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Project Report
VEHICLE EXHAUST CONTROL USING SIMULINK

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Introduction

Internal combustion engines (I.C. Engines) are those engines where combustion of fuel takes place inside the combustion chamber and power is obtained through the energy released there itself. Today's transportation on road, air, water or space is dominated by the use of energy released from combustion of petroleum products. The different notable characteristics between spark ignition (SI) engines and compression ignition (CI) engines can be mentioned as follows.

1. Compression ratio for CI engines is between 16 to 20 whereas for SI engines it ranges from 6 to 10.
2. Pressure and temperatures are relatively higher in CI engines compared to SI engines
3. CI engines are heavy and bulky while SI engines are relatively lighter and smaller in sizes
4. SI engines are high speed engines
5. Mixture of petrol and air is ignited after compression with either a spark plug or an electronic system in SI engines whereas in CI engines, only air is compressed to high pressure and temperature which is sufficient to ignite finely atomized spray of diesel which ignites instantaneously.
6. The four strokes - intake or suction, compression, power and exhaust are common in both.

Petrol and diesel vehicles are main modes of transportation, which are responsible for today's world becoming global. The two fuels when burnt in internal combustion engines provide the power for motion at the same time, exhaust gases are released in atmosphere. The composition of the exhaust gases may contain very small percentage of components, which are unacceptable as they can cause harm in human beings as well as the environment. Therefore, it is matter of concern to monitor exhaust gases as per existing government regulations also.

The presented project report deals with a simulation model of a Vehicle exhaust system developed using SIMULINK libraries.

Background theory: Exhaust system overview

Working of Petrol Engines:

A petrol engine also known as a gasoline engine is an internal combustion engine with spark-ignition, designed to run on petrol and similar volatile fuels.

In most petrol engines, the fuel and air are usually mixed after compression. The pre-mixing was formerly done in a carburettor, but now it is done by electronically controlled fuel injection, except in small engines where the cost/complication of electronics does not justify the added engine efficiency. The process differs from a diesel engine in the method of mixing the fuel and air, and in using spark plugs to initiate the combustion process. In a diesel engine, only air is compressed (and therefore heated), and the fuel is injected into very hot air at the end of the compression stroke and self-ignites.

Exhaust Gases:

The Exhaust gases emitted into the atmosphere are a combination of burned and unburnt fuel. To understand the exhaust emission and its composition, we must review some basic chemistry.

When the air/fuel (A/F) mixture is introduced into the engine, it is composed of nitrogen (78 percent), oxygen (21 percent) and other gases (1 percent) with the fuel, which is entirely 100 percent hydrocarbons (HC), in a semi-controlled ratio. As the combustion process happens, exhaust gases are produced which are composed of nitrogen (N_2), the carbon dioxide (CO_2), and water vapour (H_2O). The nitrogen (N_2), for the most part, passes through the engine unchanged, while the oxygen (O_2) reacts (burns) with the hydrocarbons (HC) and produces the carbon dioxide (CO_2) and the water vapour (H_2O). If only CO_2 and H_2O were formed then the exhaust emissions would be harmless. However, in reality such perfect combustion does not occur and during the combustion process, other compounds are formed which are hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx) oxides sulphur (SOx) and engine particulates termed as pollutants.

Hydrocarbons:

Hydrocarbons (HC) can be said to be the fuel which was not burnt during the combustion process. Incomplete combustion are rich air/fuel mixtures, low engine temperatures and improper spark timing can be considered to be the reasons for the presence of HC in the system.

Individual gas compositions can be estimated quantitatively in laboratories or on sites with the use of technique called gas chromatography.

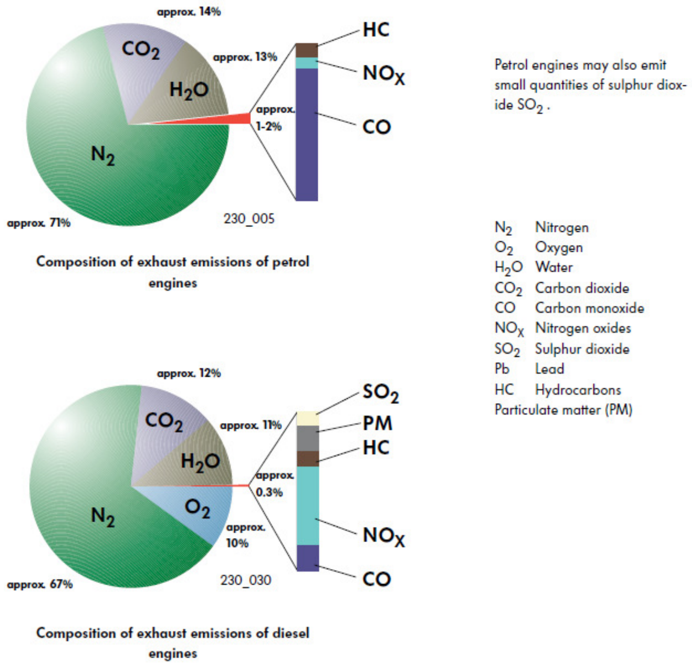

Figure 1 (a) Exhaust gases in petrol and diesel engines

(Image source: WV AUDI Self-Study Programme 230 titled 'Motor Vehicle Exhaust Emissions Composition, emission control, standards, etc.', Basics pg. 6)

Based on the above theory and understanding working of the system, it is possible to develop a model of the exhaust system for a vehicle in MATLAB using SIMULINK libraries.

