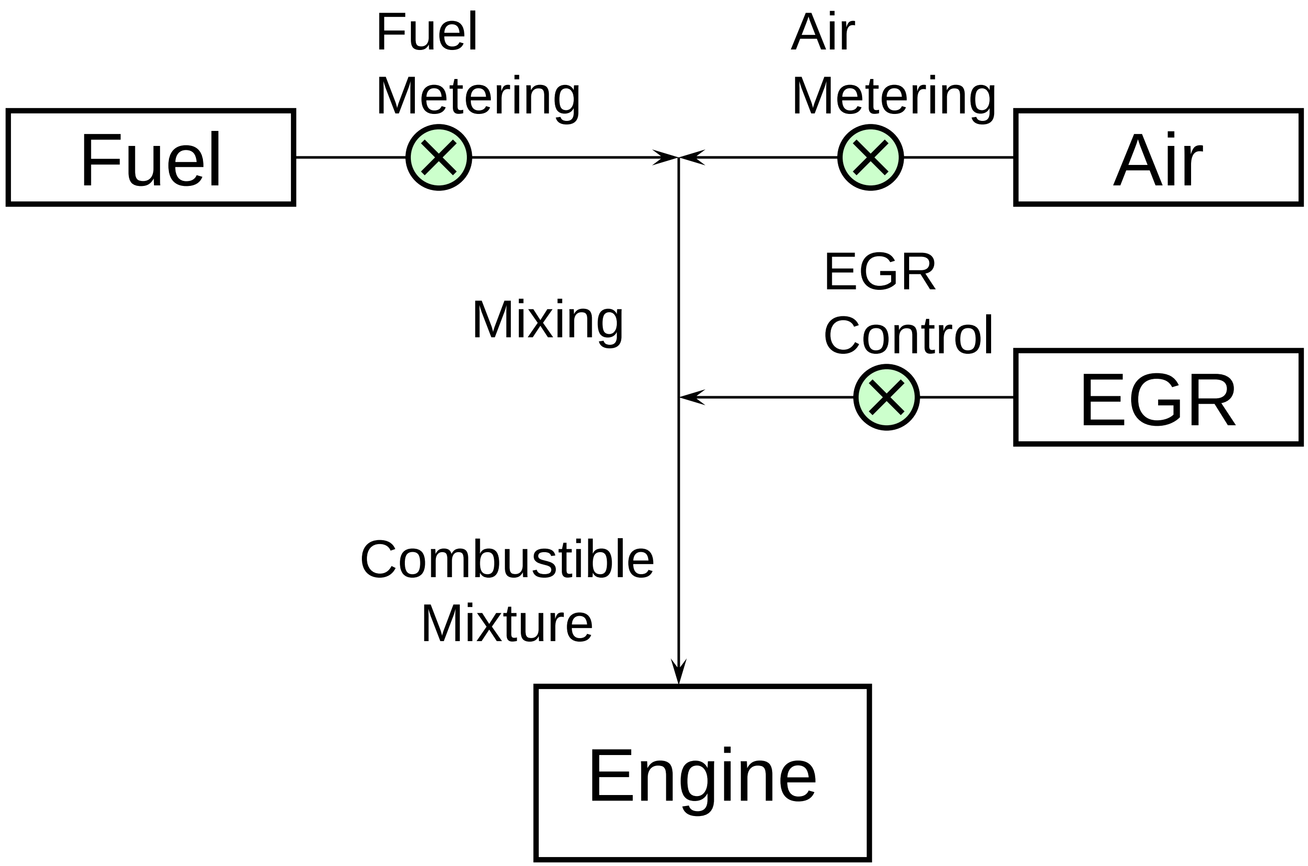
2.61 Internal Combustion Engines
Spring 2008

SI Engine Mixture Preparation

1. Requirements
2. Fuel metering systems
3. Fuel transport phenomena
4. Mixture preparation during engine transients
5. The Gasoline Direct Injection engine

