Effect of SI Engine Design and Operating Variables on Emissions

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SI Engine Variables and Emissions

Any engine variable that affects oxygen availability during combustion would influence CO emissions. The factors which influence flame quenching, quench layer thickness and post flame oxidation control engine out HC emissions. The burned gas temperature-time history and oxygen concentration control NO formation and emission. Hence the engine variables that influence burned gas temperature and oxygen concentration would affect the NO emissions.
Principal design and operating variables affecting engine emissions are:

Design Variables :

- Compression Ratio
- Combustion chamber surface to volume ratio
- Ignition timing
- Valve timings and valve overlap
- Air motion, swirl tumble etc
- Charge stratification

Operating Variables :

- Air-fuel Ratio
- Charge dilution and exhaust gas recirculation (EGR)
- Speed
- Load
- Coolant temperature
- Transient engine operation: acceleration, deceleration etc.

The effect of some variables discussed below is typical in nature and variations in the trends with specific engine design change are observed.

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Module 3:Influence of Engine Design and Operating Parameters on Emissions

Lecture 14:Effect of SI Engine Design and Operating Variables on Emissions

Compression Ratio

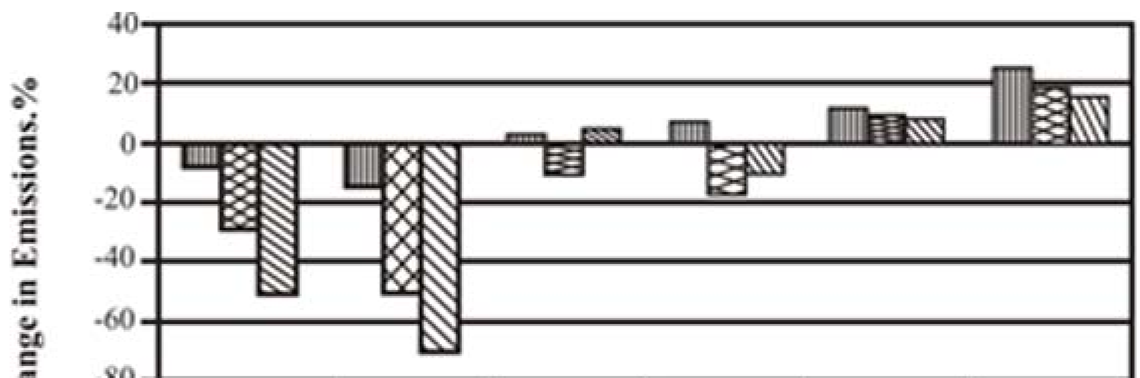
The effect of compression ratio on engine emissions is shown on Fig. 3.1. The typical effect observed when the engine CR was reduced from 10:1 (CR used on high performance engines during pre-emission control period) to 8.5 and 7.0:1 are given on this figure.
Use of high CR results in

(i) Higher burned gas temperature
(ii) Lower residual gas content

These lead to higher NO emissions on volume basis. However, as engine efficiency increases with increase in compression ratio, brake specific NO emissions decrease. High CR combustion chambers result in

(i) High surface to volume ratio and
(ii) A proportionately higher crevice volume.
(iii) Lower exhaust gas temperatures

Thus the volume of flame quenching regions increases resulting in higher HC emissions. The problem is further enhanced as due to lower exhaust gas temperatures oxidation of the unburned HC is reduced during exhaust process. These factors result in an increase in HC emissions with increase in engine CR. At lower CR% fuel efficiency is also reduced thus increasing specific CO emissions.



	HC Emissions CR =8.5	HC Emissions CR =7.0	Nox Emissions CR =8.5	Nox Emissions CR =7.0	CO Emissions CR =8.5	CO Emissions CR =7.0
1500 rpm	-7	-14	2	-7	12	25
2000 rpm	-28	-50	-10	-17	9	18
2500 rpm	-50	-70	3	-10	8	16

Figure 3.1	Effect of reduction in compression ratio from 10:1 to 8.5:1 and 7.0:1 on SI engine emissions

Ignition Timing

The effect of ignition timing on NO and HC emissions is shown on Fig 3.2 When ignition occurs earlier in the cycle more heat is released before and around the top dead center. Thus, with advanced ignition timings higher peak cylinder pressures and temperatures result. As has been discussed lecture 5 with increase in combution temperatures NO formation increases. Hence , higher NO emissions are obtained as the ignition timing is advanced.

As the ignition timing is retarded more burning takes place during expansion stroke resulting in lower peak combustion pressures and a lower of mass of charge is pushed into crevice volume. Also, at the retarded ignition timings exhaust gas temperature increases as the engine thermal efficiency is reduced. In the hotter exhaust gas with the retarded ignition timing higher oxidation rates of the HC and CO in the exhaust system are obtained.. Due to these reasons, lower HC emissions are obtained with retarded ignition timings. The disadvantage of the retarded ignition timing is lower engine efficiency, lower power and a poorer fuel economy.