Why Exhaust control is needed?

- Exhaust gases are pollutants made up of NOx, CO, HC and unburnt fuel
- Gases measured in form of % Exhaust
- CO and HC are toxic and harmful to humans

- Government sets laws called 'Emission Standards' to govern air pollutants (g/km) released into the atmosphere (E.g. Euro 6)
- Every new standard is towards lowering the % further
- Only vehicles satisfying the standards can be sold
- Hence, vehicle makers need to adhere to requirements
- Exhaust control is the solution to meet these needs

Vehicle Emissions

The Emphasis on air quality is increasing as the technology is advancing due to which now almost all nations around the globe are more conscious on the vehicle emissions and incorporate stricter norms for ensuring lesser pollution for a safer earth in future.

The emissions issue is dependent on the internal combustion engine, which converts the chemical energy stored in fuel into heat, released by simple combustion process. Whenever perfect combustion occurs, it changes hydrocarbons (HC) into carbon dioxide (CO_2) and water (H_2O).

In truth, perfect combustion exists in only lab conditions and thus, at a given time, it is possible that the result is less than perfect combustion and undesirable emissions are occurring.

The three major pollutants identified for any vehicle emissions are carbon monoxide (CO), hydrocarbons (HC), and oxides of nitrogen (NOX) as mentioned earlier. Carbon monoxide (CO), is incompletely burned fuel. High (CO) is the appears when a rich air/fuel mixture is present. Hydrocarbons (HC) is simply unburned fuel that have escaped the combustion cycle.

Oxides of nitrogen (NOX) are a difficult to estimate. At engine combustion temperatures, nitrogen (which makes up more than 70% of our atmosphere) bonds with oxygen to form oxides of nitrogen (NO_X).

The exhaust gas recirculation valve (EGR) is designed to introduce metered amounts of exhaust gases back into the intake manifold which displaces a portion of the incoming air/fuel mixture to the cylinders, this can reduce high combustion temperatures and reduce NO_X.

Although CO_2 is not a pollutant, CO_2 is actually a by-product of a good or a perfect combustion. Amount of CO_2 is the highest when the combustion efficiency of the engine and catalytic converter are maximum. CO_2 gets trapped in the atmosphere and causes the greenhouse effect. It is responsible for global warming which has alarmed scientists all over the globe and now concentrated efforts are being directed towards minimizing the effect of CO_2 and the European exhaust emissions Commission has set out rules for monitoring the CO2 emissions of new cars.

The emission standards in Europe were first introduced in 1970. Later, in 1992 the 'Euro 1' standard was introduced after 22 years where fitting of catalytic converters to petrol cars to reduce carbon monoxide (CO) emissions was made mandatory.

The latest standard, 'Euro 6', now applies to all new cars from September 2015 and reduces some pollutants by 96% compared to the 1992 limits, where the addition of an extended on-road emission test known as Real Driving Emissions or RDE has been made inevitable.

Emissions Control

To control exhaust emissions in order to reduce the total engine pollutants, two types of systems are used:

1. the air-injection system
2. the exhaust gas recirculation (EGR) system.

In case of an air-injection system, air is injected into the exhaust manifold using a pump, where the air combines with unburned HC and CO at a high temperature to assist the combustion process. A large percentage of the pollutants can be burned by this method which could have been discharged by the exhaust system.

In EGR, a certain portion of exhaust gases are directed back into the cylinder head and are combined with the fuel-air mixture before entering the combustion chamber. These lower the temperature of combustion which reduces NO_x formation.

Another area for exhaust control is the catalytic converter which is essentially an insulated chamber containing ceramic pellets or a ceramic honeycomb structure coated with a thin layer of metals such as platinum and palladium. As the exhaust gases pass through this structure, the metals act as catalysts to induce the HC, CO, and NO_x in the exhaust to convert them to water vapour, CO_2, and N_2.

Improvements in combustion process are now-a-days influenced by the use of computerized control using programmable hardware like the microcontrollers as Engine control unit. This control ensures the most efficient operation of the entire systems and ensures more precise air-fuel mixtures, creating greater efficiency in combustion and lower generation of pollutants.

