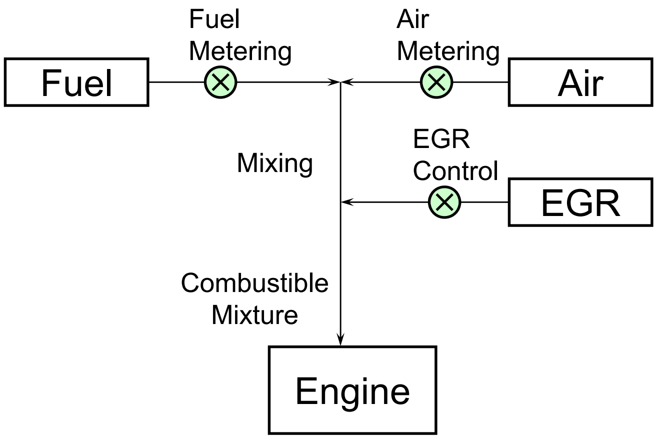
SI Engine Mixture Preparation

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

MIXTURE PREPARATION


Fuel

Fuel Metering

Air Metering

Air

Mixing

EGR Control

EGR

Combustible Mixture

Engine

MIXTURE PREPARATION

Parameters

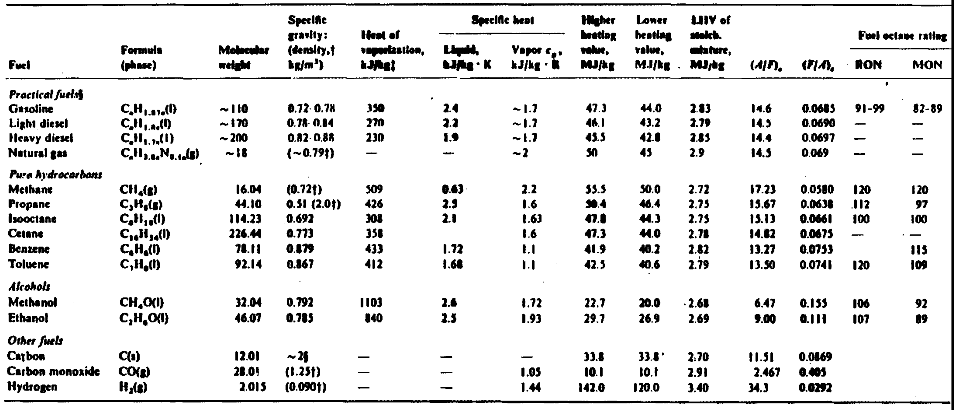
- -Fuel Properties
- -Air/Fuel Ratio
- -Residual/Exhaust Gas Fraction

Impact

- - Driveability
- - Emissions
- - Fuel Economy

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

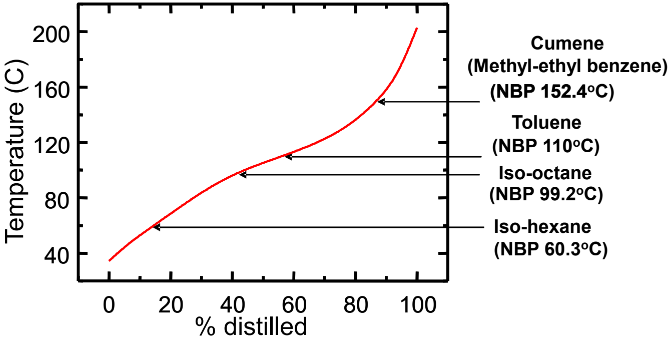
Fuel properties (Table D4 of text book)



Fuel	Formula (phase)	Molecular weight	Specific gravity: (density,† kg/m³)	Heat of vaporization, kJ/kg‡	Specific heat: Liquid, kJ/kg · K	Specific heat: Vapor c_p, kJ/kg · K	Higher heating value, MJ/kg	Lower heating value, MJ/kg	LHV of stoich. mixture, MJ/kg	$(A/F)_s$	$(F/A)_s$	Fuel octane rating: RON	Fuel octane rating: MON
Practical fuels§													
Gasoline	$C_nH_{1.87n}(l)$	~110	0.72-0.78	350	2.4	~1.7	47.3	44.0	2.83	14.6	0.0685	91-99	82-89
Light diesel	$C_nH_{1.8n}(l)$	~170	0.78-0.84	270	2.2	~1.7	46.1	43.2	2.79	14.5	0.0690	—	—
Heavy diesel	$C_nH_{1.7n}(l)$	~200	0.82-0.88	230	1.9	~1.7	45.5	42.8	2.85	14.4	0.0697	—	—
Natural gas	$C_nH_{3.8n}N_{0.1n}(g)$	~18	(~0.79†)	—	—	~2	50	45	2.9	14.5	0.069	—	—
Pure hydrocarbons													
Methane	$CH_4(g)$	16.04	(0.72†)	509	0.63	2.2	55.5	50.0	2.72	17.23	0.0580	120	120
Propane	$C_3H_8(g)$	44.10	0.51 (2.0†)	426	2.5	1.6	50.4	46.4	2.75	15.67	0.0638	112	97
Isooctane	$C_8H_{18}(l)$	114.23	0.692	308	2.1	1.63	47.8	44.3	2.75	15.13	0.0661	100	100
Cetane	$C_{16}H_{34}(l)$	226.44	0.773	358		1.6	47.3	44.0	2.78	14.82	0.0675	—	—
Benzene	$C_6H_6(l)$	78.11	0.879	433	1.72	1.1	41.9	40.2	2.82	13.27	0.0753		115
Toluene	$C_7H_8(l)$	92.14	0.867	412	1.68	1.1	42.5	40.6	2.79	13.50	0.0741	120	109
Alcohols													
Methanol	$CH_4O(l)$	32.04	0.792	1103	2.6	1.72	22.7	20.0	2.68	6.47	0.155	106	92
Ethanol	$C_2H_6O(l)$	46.07	0.785	840	2.5	1.93	29.7	26.9	2.69	9.00	0.111	107	89
Other fuels													
Carbon	$C(s)$	12.01	~2§	—	—	—	33.8	33.8	2.70	11.51	0.0869		
Carbon monoxide	$CO(g)$	28.01	(1.25†)	—	—	1.05	10.1	10.1	2.91	2.467	0.405		
Hydrogen	$H_2(g)$	2.015	(0.090†)	—	—	1.44	142.0	120.0	3.40	34.3	0.0292		