MIXTURE PREPARATION



MIXTURE PREPARATION

Parameters

-Fuel Properties
-Air/Fuel Ratio
-Residual Gas Fraction

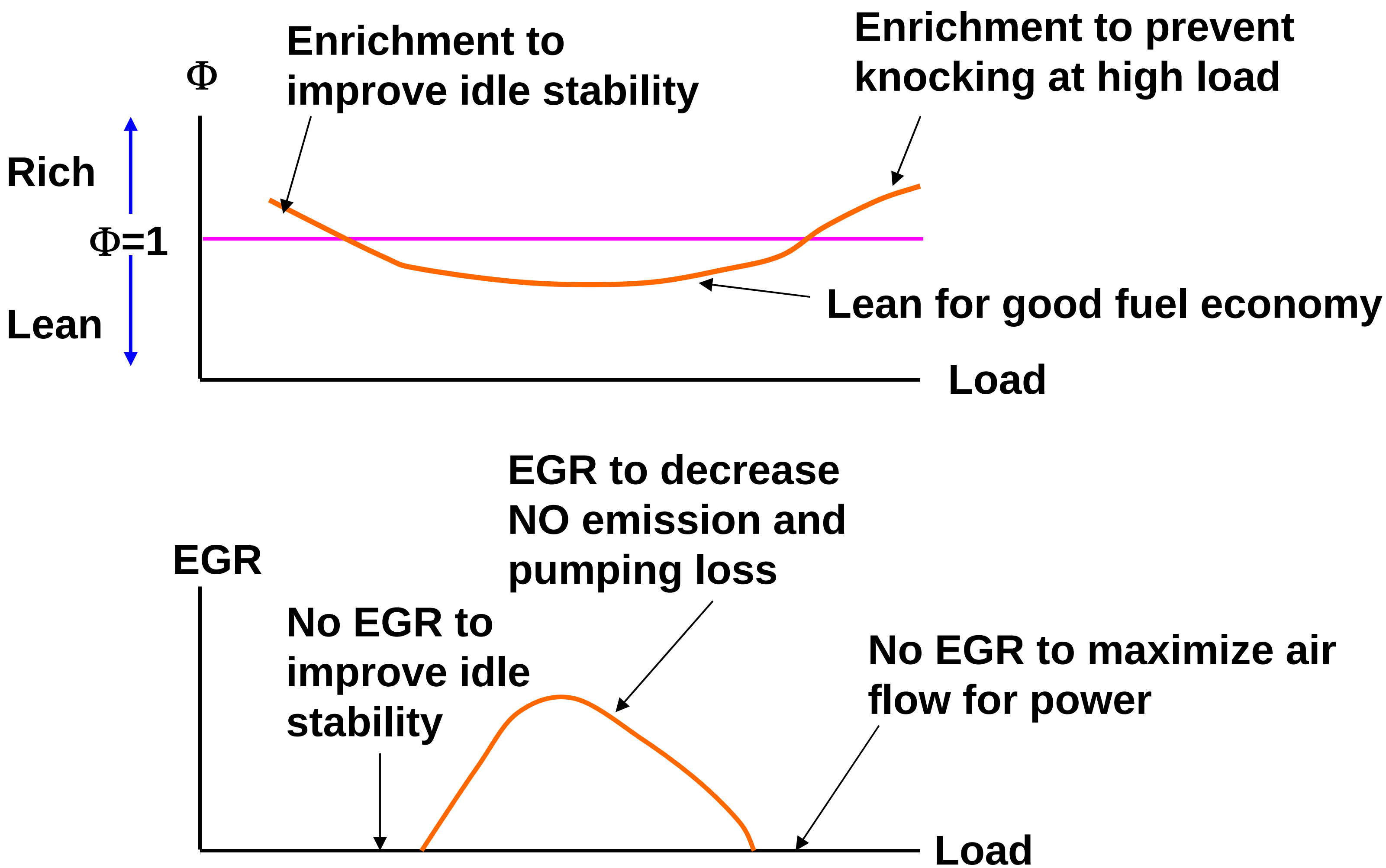
→

Impact

- Driveability
- Emissions
- Fuel Economy

Other issues: Knock, exhaust temperature, starting and warm-up, acceleration/ deceleration transients