SIMULINK Model Features

The model developed has the following features-

1. It is a simplified SIMULINK model to display exhaust gases in a petrol engine
2. Focusses on keeping A/F Ratio closer to ideal.
3. Controls fuel nozzle diameter for this, Air diameter has been kept constant for that particular case to be able to show fuel nozzle area control for achieving the desired ideal A/F ratio.
4. Uses feedback loop to show effect of Exhaust control
5. With and without feedback loop effect is available through manual switch as we wanted to show both the effect of using feedback on Exhaust gases and when no feedback is present in the same model.

Model Development Approach

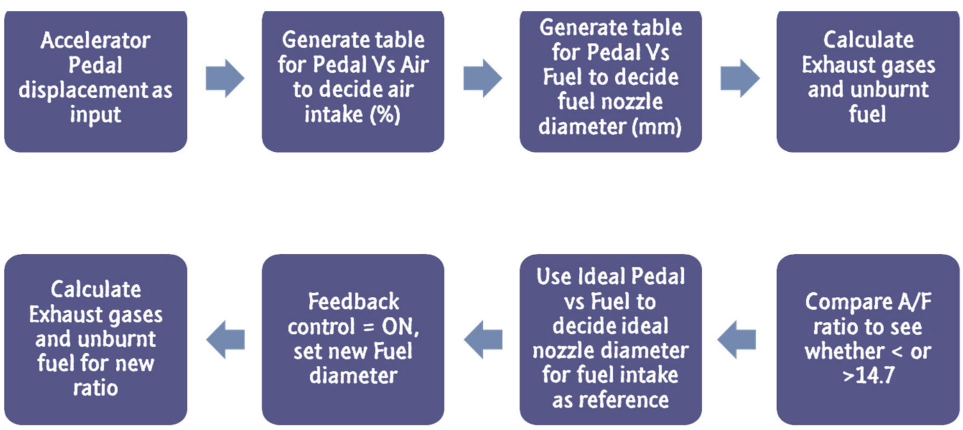

Figure 1 (b) SIMULINK Model Development Approach

According to the steps shown in figure 1 (b) above, we started with estimating the inputs based on some assumed values. This gave us accelerator displacement values and respective % valve openings to arrive at A/F ratios.

Based on this, we further calculated, exhaust gas compositions and used the ideal values to correct the system through a feedback loop.

Assumptions:

The following assumptions were made before beginning the modelling to keep the system in SIMULINK simple and easy to understand.

- Chemistry or Complex equations of combustion in an Engine has been ignored. Instead, suitable percentages of exhaust gas formations have been used in the form of 1D lookup table to mimic the amount of exhaust gas formed based on a captured A/F ratio.
- The objective of the project is to demonstrate an exhaust system capable of controlling the output using an active feedback meaning that the corrections in values are immediately applied when the feedback is ON
- Data used to model the system is appropriately assumed to seem realistic enough since access to those real values is a part of engine and exhaust design which is beyond the scope of this study.
- Therefore, we emphasize on displaying the logic used to develop the system and not on the accuracy of the values available as output.
- These values could easily be changed if and when actual data might be made available.

Pedal Position	10	mm
Valve area opening, air	95	%
Valve area opening, fuel	100	%
diameter, air	50	mm
diameter, fuel	4	mm
no of fuel jets	4	

AIR INTAKE		
Air flow velocity	2	m/s
Air inflow valve area	0.0019	m2
Air flow volume	0.004	m3/s
Air density	1.292	kg/m3
Air mass flow	0.005	kg/s

FUEL INTAKE		
Fuel valve velocity	0.010	m/s
Fuel inflow valve area	0.00001	m2
Total area	0.00005	m2
Volumetric flow rate, fuel	0.0000005	m3/s
Gasoline density	719.7	kg/m3
Fuel MFR	0.00036	kg/s

Calculated AIR FUEL RATIO (AFR)	14.0
Type of Mixture	RICH

Figure 2: Sample Calculations for designing the system

Figure 2 shows a sample calculation that we performed in MS Excel for a pedal displacement of 10mm with other assumed values and found the A/F ratio to be 14.0 i.e. RICH.

Similarly, we used the same excel sheet to estimate other A/F ratios for displacements between 0 to 10mm as illustrated in figure 3.

Pedal vs valve opening				
mm	% Air	% Fuel	AFR	
0.1	0.5	0.48	15.3	LEAN
0.5	15	15	12.7	RICH
1	10	20	7.3	RICH
2	20	18	16.3	LEAN
5	50	50	14.7	IDEAL
7	70	65	15.8	LEAN
10	95	100	14	RICH

Figure 3: Pedal vs Valve opening for A/F ratios

The % air and % fuel values have been intentionally set different to keep irregularity in the model mimicking a realistic scenario so that feedback loop effect can be seen on the system when it is switched ON.

SIMULINK Blocks used

The figure 4 shows the blocks used from the SIMULINK library for generating the exhaust system model.

For inputs and outputs, sources, port and subsystems and sink libraries were used and for mathematical operations, Math library along with lookup tables was used.