Gasoline evaporative characteristics

Distillation curve (ASTM D86) of UTG91 (a calibration gasoline)



Cumene
(Methyl-ethyl benzene)
(NBP 152.4°C)

Toluene
(NBP 110°C)

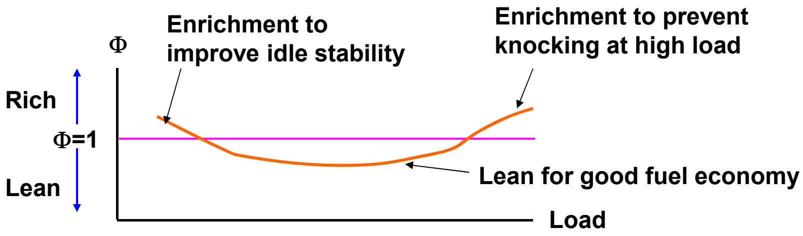
Iso-octane
(NBP 99.2°C)

Iso-hexane
(NBP 60.3°C)

- Reid Vapor pressure (ASTM D323):
  - equilibrium pressure of fuel and air of 4 x liquid fuel volume at 37.8°C
- T_{10}, T_{50}, T_{90}
  - Temperature at 10, 50 and 90% distillation points
- Driveability Index (DI)
  - For hydrocarbon fuels: $DI = 1.5\,T_{10} + 3\,T_{50} + T_{90}$ (T in °F)

RVP: winter gasoline ~ 11 psi (0.75 bar); Summer gasoline ~ 9 psi (0.61 bar); California Phase 2 fuel = 7 psi (0.48 bar)
DI: range from 1100 to 1300; Phase II calibration gasoline has DI=1115; High DI calibration fuel has DI 1275.

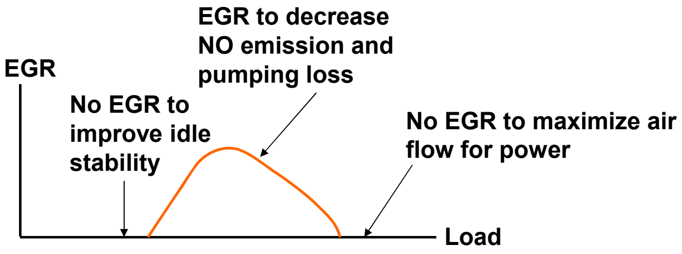
Equivalence ratio and EGR strategies (No emissions constrain)