Equivalence ratio and EGR strategies
(No emissions constrain)



Requirement for the 3-way catalyst

FUEL METERING

- Carburetor
  - A/F not easily controlled
- Fuel Injection
  - Electronically controlled fuel metering
    - Throttle body injection
    - Port fuel injection
    - Direct injection

Injectors

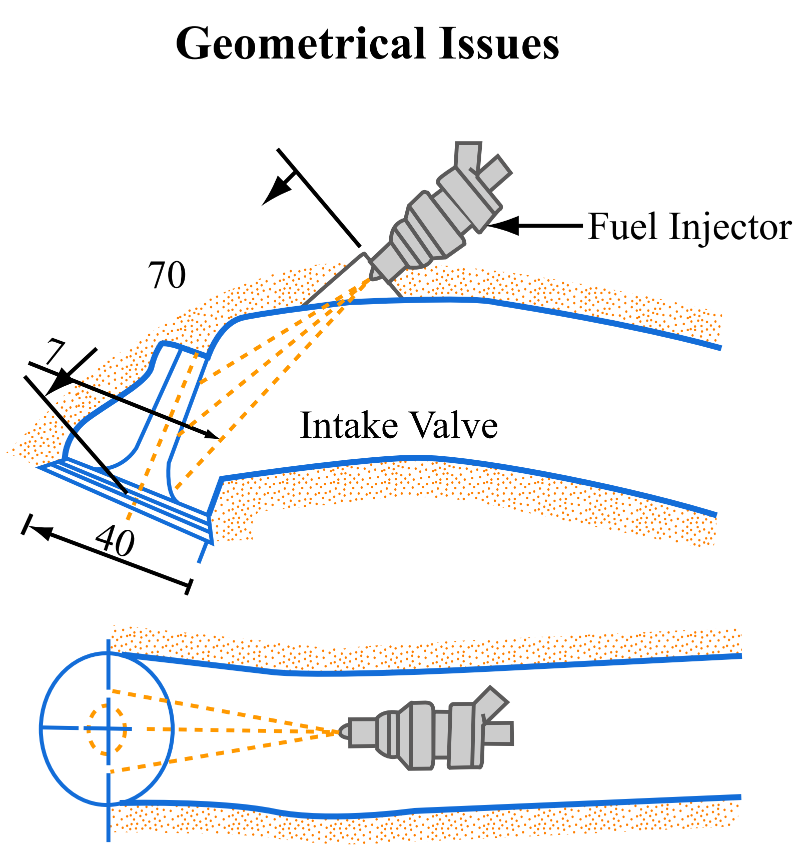
PFI injectors

- Single 2-, 4-,…, up to 12-holes
- Injection pressure 3 to 7 bar
- Droplet size:
  - Normal injectors: 200 to 80 μm
  - Flash Boiling Injectors: down to 20 μm
  - Air-assist injectors: down to 20 μm

GDI injectors

- Shaped-spray
- Injection pressure 50 to 150 bar
- Drop size: 15 to 50 μm

PFI Injector targeting



Arrangement of fuel injector and intake valve

Figure by MIT OpenCourseWare.

Image removed due to copyright restrictions. Please see any illustration of an engine control system, such as that in the *Bosch Automotive Handbook*. London, England: John Wiley & Sons, 2004.