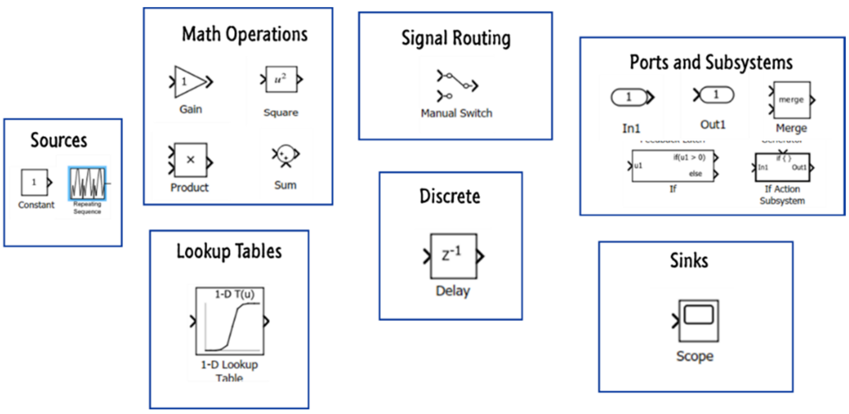

Figure 4: SIMULINK Library Blocks used for system model

A discrete delay block to estimate feedback was used to avoid algebraic loop and impart stability to the system. A manual switch from Signal Routing library was used to allow turning ON/OFF of the feedback i.e. the exhaust control loop.

System Block Diagram

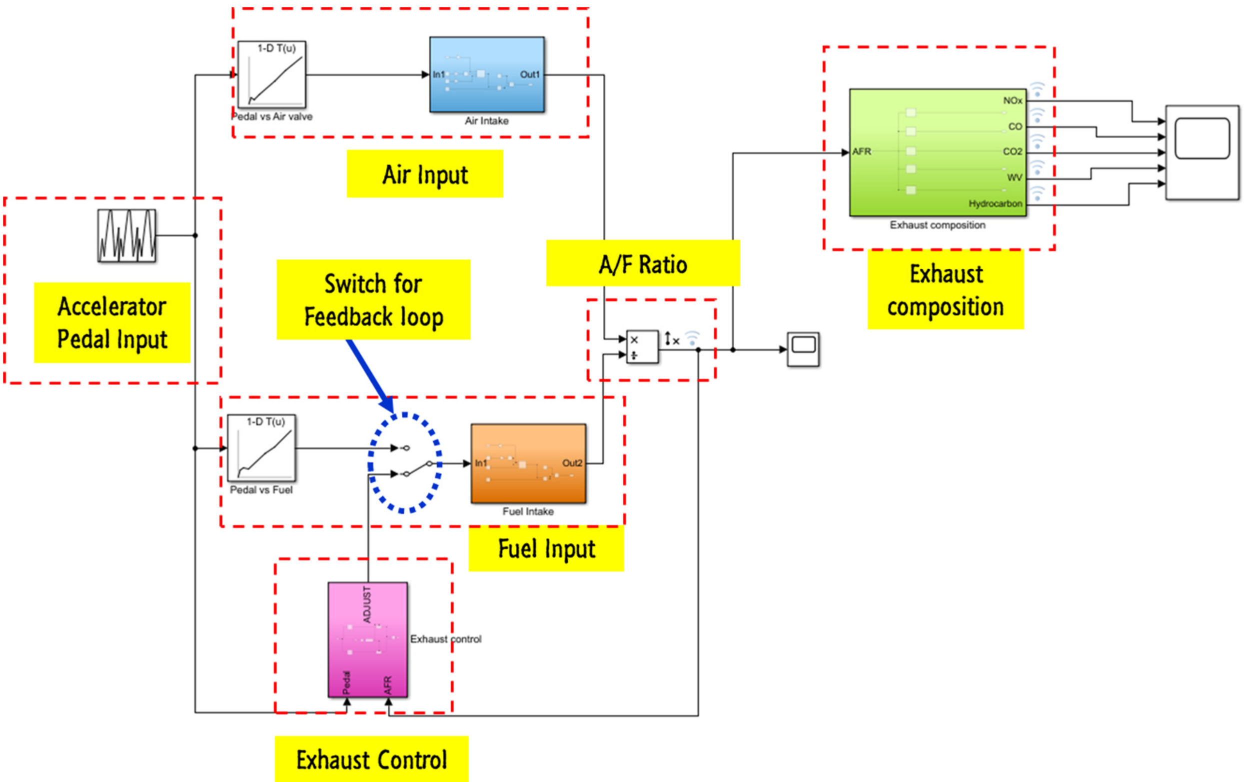

Figure 5: Exhaust System Model in SIMULINK

The figure 5 shows the developed Exhaust control model in SIMULINK.