Enrichment to improve idle stability

Enrichment to prevent knocking at high load

Lean for good fuel economy



EGR to decrease NO emission and pumping loss

No EGR to improve idle stability

No EGR to maximize air flow for power

Requirement for the 3-way catalyst

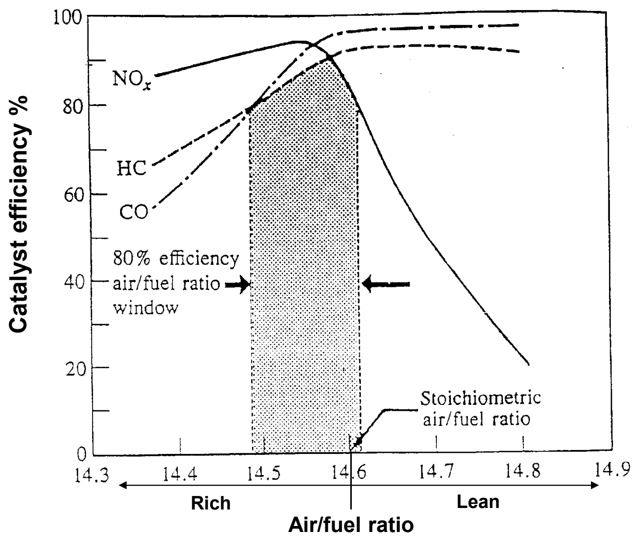


Fig 11-57

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

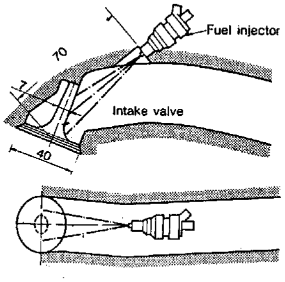
- Single 2-, 4-,…, up to 12-holes
- Injection pressure 3 to 7 bar
- Droplet size:
  - Normal injectors: 200 to 80 μm
  - Flash Boiling Injectors: down to 20 μm
  - Air-assist injectors: down to 20 μm

GDI injectors

- Shaped-spray
- Injection pressure 50 to 250 bar
- Drop size: 10 to 50 μm

PFI Injector targeting

GEOMETRICAL ISSUES



Arrangement of fuel injector and intake valve

INTAKE PORT THERMAL ENVIRONMENT

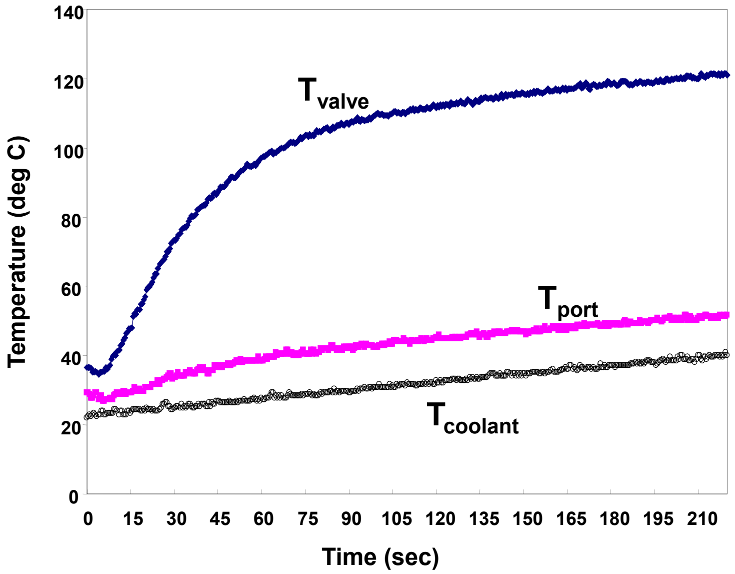
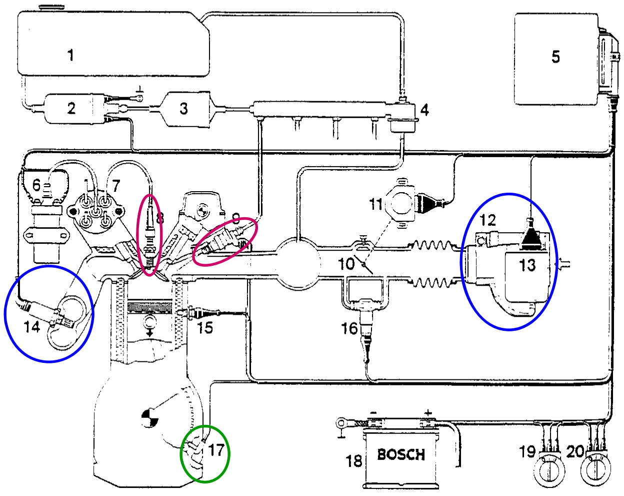


Diagram of a typical Motronic system.
1 Fuel tank, 2 Electric fuel pump, 3 Fuel filter, 4 Pressure regulator, 5 Electronic control unit, 6 Ignition coil, 7 High-voltage distributor, 8 Spark plug, 9 Injection valve, 10 Throttle valve, 11 Trottle-valve switch, 12 Air-flow sensor, 13 Air temperature sensor, 14 Lambda sensor, 15 Engine temperature sensor, 16 Idle-speed actuator, 17 Reference-mark and engine-speed sensor, 18 Battery, 19 Ignition/starter switch, 20 A/C switch.



