in the Indian Central Motor Vehicles Rules (CMVR) for different categories of vehicles [1]. Simulation using Linear Acoustic Model in AVL Boost is helpful to the designers to check their concepts virtually for relative improvements and avoid time consuming experiments. The linear acoustics model is made up of a source, a system and a termination, no matter how complex or how many elements are used in the modeling. Thus noise parameters like insertion loss and transmission loss can be obtained during the design stage itself. Further, the calculations can be used to validate the measurement data in an actual experiment.

Standard procedure and guidelines for measurement of noise are laid down [1]. The leveled test site consists of a central acceleration section surrounded by a substantially flat dry track to maintain the rolling noise low. There should be no obstacle that affects the sound field within the vicinity of the microphone and the sound source. The measurements are not to be done in adverse weather conditions such as rain,

storm and the heavy winds that would affect noise, instruments and test results. For measurements, the A-weighted sound level of the background noise should be at least 10dBA below the sound level produced by the vehicle.

SIMULATION OF TRANSIENT OPERATION

For the transient cycle simulation of the vehicle, the following important inputs are required:

- Model of the silencer
- Driving cycle (velocity versus time)
- Full model of the turbocharger and combustion
- Engine control unit (ECU): for defining the fuel quantity, rate of injection maps.
- Vehicle gear ratios
- Inertial values for gear trains, engine and the vehicle

Silencer Model

The layout of the experimental silencer is given in Fig. 1. The silencer is split into several sections to prepare a linear model, Fig. 2 [2, 3]. The three pipes 7, 8 and 9 in Fig. 1 are represented by a single pipe of equal cross sectional area and equal porous area. This enabled representing this complex geometry elegantly as a pipe-in-pipe (PIP₂) model. Two pipe-in-pipe (PIP₁, PIP₂) sections and one perforation (PER₁) are introduced. The interconnections are made using pipes 29, 37, 32, 33, 35, 40 and 43. The pipe 33 jutting into the central chamber is suitably specified. The rectangular cross section of the outer can is converted to a circular section of equal cross sectional area. Therefore pipes 30, 41, 42, 39, 34, 35 and 36 are represented by equivalent circular pipes. One of the ends (SB₂, SB₆, SB₃ and SB₄) of each pipe 30, 39, 41, 42, 34 and 36 has a boundary with zero flow coefficients to simulate a wall. Junctions J₁₀, J₉ and J₁₁ are used to combine two or more pipes. Pipe 43 corresponds to the duct from the silencer to the atmosphere. The end of 43 open to the surroundings is terminated by SB₅ with a flow coefficient equal to 1 in both the directions. The microphone MIC₁ is connected to the end of pipe 43 by specifying its x, y and z positions with respect to the outlet of the pipe and its position with respect to the ground. This system is entered into the graphic user interface (GUI) of the AVL-Boost as shown in Fig. 3.