The blocks of this system are-

1. **Air Input**

   This block computes the quantity of air entering the engine using the percentage opening of the Air valve based on a 1D lookup table for the same as one of the input along with assumed air velocity (dependent on vehicle speed and other environmental factors)

2. **Fuel Input**

   This block calculates the amount of fuel entering the engine using the selected fuel nozzle diameter based on the 1D lookup table for the same

3. **A/F Ratio**

This block takes A/F ratio as reference and estimates the percentage combustion of the Air Fuel mixture. In case the A/F Ratio is not ideal of 14.7:1 then, the combustion percentages vary if the mixture is rich, leading to unburnt fuel and as a result- hydrocarbons which are undesirable and need to be kept to a minimum possible value.

4. **Exhaust composition**

Based on the previous block's output, the amount of exhaust gas produced and unburnt fuel are analysed to estimate the quantity of NOx, CO, Hydrocarbons and SOx with particulate matter.

As per actual real measurements, these are expressed in terms of g/km. In our model, we are expressing these values in mg per unit time but these are compiled in a table in the results section with projected g/km values.

5. **Exhaust control**

This is the feedback block which controls the fuel quantity in the system.

Function of each system block

1. Pedal input (Accelerator Displacement)

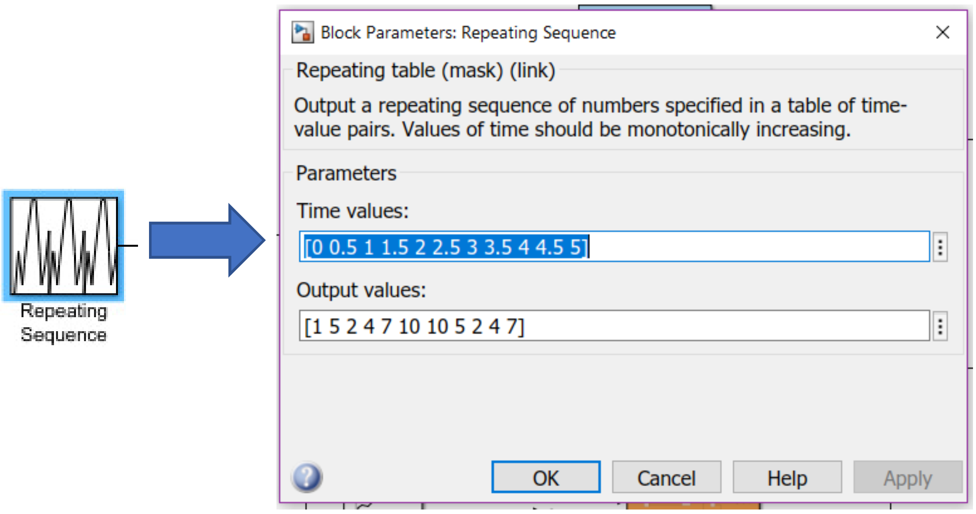

Figure 6: Accelerator Pedal Displacement as input

This block is the first block in the system and works as input to drive the system; includes a repeating sequence with pedal displacement values in mm vs time t s values as seen in following figure. This block is further connected to two 1D lookup tables for Air valve and Fuel valve which provide % valve opening based on the displacement value

2. Air Intake block (Air input for engine)

This block accepts input from previous 1D lookup table for pedal vs air. As seen in the figure below, the assumed air valve diameter is 50mm and input 1 is the % valve opening input which is multiplied with the area of the air inlet pipe to get effective area for a certain pedal displacement.

The effective area is further multiplied with an assumed air velocity of 2m/s to estimate the Air volume entering the engine and when multiplied with Air density, it gives the air mass flow rate.

This step is important as the value is one the factors to calculate the A/F ratio.

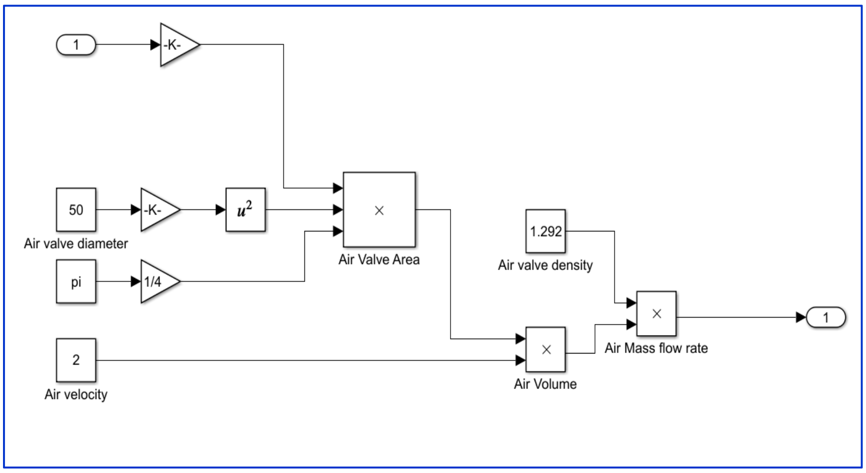

Figure 7: Air Input block

3. Fuel Intake block (Fuel input for engine)

This block accepts input from previous 1D lookup table for pedal vs fuel. As seen in the figure below, the assumed fuel valve diameter is 4 mm and input 1 is the % valve opening input which is multiplied with the area of the fuel nozzle to get effective area for a certain pedal displacement. Also, not shown in figure is the number of nozzles for a vehicle which is aptly assumed as 4 for the current case.