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**

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

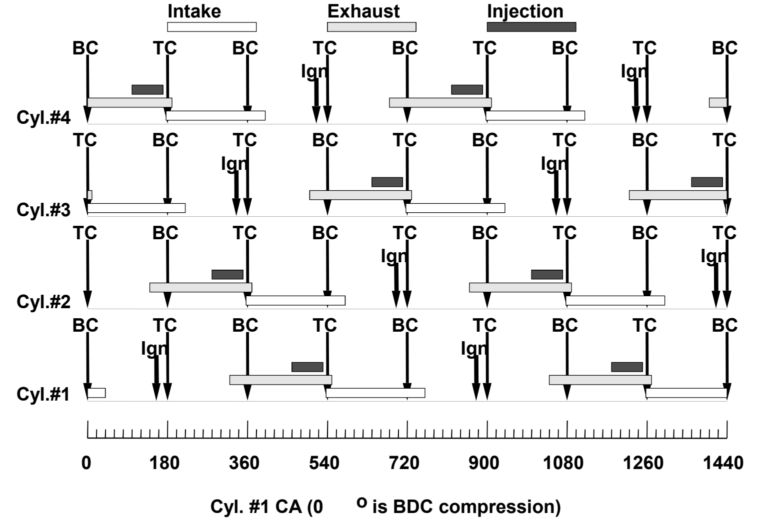
$$\rho = P/RT_a$$

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

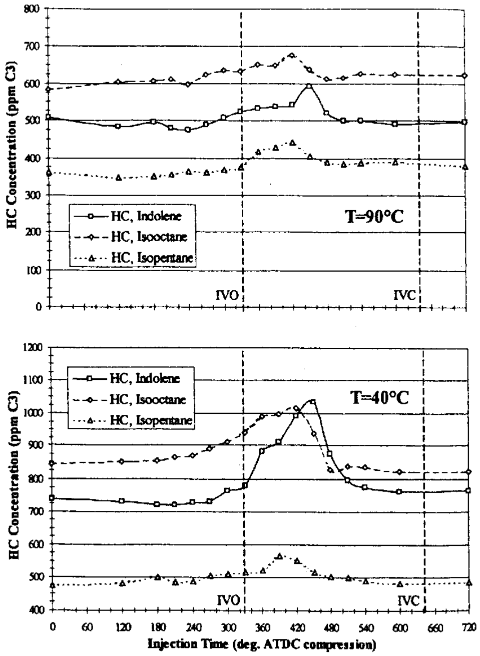
FEATURES OF ELECTRONICALLY CONTROLLED FUEL INJECTION SYSTEM

- Sensors
  - Air temperature
  - Engine Speed
  - Manifold air pressure (MAP) / air flow rate
  - Exhaust air/ fuel equivalence ratio (Λ): EGO (and UEGO)
  - Coolant temperature
  - Throttle position and throttle movement rate
  - Crank and cam positions
- Controls
  - Injection duration
  - Spark timing
  - Other functions
    - ➢ Idle air, carbon canister venting, cold start management, transient compensation, ….

ENGINE EVENTS DIAGRAM



Effect of Injection Timing on HC Emissions

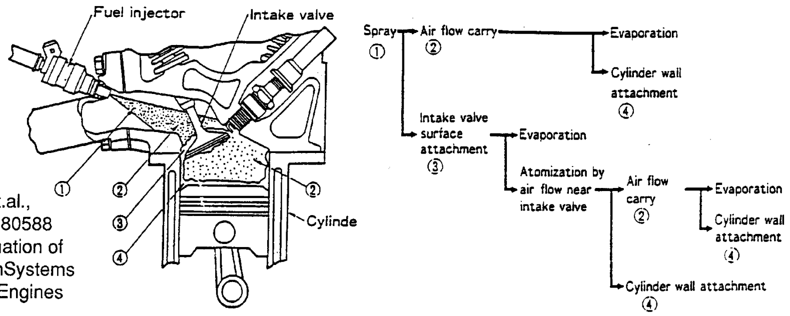


SAE Paper 972981
Stache and Alkidas

Engine at 1300 rpm
275 kPa BMEP

Injection timing refers to start of injection

Mixture Preparation in PFI engine



From Nogi et.al.,
SAE Paper 880588
“Mixture formation of
Fuel InjectionSystems
in Gasoline Engines

Diagram of mixture formation process

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 $P_e > P_i$
- **EVC 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

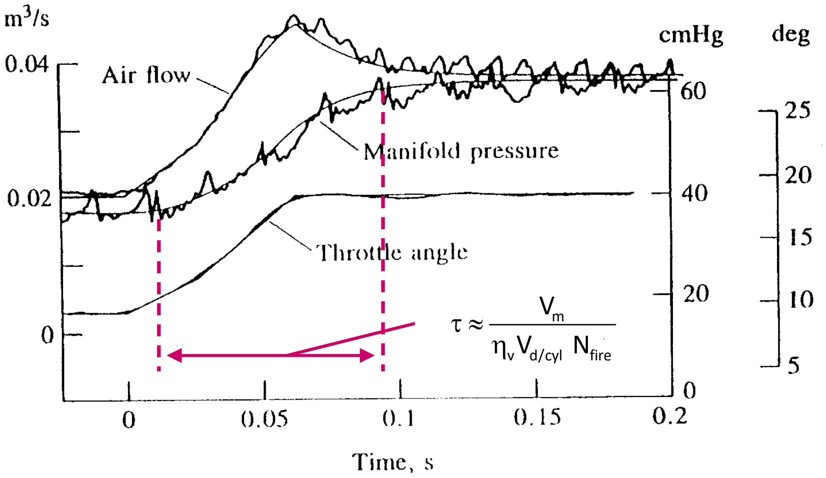
Engine Transients

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

Transients need special compensations because:

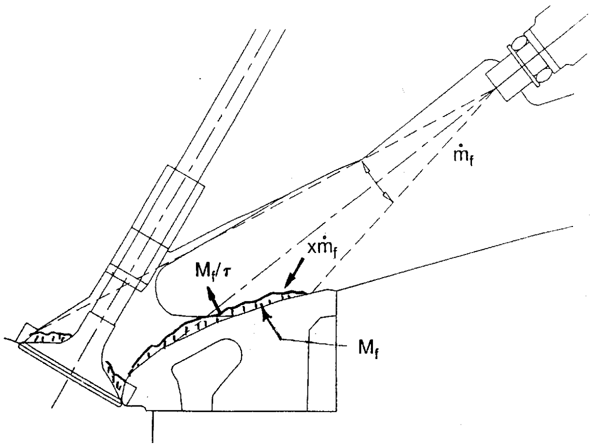
- Sensors do not follow actual air delivery into cylinder
- Fuel injected for a cycle is not what constitutes the combustible mixture for that cycle

Manifold pressure charging in throttle transient



Aquino, SAE Paper 810484

Fuel-Lag in Throttle Transient



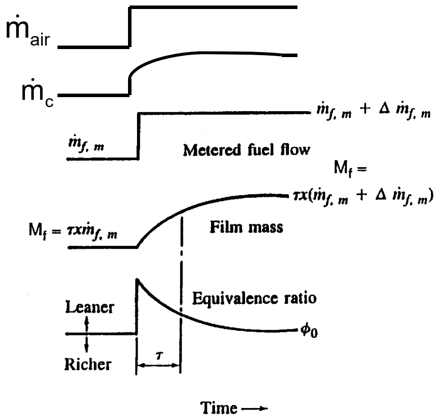
The x-τ Model

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

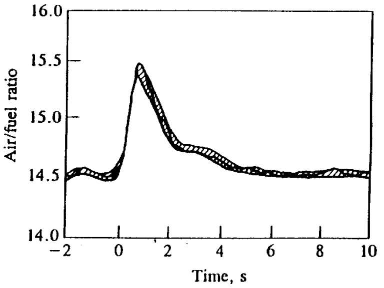
$$\dot{m}_c = (1-x)\dot{m}_f + \frac{M_f}{\tau}$$

$\dot{m}_f$ = Injected fuel flow rate
$\dot{m}_c$ = Fuel delivery rate to cylinder
M_f = Fuel mass in puddle