Engine management system

From Bosch Automotive Handbook

Fuel Metering

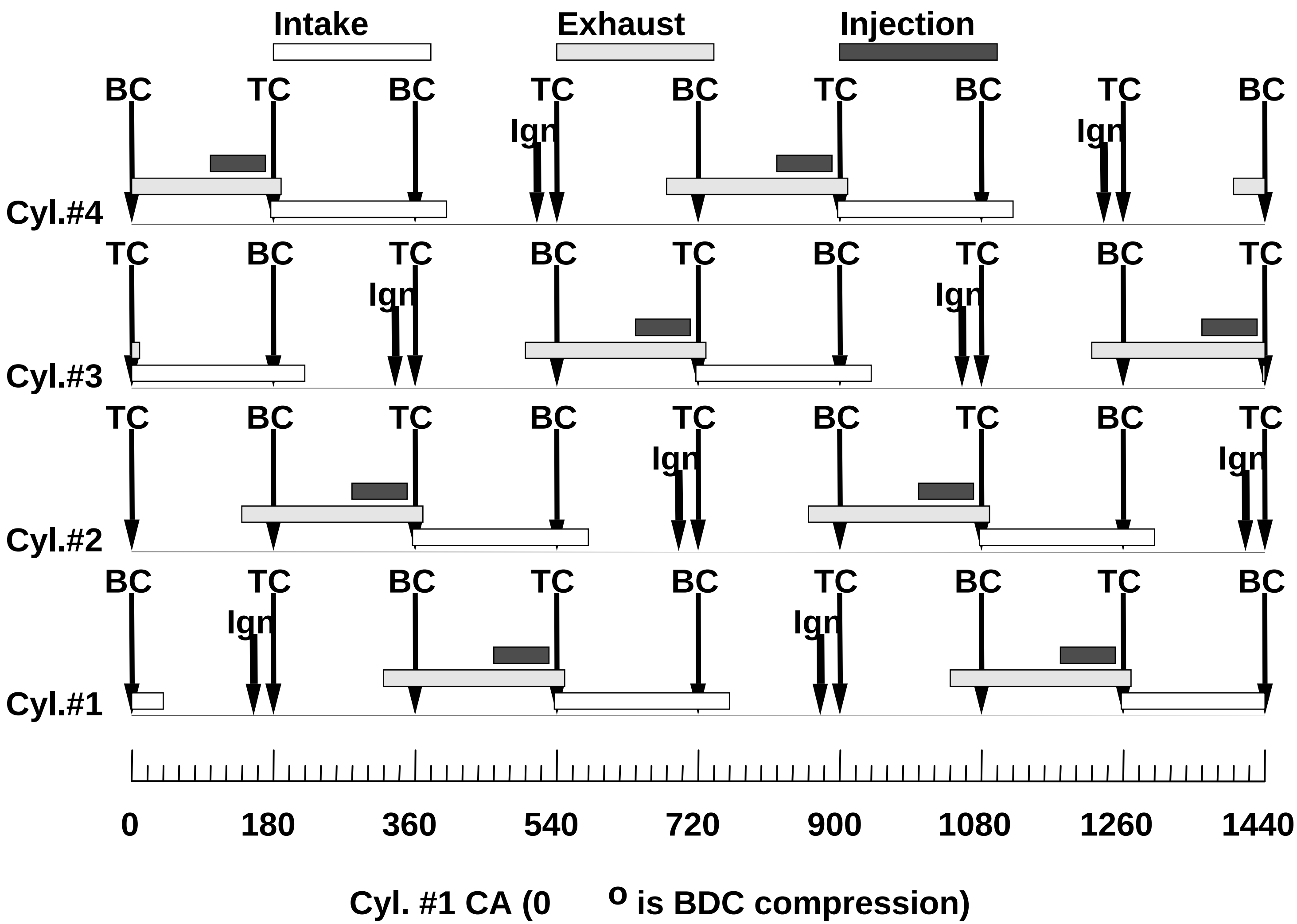
- **A/F ratio measured by λ sensor (closed loop operation)**
  - **feedback on fuel amount to keep λ=1**
- **Feed-forward control (transients):**
  - **To meter the correct fuel flow for the targeted A/F target, need to know the air flow**
- **Determination of air flow (need transient correction)**
  - **Air flow sensor (hot film sensor)**
  - **Speed density method**
    - **Determine air flow rate from MAP (P) and ambient temperature (T_a) using volumetric efficiency (η_v) calibration**

