Future Trend and New Engine Technologies to Meet Emission Regulations

HANYANG UNIVERSITY

Prof. Ki-hyung Lee
Global megatrends impacting our business

Connectivity
By 2020, 50 billion devices will be connected.

Urbanization
60% of the world population lives in cities.

Demographics
The group of over 65-year-olds is growing twice as fast as all others.

Energy and climate
The likelihood of restricting global warming to only 2 °C is very low.

Efficient combustion engines
Near Zero Impact on Air Quality
Driving pleasure with powerful performance

Hybrid powertrains
Connected mobility
Efficient transport and logistics

Automated mobility

Urban mobility

Connected services

Comfortable travel

Electrification
Recharging infrastructure
Affordable mobility

Efficient engines
Alternative fuels

Electromobility

Source: BOSCH
Awareness of Issues

Automotive Powertrain Issues

- Global development of industry & technology in the 21st century
- Accelerated consumption of fossil fuels
  - 1. Energy issues
  - 2. CO₂ reduction (global warming measures)
  - 3. Air quality issues

Three issues: Energy issues, CO₂ reduction, air quality issues

Source: Toyota
CO₂ Regulation for various countries

- EU 2030년, 2021년 대비 37.5% 감축 결정 (~60g/km)
- USA: 40 (2017) → 56 mpg (2025)
- China: 6.4 (2017) → 4.0 L/100km (2025)
- Korea: 140 (2017) → 82 g/km (2025)

単位: g/km

ONLY 1-YEAR LEFT

source: ICCT 2017.6

Source: Hyundai
Exhaust Emission Regulations (PM, NOx)

유럽 규제
단위: mg/km

미국 규제
단위: mg/km

주행사이클: NEDC > WLTC + RDE

PN 규제 적용
6.0 x 10^-11 [#/km]

NMOG + NOx

PM

2015  2017  2019  2021  2023  2025
3  3  3  3  3  1

*MPhase in from 2025 to 2028

HANYANG UNIVERSITY
How to prepare for 2030?

- Improvement of thermal efficiency for current engines
- Find the new powertrain source for 2030

Source: Hyundai
Powertrain trend beyond 2025

- High energy battery
- Increase mileage
- Building Infrastructures
- Cost competitiveness

- Improve engine efficiency
- Increased engine performance
- Synthetic fuel development
- Component Quality Management

Diversification of power sources

Source: Hyundai
Trend of Powertrain - key strategy for 2030

- CO₂
- Improve powertrain efficiency
- Renewable energy
- MHEV, PHEV HEV, EV
- Fuel cell EV

Dependency on Petroleum

Source: Hyundai
Outlook for powertrain type

- Internal combustion engine in 2030 still dominating propulsion system
- Hybridization and electrification will proceed – increased electric range pushed by legislation

Bosch expects growing market penetration of 48V systems in all vehicle segments. Drivers: CO₂ reduction, growing electrical power demand (comfort functions), highly-automated driving.

Source: BOSCH
Expected global sales volume in 2030
(# Base scenario; vehicle sales include passenger cars and light commercial vehicles up to 3.5 tons)

Passenger car powertrain type forecast for 2030 in million units
(# Base scenario;)

2030 light-duty vehicles sales
(#Base scenario)

Source: FEV
In common, researches on improvement of fuel economy by optimizing the valve system.
- VVT / VVL is applied to achieve optimal intake and exhaust efficiency in all operating conditions.
- The thermal efficiency is increased by applying the Miller cycle.
Scenario for Accomplishing Target of Engines

**Fuel Economy Target:** ‘30년 50% Thermal Efficiency (Engine)

- **Phase-in 130g CO₂**
- **95g CO₂/km**
- **67g CO₂/km**

**Future of Engine**

- **Key words** - Convergence:
  - SI/CI combustion
  - SI/CI components
  - SI/CI fuel
  - SI/CI performance

**Fuel Economy**

- **Diesel (Cl)**
  - ‘15년
  - Oxidation catalysts
  - Diesel Particulate Filter
  - ~15% diff.
  - Dual-EGR & Lean NOx Trap
  - Advanced Aftertreatment Thermal management
  - VVT GDI (SIDI)

- **Gasoline (SI)**
  - ‘20년
  - Down-sizing w/ Boost
  - Cooled EGR VCR
  - Lean Miller cycle
  - VVT/E-Boost