Fuel transient in throttle opening



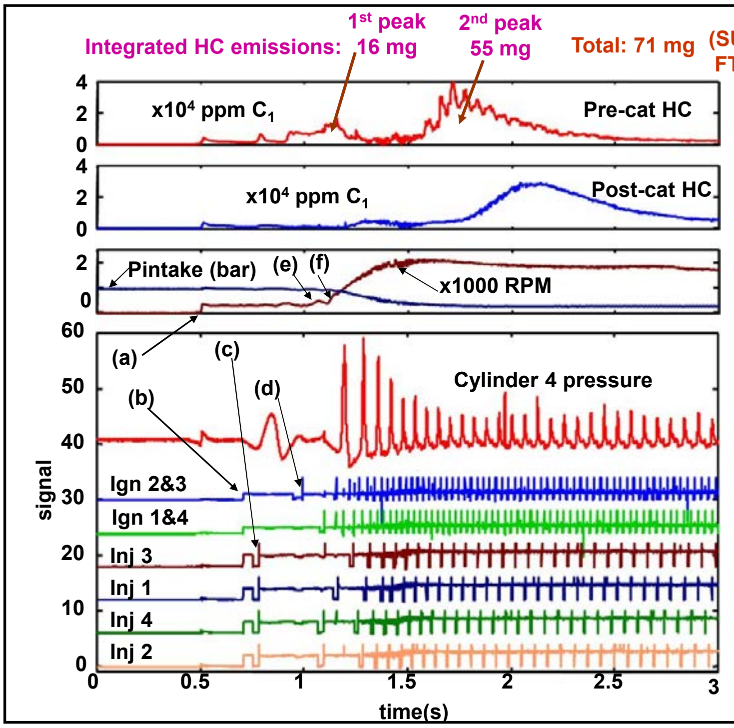
Model prediction



Observed results

Fig 7-28

Uncompensated A/F behavior in throttle transient



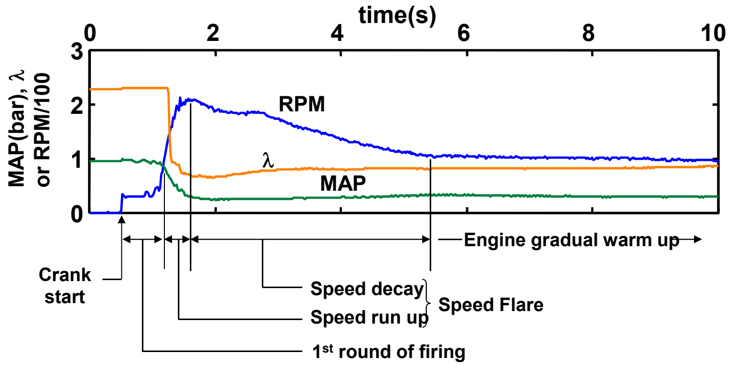
Engine start up behavior

2.4 L, 4-cylinder engine

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

Firing order 1-3-4-2

Engine start up behavior

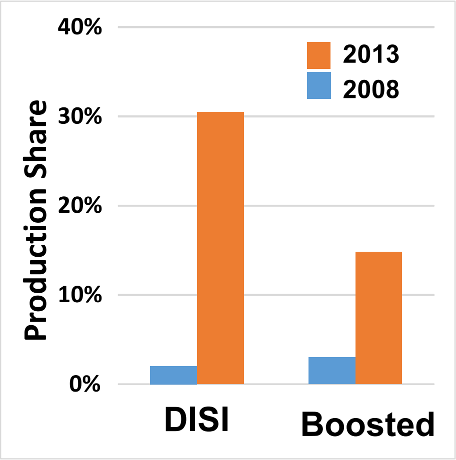


Pertinent Features of DISI Engines

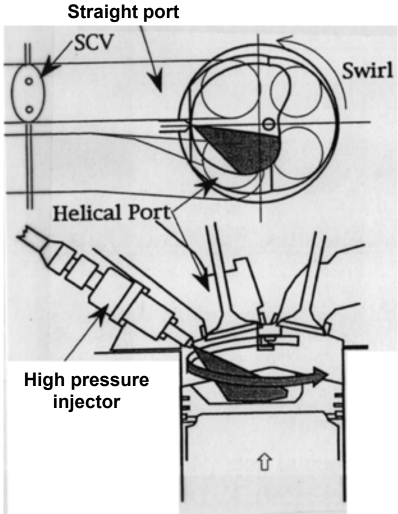
1. Precise metering of fuel into cylinder
   - Engine calibration benefit: better driveability and emissions
2. Opportunity of running stratified lean at part load
   - Fuel economy benefit (reduced pumping work; lower charge temperature, lower heat transfer; better thermodynamic efficiency)
3. Charge 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

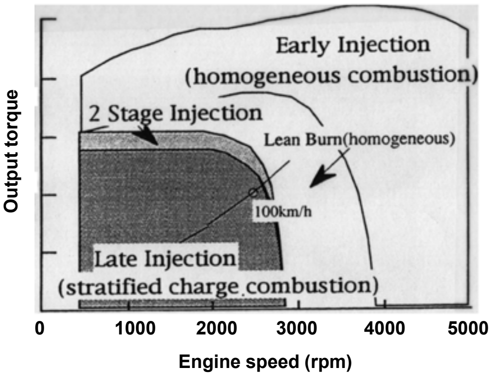
DISI technology penetration

- Significant market penetration of DISI
  - Homogeneous charge configuration
  - As enabler of the boosted-downsizing strategy

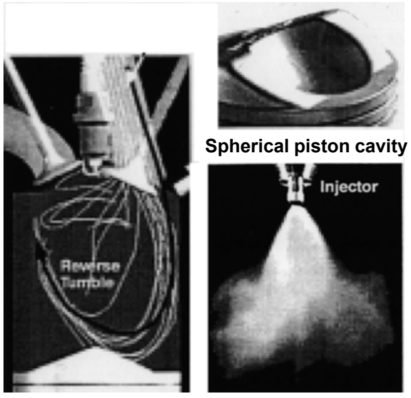


Toyota DISI Engine (SAE Paper 970540)





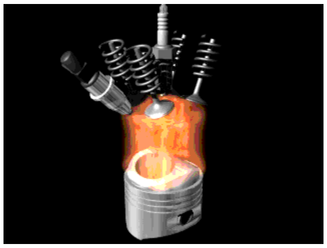
Mitsubishi DISI Engine

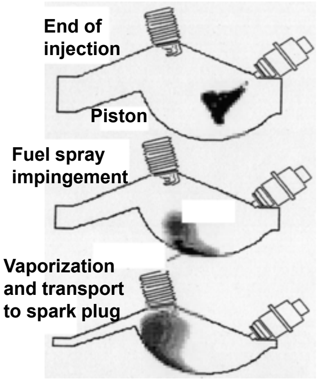


Reverse tumble

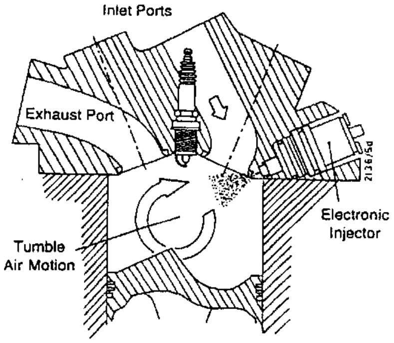
Swirling spray

(SAE 960600)