$$\dot{m}_a = \rho V_D \frac{N}{2} \eta_V(N,\rho)$$

$$\rho = P / RT_a$$

Displacement vol. V_D, rev. per second N, gas constant R

ENGINE EVENTS DIAGRAM



Effect of Injection Timing on HC Emissions

Image removed due to copyright restrictions. Please see: Stache, I., and Alkidas, A. C. "The Influence of Mixture Preparation on the HC Concentration Histories from an S.I. Engine Running Under Steady-state Conditions." *SAE Transactions* 106 (October 1997): 972981.

Engine at 1300 rpm

275 kPa BMEP

Injection timing refers to start of injection

Mixture Preparation in PFI engine

Intake flow phenomena in mixture preparation
(At low to moderate speed and load range)

Reverse Blow-down Flow

- **IVO to EVC:**
  - Burned gas flows from exhaust port because $P_e > P_i$
- **IVO to $P_c = P_i$:**
  - Burned gas flows from cylinder into intake system until cylinder and intake pressure equalize

Forward Flow

- **$P_c = P_i$ to BC:**
  - Forward flow from intake system to cylinder induced by downward piston motion

Reverse Displacement Flow

- **BC to IVC:**
  - Fuel, air and residual gas mixture flows from cylinder into intake due to upward piston motion

Note that the reverse flow affects the mixture preparation process in engines with port fuel injection

Mixture Preparation in Engine Transients

Engine Transients

- Throttle Transients
  - Accelerations and decelerations
- Starting and warm-up behaviors
  - Engine under cold conditions

Transients need special compensations because:

- Sensors do not follow actual air delivery into cylinder
- Fuel injected for a cycle is not what constitutes the combustible mixture for that cycle

Manifold pressure charging in throttle transient

Image removed due to copyright restrictions. Please see: Aquino, C. F. "Transient A/F Control Characteristics of the 5 Liter Central Fuel Injection Engine." *SAE Transactions* 90 (February 1981): 810494.