The effective area is further multiplied with an assumed fuel velocity of approx. 0.01 m/s to estimate the fuel volume entering the engine and when multiplied with fuel density, it gives the fuel mass flow rate.

This step is important as the value is the other factor to calculate the A/F ratio.

Once we have both the air and fuel mass flow rates or simply the amounts of air and fuel entering engine chamber, we can estimate the A/F ratio by dividing air quantity by fuel quantity.

This value is now used by the exhaust control block if turned ON.

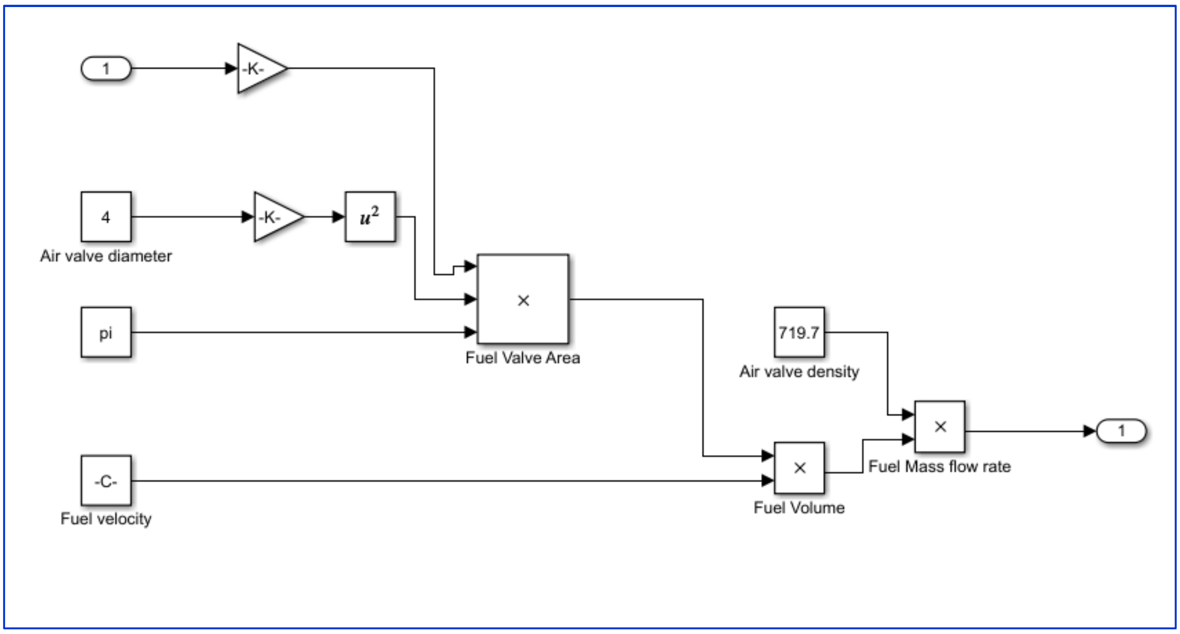

Figure 8: Fuel Input Block

4. Exhaust control block

The exhaust control block is essentially a decision block where A/F ratio from previous block is used to decide whether the fuel quantity is incorrect and based on it, a % opening for fuel valve is transmitted from this block to be used for correction. The deciding factor is obviously whether the mixture is Rich when fuel quantity needs to be reduced or Lean where more fuel is required.