When the emission control legislation was introduced for the first time around 1970 in the USA and Europe, ignition timing versus speed and manifold vacuum curves were among the first engine parameters that were modified for control of NO_x emissions due to ease of their adjustment.

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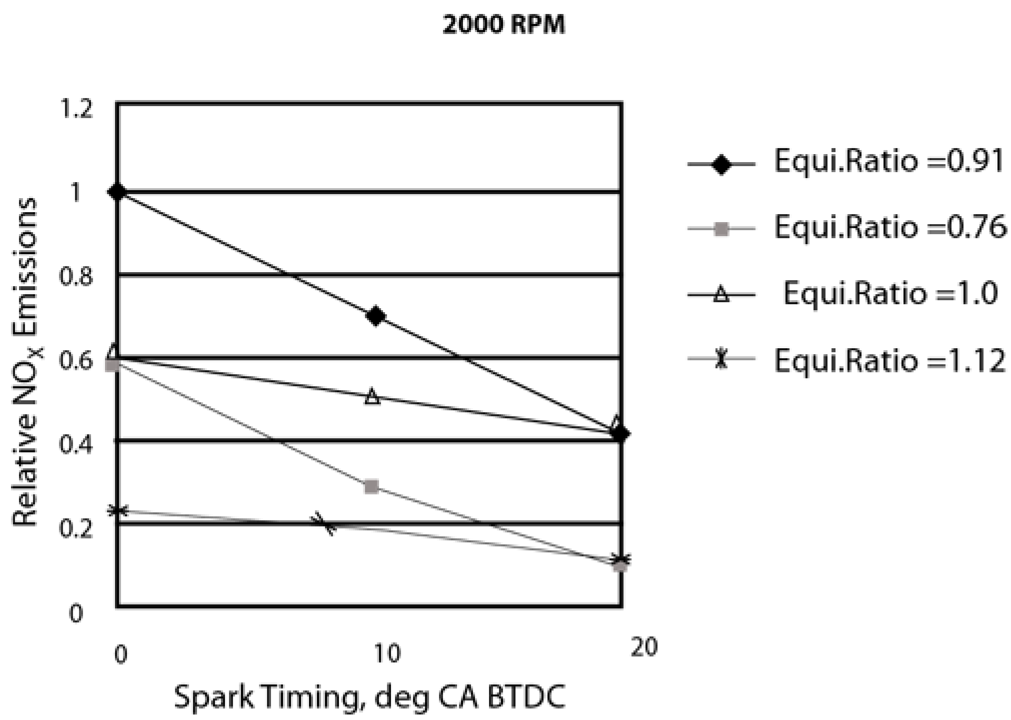

Fig 3.2(a)	Effect of spark timing on NOx emissions.

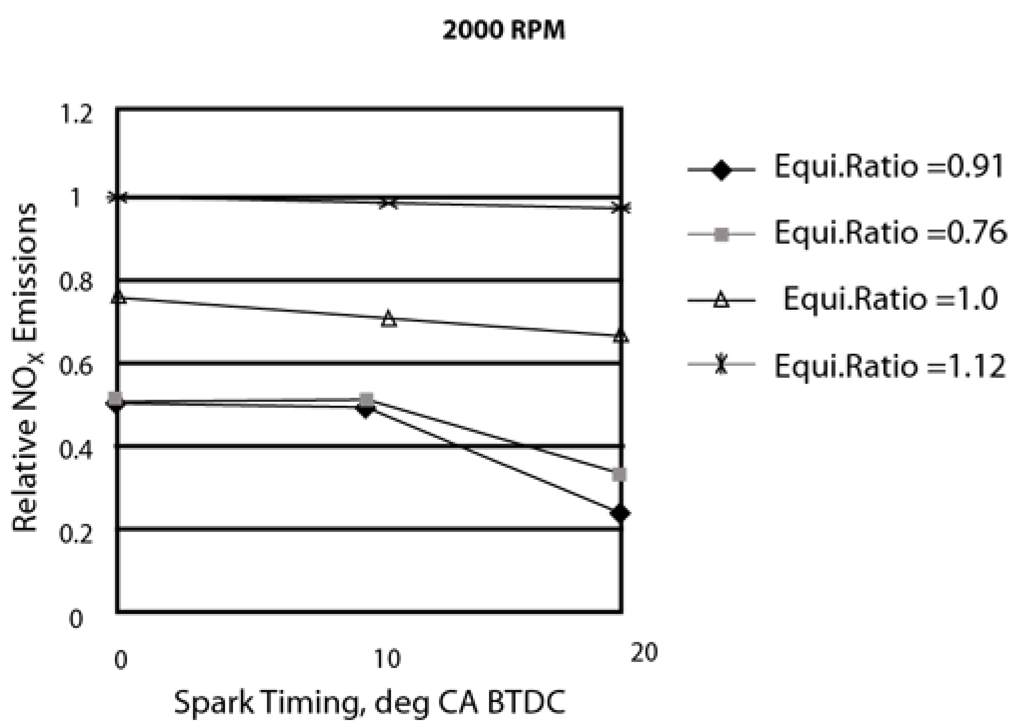

Fig	Effect of ignition timing on HC

3.2(b)	emissions.