Fuel-Lag in Throttle Transient

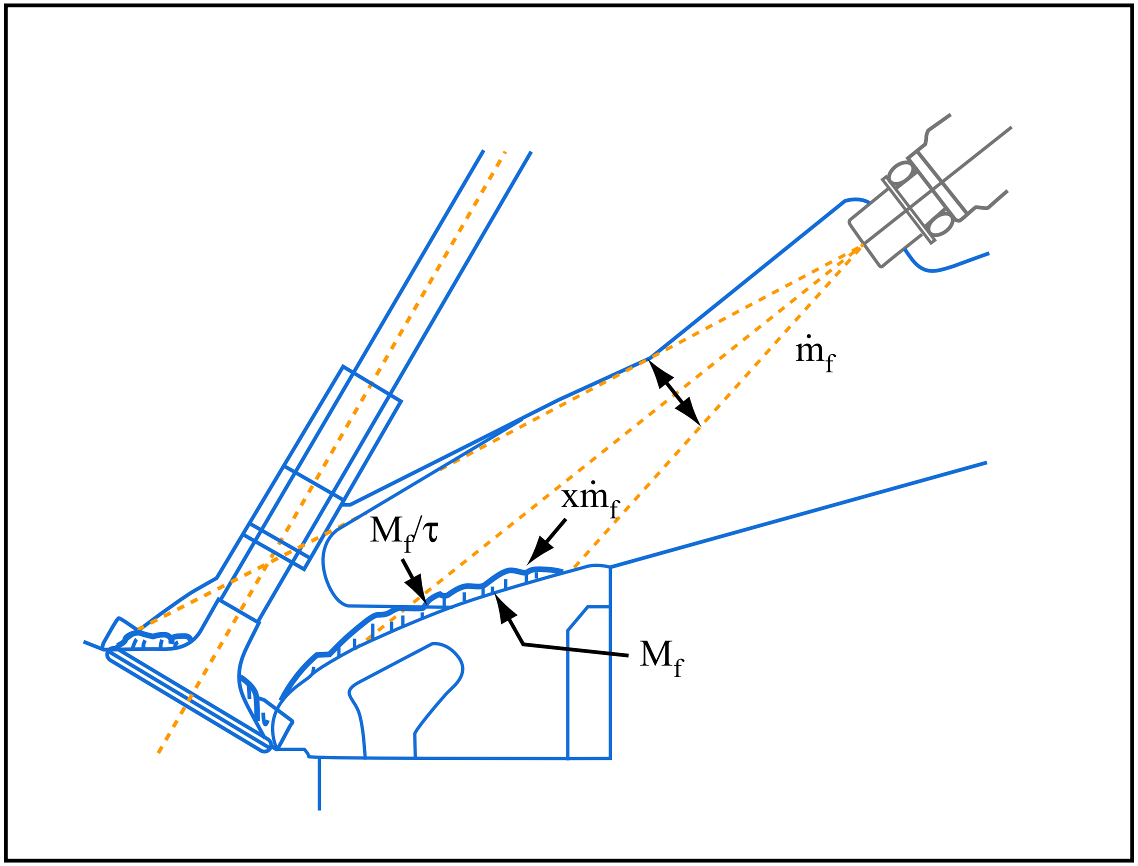


Figure by MIT OpenCourseWare.

The x-τ Model

$$\frac{dM_f}{dt} = x\dot{m}_f - \frac{M_f}{\tau}$$

$$\dot{m}_c = (1-x)\dot{m}_f + \frac{M_f}{\tau}$$

$\dot{m}_f$ = Injected fuel flow rate

$\dot{m}_c$ = Fuel delivery rate to cylinder

M_f = Fuel mass in puddle

Fuel transient in throttle opening

Fig 7-28

Uncompensated A/F behavior in throttle transient

Image removed due to copyright restrictions. Please see: Fig. 1 in Santoso, Halim, and Cheng, Wai K. "Mixture Preparation and Hydrocarbon Emissions in the First Cycle of SI Engine Cranking." *SAE Journal of Fuels and Lubricants* 111 (October 2002): 2002-01-2805.

Engine start up behavior

2.4 L, 4-cylinder engine

Engine starts with Cyl#2 piston in mid stroke of compression

Firing order 1-3-4-2

Pertinent Features of DISI Engines

1. Precise metering of fuel into cylinder
   - Engine calibration benefit: better driveability and emissions
2. Opportunity of running stratified lean at part load
   - Fuel economy benefit (reduced pumping work; lower charge temperature, lower heat transfer; better thermodynamic efficiency)
3. Charge cooling by fuel evaporation
   - Gain in volumetric efficiency
   - Gain in knock margin (could then raise compression ratio for better fuel economy)
   - Both factors increase engine output

Toyota DISI Engine (SAE Paper 970540)

Charge cooling by in-air fuel evaporation

Full load performance benefit

Images removed due to copyright restrictions. Please see: Iwamoto, Y., et al. "Development of Gasoline Direct Injection Eengine." *SAE Journal of Engines* 106 (February 1997): 970541.

Part load fuel economy gain

Images removed due to copyright restrictions. Please see Kume, T., et al. "Combustion Control Technologies for Direct Injection SI Engine." *SAE Journal of Engines* 105 (February 1996): 960600.

DISI Challenges

1. **High cost**
2. **With the part-load stratified-charge concept :**
   – **High hydrocarbon emissions at light load**
   – **Significant NOx emission, and lean exhaust not amenable to 3-way catalyst operation**
3. **Particulate emissions at high load**
4. **Liquid gasoline impinging on combustion chamber walls**
   – **Hydrocarbon source**
   – **Lubrication problem**
5. **Injector deposit**
   – **Special fuel additive needed for injector cleaning**
6. **Cold start behavior**
   – **Insufficient fuel injection pressure**
   – **Wall wetting**