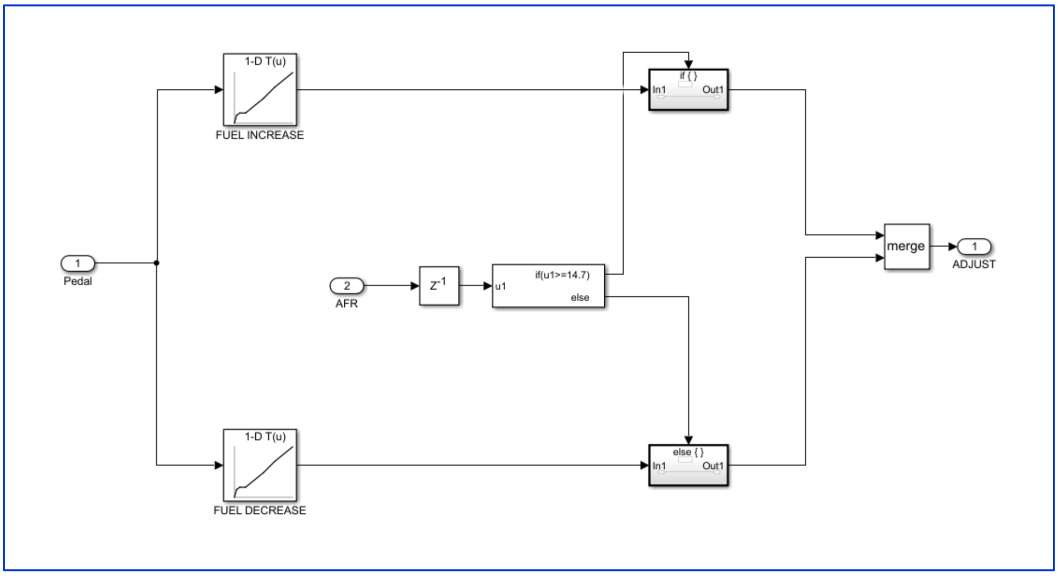

Figure 9:Exhaust Control Block

5. Exhaust composition block

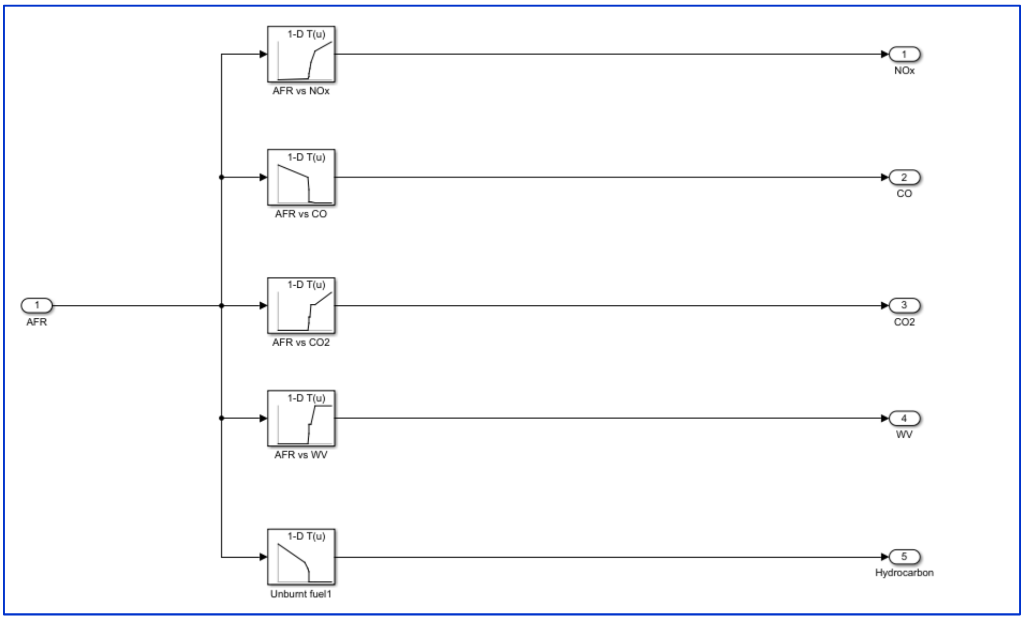

Figure 10: Exhaust Composition Block

The exhaust composition block has five different 1D lookup tables for A/F ratio vs NOx, CO, CO_2 , water vapour and SOx respectively.

These values are assumed from the literature available and thus, do not have extremely fine differentiation in values which might occur in real scenarios. These plots follow are minimizing trend when the A/F ratio is closer to ideal value of 14.7:1.