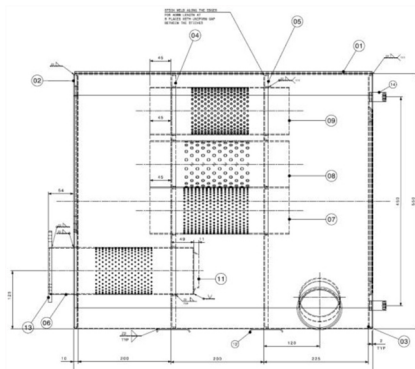


Figure 1. Silencer Layout

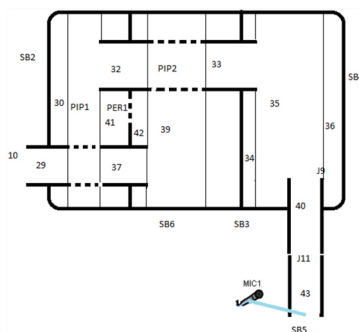


Figure 2. Representation of the silencer in Fig. 1

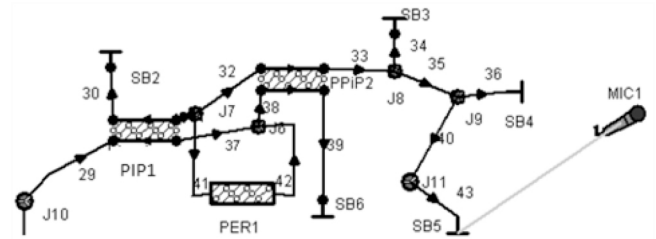


Figure 3. Linear model of the representation given in Fig. 2

Engine Model

The circuit diagram for the simulation on the graphic user interface is shown in Fig. 4 for a 6-cylinder engine. The air enters into the air-cleaner, CL₁ through the system boundary, SB₁. The air is compressed in the compressor, C of turbocharger, TC₁ and goes into the intake manifold, PL₁ via air cooler, CO₁. The fuel injected in the individual cylinders (C₁, C₂, C₃, C₄, C₅ and C₆) mixes with the incoming air. After combustion, the exhaust gas expands in the turbine, T of the turbocharger (TC₁) and finally escapes into the environment through system boundary SB₂. The thermodynamic properties are monitored at the measurement points MP₁, MP₂ etc. An ECU₁ and an Engine interface EI₁ are connected to give necessary inputs to the cylinder and the turbocharger. The ECU scheme is shown in Fig. 5 and dealt with later in Table-1. A monitor MNT₁ is connected to monitor some important variables like turbocharger speed, compressor pressure ratio etc. The grey lines are the electrical connections and the black lines are the pipe connections.

Combustion Model

AVL mixing controlled combustion (MCC) model [4, 5 and 6] is one of the accurate models available in AVL Boost for prediction of heat release rate for the given speed and fuelling. This model was further improved in reference [7] for more realistic prediction. However, in this paper the basic MCC model [5] is used. Some of the inputs (Fig. 6, 7, 8 and 9) for predicting heat release rate are

- Injector nozzle hole size
- Number of holes in injector nozzle
- Rail pressure
- Rate of Injection curve
- Combustion parameter
- Fuelling at different loads

Rail pressure and rate of injection curve are defined in the ECU for the corresponding speed and fuelling, and several important constants like the MCC combustion parameter constant. The indicated work done on the piston is calculated applying the first law of thermodynamics to the heat release

rate and heat losses to the walls. Frictional losses are subtracted from the indicated work to obtain the brake power for a given speed and fuelling.