**Emission**

- **Emission Target:** ‘20년 Post Euro-6
- **EU 6b**
- **EU 6d**
- **EU 7(?)**

**Future Combustion Technologies**

- Dual-EGR & Lean NOx Trap
- Cooled EGR
- VCR
- Advanced Aftertreatment
- Warm-Start
- Lean Miller cycle
- VVT/E-Boost
- Down-sizing w/ Boost
- Cooled EGR VCR
- Lean NOx Trap
- Advanced Aftertreatment
- Warm-Start
- Lean Miller cycle
- VVT/E-Boost
- Down-sizing w/ Boost

**BMW Module**

- **Brake Thermal Efficiency**
  - Present: 38.5%
  - Future: 50%
  - Reduction of Heat Loss
  - Exhaust Heat Recovery
  - Energy

**Source:** BOSCH
New Technologies applied to Gasoline Engines

Gasoline Engine (GDI)

High Pres. Inj. & Spray Pattern

New Combustion (GCI)

Dual Injection

Variable Compression Ratio

Injection strategy

High-efficiency ignition

CVVT/CVVL

Electrification

e-Supercharger
Lean Burn Technology

Lean Burn – Concept of Lean Burn Engine (GDI)

- **Advantage:** Intake more air than theoretically needed air, **Reduce pumping loss**
- **Disadvantage:** Combustion instability, reduced efficiency of three-way catalyst (increased NOx emissions)

**Homogeneous**

**Stratified**

Lean Burn

- Under normal operating conditions, gasoline engine operate at equivalent ratio of 1.0, which is the stoichiometric air-fuel ratio.
- In case of lean burn, the fuel is stratified around the spark plug so as to stably burn even under lean conditions.

Application Method

- The fuel is injected in the late period of the compression stroke so that fuel is not mixed with air.
- Multi-stage injection can also be applied to form a suitable mixture for combustion.
Fuel Injection Systems for GDI Engine

**Side-mounted: Wall-guided**

- Relies heavily on **in-cylinder motion** and **piston-bowl geometry**
- **Solenoid actuated injector**
- Liner, piston wetting → PM, HC ↑

**Central-mounted: Spray-guided**

- Relies heavily on **spray momentum**
- **Piezo-electric actuated injector**
- Ignitability → Effect on COV, misfire
Spray characteristics of GDI Injector

Fuel injection system

Multi injection
- Hole type fuel injection can actively utilize swirl or tumble flow for homogenous mixture formation
- The multi-hole solenoid type is most commonly used for GDI injectors.
Comparison of Spray Images

- Spray Images according to Ethanol/Gasoline Mixture Ratios

**Pinj : 250 bar, P_{amb} : 5 bar, T_{amb} : 120^\circ C**

<table>
<thead>
<tr>
<th></th>
<th>E0</th>
<th>E50</th>
<th>E100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="E0.png" alt="Image" /></td>
<td><img src="E50.png" alt="Image" /></td>
<td><img src="E100.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Comparison of Spray Diameter (SMD)

- Experimental system for SMD measurement of ethanol / gasoline mixed fuel

- Measurement of ethanol/gasoline blended fuels
  - The higher the injection pressure, the smaller the SMD
  - Fuels with a higher ethanol content have a greater SMD
  - SMD is affected by viscosity, density and surface tension

### Test Fuels

<table>
<thead>
<tr>
<th>E0, E50, E100</th>
<th>Injection pressure (bar)</th>
<th>50, 100, 150, 200, 250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection duration (ms)</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Ambient pressure (bar)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Measuring point</td>
<td>50 mm</td>
<td></td>
</tr>
</tbody>
</table>

![Graphs showing comparison of SMD for E0 and E100 fuels at different pressures.](image)
Developed TGI FFV Engine

Developed TGI FFV Engine

<table>
<thead>
<tr>
<th>Components</th>
<th>1.0 T-GDI FFV Engine (Modified)</th>
<th>1.0 T-GDI Engine (Conventional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>① High Pressure Injector</td>
<td>250bar</td>
<td>200bar</td>
</tr>
<tr>
<td>② Turbo Charger</td>
<td>터빈 전단 배압 저감 (개선율19%)</td>
<td>Base</td>
</tr>
<tr>
<td>③ Piston</td>
<td>압축비 10.5 용</td>
<td>압축비 10.0 용</td>
</tr>
<tr>
<td>④ Valve/Seat/ Piston material</td>
<td>내부식성 재질 (Cr, Ni 보강)</td>
<td>Base</td>
</tr>
<tr>
<td>⑤ Intake</td>
<td>흡압 개선 사양 (최대 0.2kPa)</td>
<td>Base</td>
</tr>
<tr>
<td>⑥ EMS</td>
<td>T-GDI FFV 엔진용 (에탄올 제어 로직 / 에탄올 센서 적용 로직 개발)</td>
<td>T-GDI 엔진 전용</td>
</tr>
</tbody>
</table>
**New Combustion Concept (Gasoline Engine)**