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Air –Fuel Ratio

The effect of air-fuel ratio on engine emissions has already been discussed in Lectures 3 , 5 and 7.

- Carbon monoxide results due to deficiency of oxygen during combustion and is reduced as the mixture is leaned. CO emissions are reduced to very low values as the mixture is leaned to ϕ = 0.90 – 0.95 i.e. air-fuel ratio is increased above the stoichiometric value by 5 to 10%. Further leaning of mixture shows very little additional reduction in the CO emissions.
- With increase in air fuel ratio, the initial concentration of hydrocarbons in the mixture is reduced and more oxygen is available for oxidation. Hydrocarbon emissions therefore, decrease with increase in air-fuel ratio until mixture becomes too lean when partial or complete engine misfire results which cause a sharp increase in HC emissions For ϕ < 0.8 engine may misfire more frequently thereby increasing HC emissions sharply.
- The highest burned gas temperatures are obtained for mixtures that are slightly (5 to 10 percent) richer than stoichiometric. On the other hand, there is little excess oxygen available under rich mixture conditions. As the mixture becomes lean, concentration of free oxygen increases but combustion temperature start decreasing. The interaction between these two parameters results in peak NO being obtained at about ϕ = 0.9 –0.95.

Residual Gas and EGR

Burned residual gases left from the previous cycle or part of the exhaust gas recirculated back to engine act as charge diluents. The charge dilution by recirculation of part of the exhaust gas back to the engine is called exhaust gas recirculation (EGR). The combustion temperatures decrease due to charge dilution caused by the residual burned gases or EGR , the decrease in combution temperatures is nearly proportional to the heat capacity of the diluents as discusses earlier. The lower combustion temperatures resulting from the residual gas dilution/EGR reduces NO formation and emissions as shown on Fig 3.3.

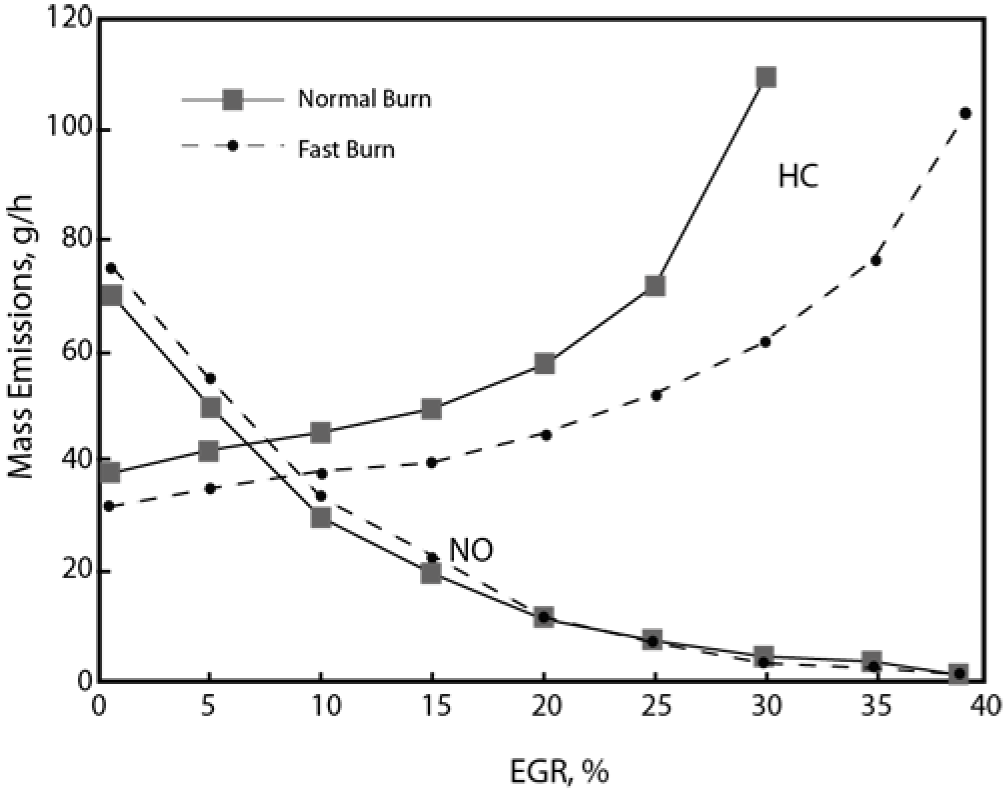

Figure 3.3	Effect of EGR on NO and HC emissions in normal burn and fast burn SI engines.