Electronic Control Unit

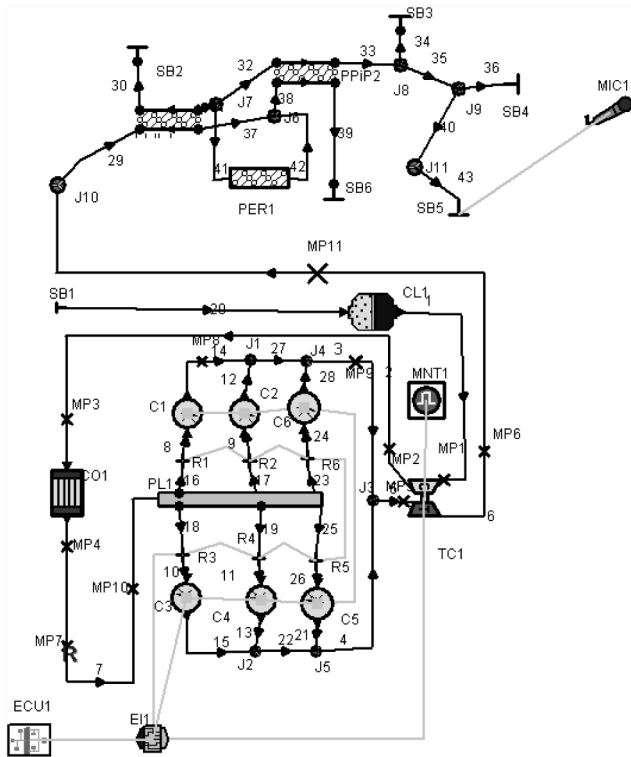


Figure 4. Layout of the engine and the silencer for simulation using AVL Boost

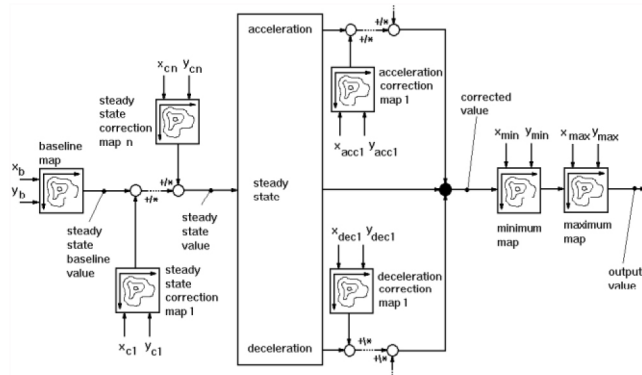


Figure 5. Flow chart for ECU x, y = sensor channels
Output value = actuator channel [6]

In most modern engines, many functions of the engine are controlled by an electronic engine management system. It is necessary to model such a control device especially for the simulation of transients. In the ECU, the same input to the unit produces different outputs depending on the state of the unit. The engine control model features three states: steady state, engine acceleration and engine deceleration. An ECU

can be created for simulation of mechanical engines as well as amply demonstrated in reference [4].

The transition from steady state to the state of engine acceleration is triggered if the gradient of the load signal versus time exceeds a threshold specified by the user. The transition to engine deceleration is triggered the same way when the negative gradient of the load signal exceeds the user specified threshold. A baseline steady state value is taken from the baseline map. This value is subjected to corrections by adding values from correction maps or by multiplying it by factors from correction maps. In the case of acceleration or deceleration, other corrections are applied to the steady state value from the corresponding acceleration or deceleration correction maps. Then it is checked whether the output is within predefined bounds which themselves are defined as maps. If it is within the maximum map or minimum map then the same value is considered as the output value. If it is outside the minimum or maximum maps then the corresponding minimum or maximum value is taken from the maps.

Table 1. Maps for the ECU and Engine Interface in Fig. 5 input for simulation

Description	Map	input		map	output
		x	y		
Baseline map	1	n	L	Fig. 6	Fuelling
	2	n	f	Fig. 9, typical at 1500 rpm	Rate of injection against crank angle
	3	n	f	Fig. 8	MCC Combustion parameter
	4	n	-	Fig. 7	Common rail injection pressure (input to MCC combustion model)
Steady state correction	1	-	-	Table- 2	-
Acceleration correction	-	-	-	none	-
Deceleration correction	-	-	-	none	-
Minimum correction	1	n	π	-	Fuelling = 0
Maximum correction	1	n	π	e.g., Table- 3	fuelling