Simulation Results

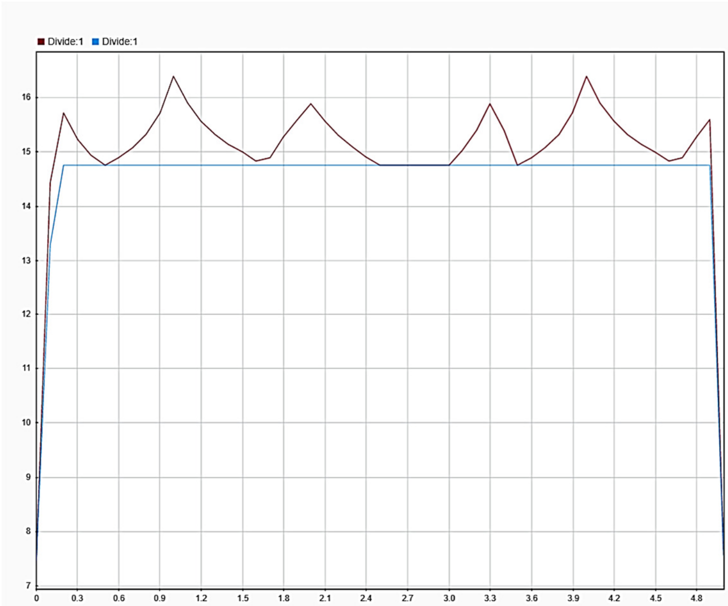

Figure 11: A/F Ratio for without and with exhaust control

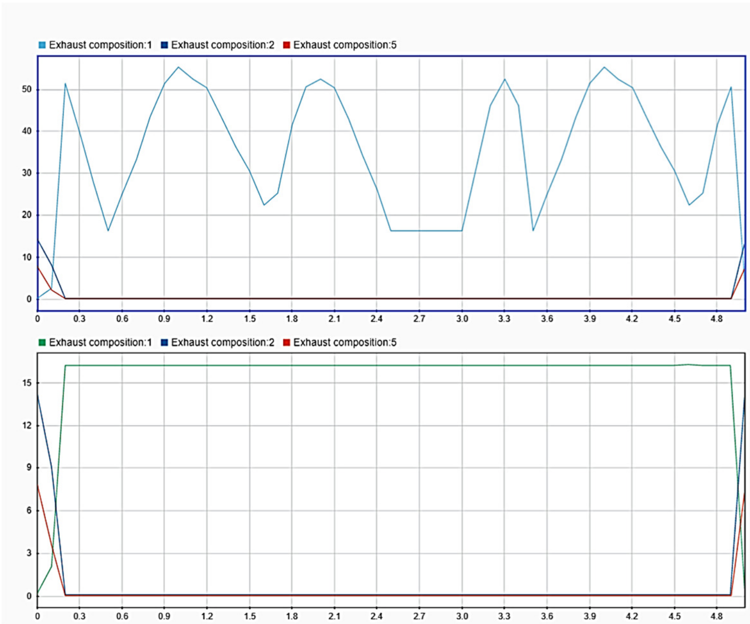

Figure 12: Exhaust composition without and with exhaust control

With feedback loop of Exhaust control as ON, the fuel quantity (entering the engine) gets adjusted to reach closer to the ideal A/F ratio of 14.7:1 as evident in the graphs in Results section. This brings down the exhaust gases proportions when the A/F ratio is near to the expected ideal value.

Figure 10 show that the varying input from the pedal input block results into a wavy plot for A/F ratio when the exhaust control block is OFF and the same input results into a smooth curve nearing 14.7 value when exhaust control is ON. Figure 11 represents the variations in the exhaust gases proportions without and with exhaust control respectively.

Transfer function tf of a system

Static gain or G(0) of a system is the ratio of output and input under steady state condition. Thus, the tf value can be said as a generalized value of G(0).

Transfer function tf of a system is defined as the ratio of the output of a system to the input of a system, in the Laplace domain when initial conditions are considered as zero.

As per project requirement, we have tried to estimate the transfer function of the system using Linear Analysis option in SIMULINK.

For this, the following steps were followed-

1. We need to identify the control loop in the system. In our case, the control loop exists between the pedal (accelerator displacement) input and the A/F ratio estimating block. These are called the linearization points.
2. Once these linearization points are identified, we define the path of input as “open loop input” and the output path as “open loop output”.
3. From the Analysis tab from toolbar menu, we select the control design option and further “linear analysis”.
4. From plots in linear analysis window, we select step response plot to linearize the system and wait for SIMULINK to finish linearization
5. Once done, we get a variable called ‘linsys1’ which we now copy to MATLAB workspace
6. This variable can be plotted and now the transfer function can be queried in MATLAB command window as shown in figure below.

```
Trial>> h=tf(linsys1)

h =

  From input "Repeating Sequence" to output "Divide":
  -1.845

Name: Linearization at model initial condition
Static gain.
```

Figure 13:Transfer function of the SIMULINK model

7. Using this method, the transfer function was found to be -1.845 for initial condition.
8. This essentially would mean that for a positive step input the output moves in the reverse direction which is possible.

Conclusion

The Vehicle Exhaust Control model was successfully developed in SIMULINK using MATLAB 2018a version. The developed model was simulated for t=5s for a given repeated sequence input of accelerator pedal displacement values between 0 to 10 mm with default simulation settings and the transfer function estimated for the feedback loop was found to be a single value of -1.845 for the static gain linearization using Linear analysis option in SIMULINK.

The model is able to exhibit control over the Fuel input for different values of A/F Ratio as calculated in the model at each time t (s). Also, the exhaust composition plots for all the gases NOx, CO and SOx show correct trends when plotted and compared for both feedback and no feedback simulations.

Future Scope

Since the model is a simplified version of an important vehicle system it can be developed further to implement more elements and subsystems to replicate the actual physical system even more closely.

Catalytic converter with Oxygen sensor could be implemented as additional element in the model as a technique to control exhaust system.

Currently this model relies on assumed data based on concepts in textbooks and literature available for research on the internet. However, access to real life data and lab test data can assist in improving and fine tuning the model.

The model could also be tested by controlling Air quantity instead of Fuel as employed currently which might be a challenge as the air quality depends on the environment and might vary in some conditions.

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