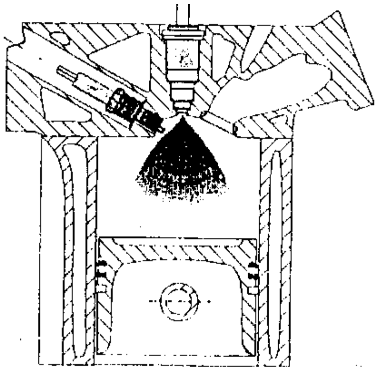




Wall-guided versus spray-guided injection


Wall-guided injection
(injector relatively distant from spark plug)

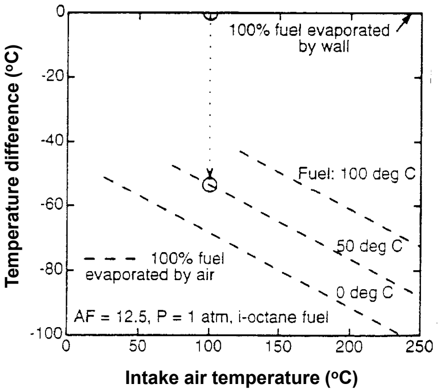
SAE 970543 (Ricardo)


Spray-guided injection
(injector relatively close to spark plug)

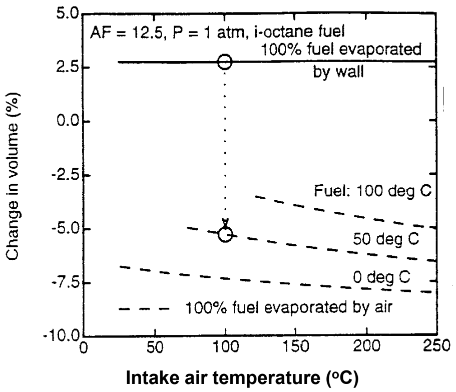
SAE 970624 (Mercedes-Benz)