π = Pressure ratio across the turbo compressor

n = speed

L = Torque/load

f = fuelling

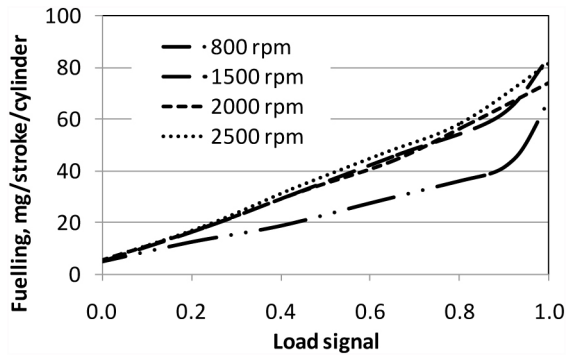


Figure 6. Variation of fuelling with load signal for various speeds

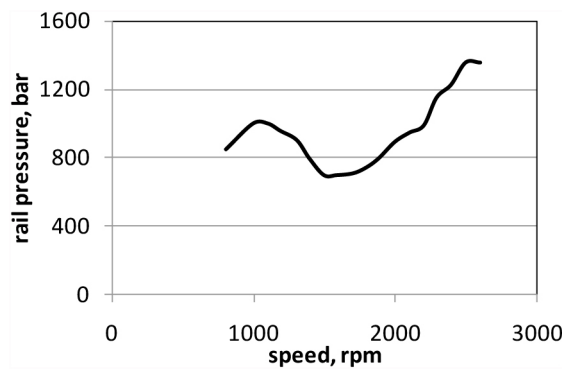


Figure 7. Variation of rail pressure with speed

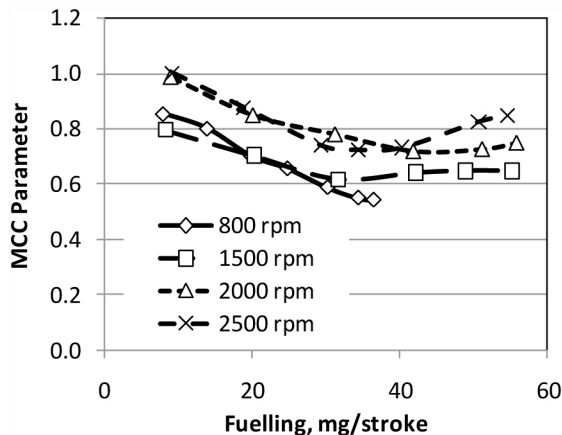


Figure 8. Variation of MCC combustion parameter with fuelling for various speeds

ECU data for the 165kW engine given for simulation is shown in Tables- 2 and 3, and Fig. 6, 7, 8 and 9. During simulation, based on engine speed and load, the ECU selects the corresponding fuelling required per cylinder from the baseline map plotted as graph in Fig. 6. To the base value, the steady state correction values are applied based on the load changes. For brevity, the correction applied is same for all, irrespective of the load change. The fuelling obtained is

compared against the maximum and minimum maps. The minimum quantity of fuelling is specified zero (in an actual engine a very meagre amount of fuel is injected to keep the injector tip cool) and the maximum quantity of fuelling depends on speed and boost pressure, e.g., as shown in Table-3. If the fuelling exceeds the maximum or minimum value, then the corresponding maximum or minimum value would be taken. Otherwise, the fuelling that is obtained after the correction maps is considered as the final value for the cylinders. For the fuelling and speed, the MCC combustion parameter and rate of injection curve were decided from the maps shown in Figs 8 and 9. The rail pressure is selected based on the engine speed alone as shown in Fig. 7. All these three inputs are required for simulating the MCC combustion model. With speed changing every cycle, the importance of ECU is evident from the above graphs.

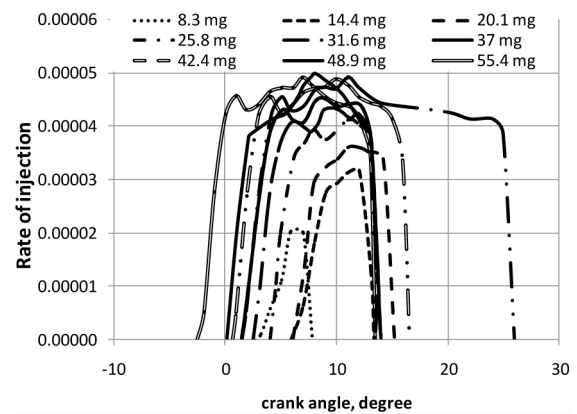


Figure 9. Rate of injection curves for different fuelling at 1500 rpm

Table 2. Data for steady state correction map

Steady state Correction	state	Parameter	n time	ff time
Positive changes	load	Lag time for correction	1 s	1 s
		Time constant for correction	1 s	1 s
Negative changes	load	Lag time for correction	1 s	1 s
		Time constant for correction	1 s	1 s

Table 3. Maximum values map for fuelling, $\text{mm}^3 \text{ stroke}^{-1} \text{ cylinder}^{-1}$

Boost pressure, kg cm^{-2}	Speed, rpm				
	500	1000	1500	2000	2500
0.0	35	35	35	35	35
1.0	35	35	35	35	35
1.5	52	52	52	52	52
2.0	75	75	85	85	75
2.5	75	75	85	85	75

Either the load signal or a desired engine speed can be selected as the guiding input signal of the ECU. If desired