As the EGR is increased the combustion rates become more and more slow, and combustion becomes unstable. With increase in EGR cycle-to-cycle combustion variations increase and, more and more engine cycles having only partial combustion are observed . The frequency of partial burn cycles increases and these turn into misfired cycles at EGR rates of about more than 20%. . In the partial burn and misfire cycles, combustion remains incomplete and results in high HC emissions. Moreover with EGR the burned gas temperatures are reduced and post-flame oxidation also reduces. Increase in HC becomes sharp as EGR increases beyond about 20 percent for a normal combustion engine. With EGR rates of 20 percent or higher Fast burn engines due to higher flame speeds have higher burned gas temperatures and tolerate higher EGR rates before the combustion
becomes very unstable and loss in fuel efficiency becomes unacceptably high. Fast burn rates are usually obtained by use of high air swirl and increasing turbulence in the charge through use of suitable designs of intake valve port and the combustion chamber.
The amount of charge dilution or EGR is usually limited to below 15% due to its adverse impact on engine performance causing power loss, high specific fuel consumption and high unburned fuel emissions.

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Engine Speed

Volumetric efficiency of the engine changes with speed, it being highest in the mid-speed range. At high engine speeds the volumetric efficiency generally decreases resulting in high residual gas dilution. Although heat transfer rates increase with increase in engine speed as a result of higher turbulence, but total amount of heat transfer is lower due to shorter cycle time. This gives higher gas temperatures at higher speeds. However, at high speeds a shorter time is available for NO formation kinetics. The net result is a moderate effect of speed on NO although this is specific to the engine design and operating conditions. Increase in exhaust gas temperatures at higher speeds enhances post flame oxidation of unburned hydrocarbons. A reduction of 20 to 50 percent in HC emissions has been observed with increase in speed from 1000 to 2000 rpm.

Cold Start and Warm-up Phase

Engine cold start and warm-up phase contribute significantly to unburned hydrocarbons. One of the main sources of HC emissions during cold start and engine warm-up period is very rich fuel-air ratio needed for ignition and combustion for several seconds after engine start. During cold start, the engine has to be over-fuelled 5 to10 times the stoichiometric amount of gasoline. To obtain robust ignition on the first cycle on cold start, a fuel vapour- air equivalence ratio above lean threshold limit (f = 0.7-0.9) is required. This threshold is independent of the engine coolant temperature. The fuel-air equivalence ratio supplied to the engine during cold start is in the range, f = 4 to 7.

For the first few engine cycles, a large fraction of inducted fuel is stored as liquid film in the intake port and cylinder as only the most volatile fractions evaporate when the engine is cold. The liquid fuel films do not participate in combustion and is emitted as unburned fuel emissions.

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Coolant Temperature

As the coolant temperature is increased, the contribution of piston ring zone crevice becomes lower due to decrease in gas density within this crevice. Secondly, the top piston-land side clearance is also reduced due to higher thermal expansion of the piston. A thinner oil film and reduced fuel vapour solubility would result in reduced absorption of fuel vapours in engine oil. Increased postflame oxidation at high temperatures also contributes to reduction in HC emissions. Increase in coolant temperatures has been observed to reduce HC emissions by about 0.4 to 1.0 % per K increase in temperature. An increase in the coolant temperature from 20 to 90º C, roughly results in 25% lower HC emissions and hence, the need of a rapid engine warm up is obvious.

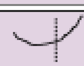
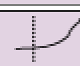
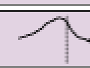
For reduction of the cold start and warm up HC emissions, an important area of development is to improve the fuel injection and delivery to the cylinder with minimum wall wetting. Over-fuelling during cold start and warm-up is to be kept at a minimum, while still forming the combustible charge.

Summary

The effects of some of the important engine design and operating variables on emissions from SI engines are summarized below Table 3.1.

Table 3.1

Effect of SI Engine Design and Operating Variables on Exhaust Emissions
(Source: IC Engines - Combustion and Emissions by Pundir, 2010)

Variable Increased	HC	CO	NO_X
Fuel-air equivalence ratio			
Compression ratio	↑	-	↑
Surface/volume ratio	↑	-	↓
Bore/stroke ratio	↑	-	↓
Ignition timing advance	↑	-	↓
Port fuel injection	↑	↓	↓
Engine speed	↑	-	↑↓
Engine load	↑	-	↑
Coolant temperatures	↓	-	↑
Combustion chamber deposits	↓	-	↑
EGR	↓	-	↓
Intake swirl and turbulence	↓	-	↑
↑= increase; ↓ = decrease; ↑↓= uncertain; - = no effect			