Charge cooling by in-air fuel evaporation

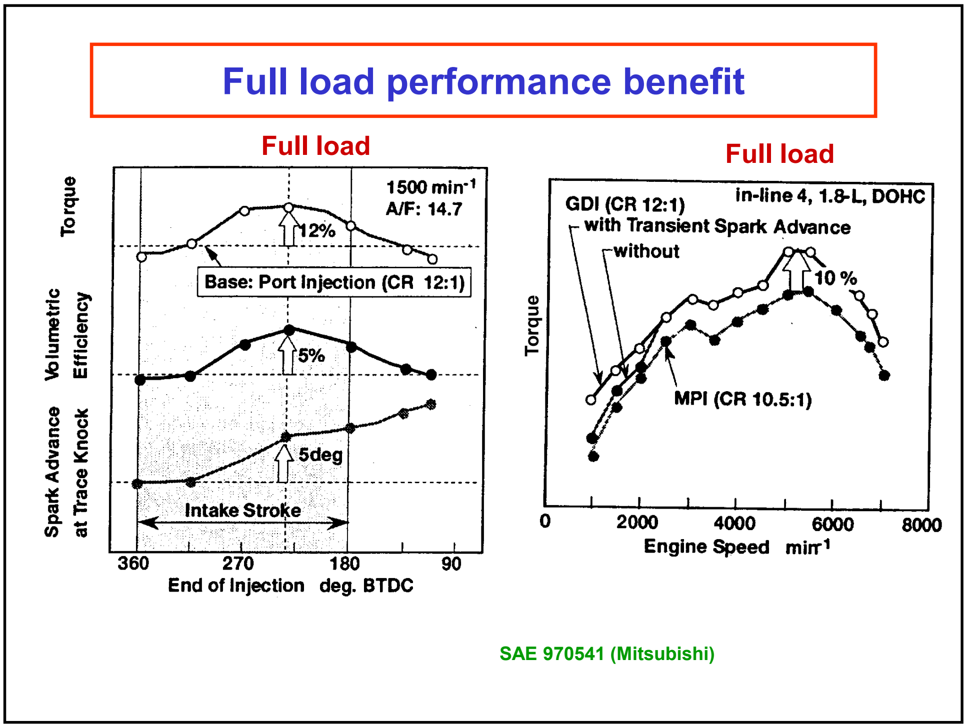
Charge cooling effect



Lowering of intake volume

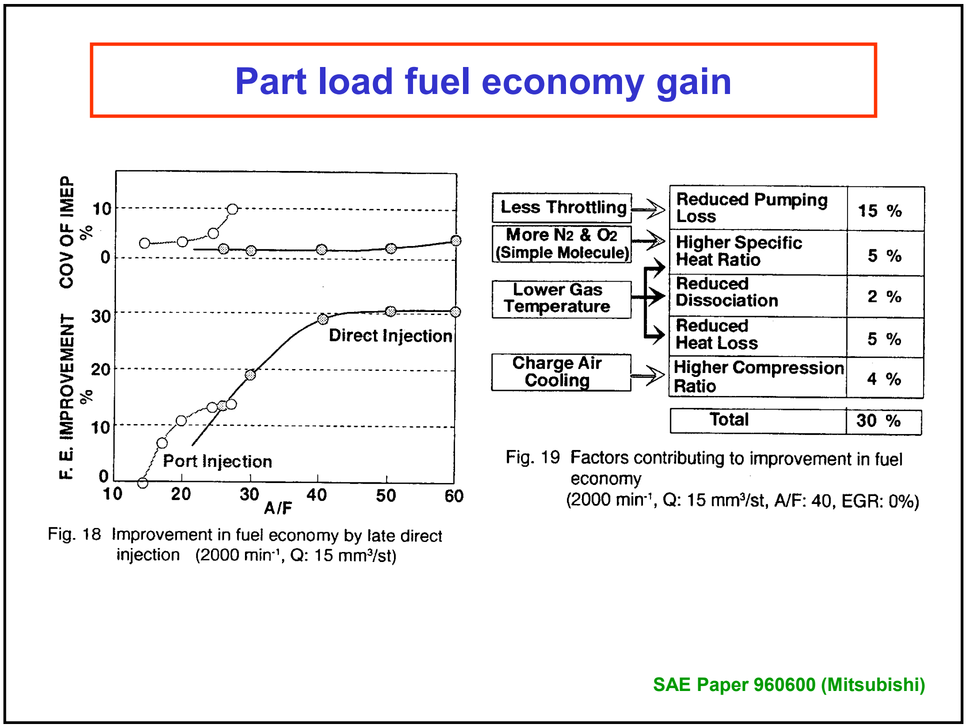


Anderson, Yang, Brehob, Vallance, and Whiteabker, SAE Paper 962018



Full load performance benefit

SAE 970541 (Mitsubishi)



Part load fuel economy gain

Fig. 18 Improvement in fuel economy by late direct injection (2000 min^{-1}, Q: 15 mm^3/st)

Less Throttling →	Reduced Pumping Loss	15 %
More N2 & O2 (Simple Molecule) →	Higher Specific Heat Ratio	5 %
Lower Gas Temperature →	Reduced Dissociation	2 %
	Reduced Heat Loss	5 %
Charge Air Cooling →	Higher Compression Ratio	4 %
	Total	30 %

Fig. 19 Factors contributing to improvement in fuel economy (2000 min^{-1}, Q: 15 mm^3/st, A/F: 40, EGR: 0%)

SAE Paper 960600 (Mitsubishi)

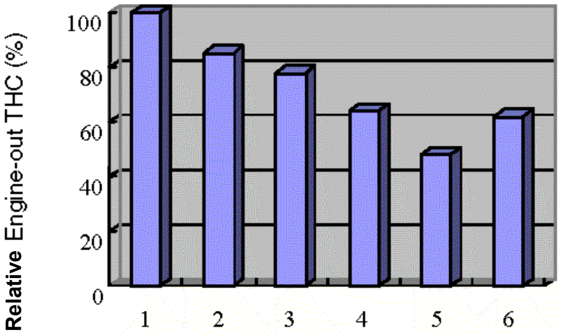
DISI Challenges

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

Comparison of cold start HC emissions

(Koga, Miyashita, Takeda, and Imatake, SAE Paper 2001-01-0969)

Cumulative engine out HC in the first 10 seconds of cold-start



1:Conventional DISI

2.Engine Starting W/5MPa

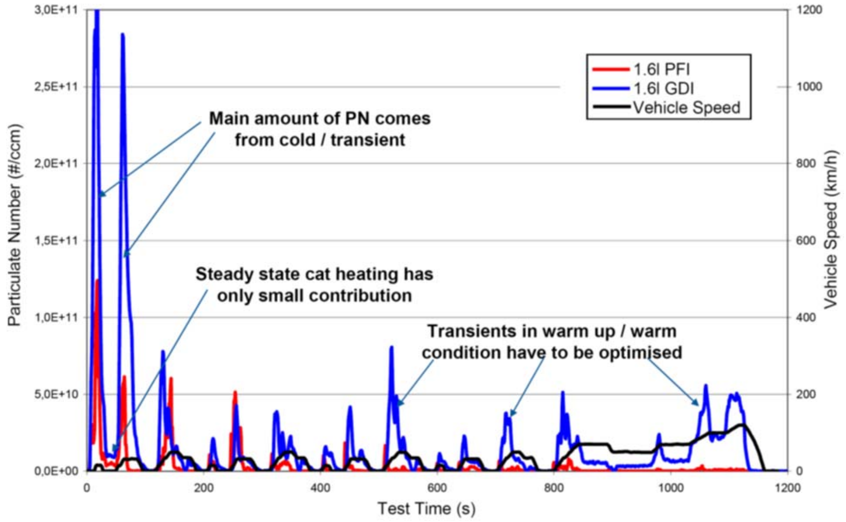
3.Late intake valve opening

4. 2 + late injection

5: 4 + heated fuel injection

6: MPI

Significant particle numbers in cold start



Main amount of PN comes from cold / transient

Steady state cat heating has only small contribution

Transients in warm up / warm condition have to be optimised

SAE 2011-01-1219

2.61 Internal Combustion Engines
Spring 2017