**GCI (Gasoline Compression Ignition)**

- Apply diesel combustion to GDI gasoline engines
- Without spark plugs, self-ignition of the gasoline mixture is used for combustion
  - Advantage: Decreased Soot and NOX, Improve fuel economy (Decrease pumping loss)
  - Disadvantage: Low self-ignitability (low certain number) makes combustion difficult

---

**GM-Saturn Aura**

- Saturn Aura Engine Features
  - Operating mode: HCCI mode @ from idle up to 55 miles per hour
  - SI Mode @ higher speeds or during heavy engine load
  - 2-Step Valve Lift
  - Dual Cam Phaser
  - Cylinder Pressure Sensor
  - GDI Injector
  - Fuel economy: up to 15% fuel savings

<table>
<thead>
<tr>
<th>Engine</th>
<th>2.2L Ecotec + HCCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>179 hp</td>
</tr>
<tr>
<td>Torque</td>
<td>230 N·m</td>
</tr>
</tbody>
</table>

**GDCI (Gas Direct injection Compression Ignition)**

- System level integration for GDCI combustion
- Vehicle Fuel Economy Improvements of +25% (target)

**Engine Combustion & Optical Diagnostics Lab.**

Source: Delphi
VCR (Variable Compression Ratio) – Nissan (Infiniti)

- The compression ratio can be mechanically changed while engine is running
- The compression ratio can be changed according to operating conditions
- **Purpose:** Increase the efficiency by increasing compression ratio in low load
  Reduce compression ratio in high load to prevent knocking

Technology Benefits

- Significant **engine mass reduction** over the base engine while exceeding its output levels.
- 33% **lesser vibration** over an I4 engine, eliminates the need of balancer shaft
- 44% **lesser cylinder friction**, eliminates the need of cylinder liners
- Dual injection (MPI & GDI) – **Minimized particulate emissions.**

VC-T (Variable Compression-Turbocharged) – Nissan Infiniti

- Changeable Range: 8:1~14:1
- Fuel economy increased by 30%
- 4 Cylinder 2.0 Liter
Miller Cycle and Variable Valve System

- Miller Cycle
- Compression ratio 12.5:1 → Improved efficiency
- Early intake valve closing → Lower Temperature
- Optimized charge motion → Rapid flame propagation

Source: VW
New Ignition System

Comparison of ignition systems

STANDARD PLUG
Technology for improving thermal efficiency through injection fuel and water simultaneously
Improvement of Efficiency for Various Technologies

Source: FEV

Indicated efficiency / %

- $\lambda = 1.0$
- EGR 25%
- CR 11.8
- Base

- $\lambda = 1.0$
- EGR 25%
- CR 11.8
- Miller

- $\lambda = 1.6$
- CNG
- CR 14.7

- $\lambda = 1.0$
- EGR 27%
- CR 13.5
- 2-Butanone

- $\lambda = 1.65$
- CR 14.7
- Miller

- $\lambda = 1$
- s/B↑, V_H↑

- $\lambda > 2$
- Pre-chamber

- Layout for narrow operation region

- + Exhaust energy recovery

Source: FEV
Methods for challenging emission / fuel economy regulations

Future gasoline engine technology

- High CR
- Cooled EGR
- Smart cooling (Electrification, thermal management)
- Control (emission, fuel)
- Flexible VVA
- cylinder Deactivation (CDA)
- Optimized combustion (lean burn(stratified), octane boost fuel)
- High performance turbo/supercharger for downsizing
- Friction reduction
- Stop/Start system
- Waste heat recovery
- FlexFuel
- Variable CR
- Flexible VVA
- Cooled EGR
- Control (emission, fuel)

Emissions
- Optimized combustion
- Cooled EGR
- Flexible VVA

Fuel Economy
- High CR
- Flexible VVA
- Friction reduction
- Waste heat recovery
- Stop/Start system
- Cylinder Deactivation
New Technologies applied to Diesel Engines

Diesel Engine

New Combustion (HCCI)

Piston Shape Optimization

High Pressure Injection

High Pressure Injection
Promoting fuel atomization
Multiple Injection

Turbo Chager

High efficiency & low cost after treatment system

- DOC
- CPF
- CRT
- DPF
- SCR
- LNT

EGR control optimization
-Hybrid EGR (HP+LP)-

Waste Heat Recovery

- Intercooler
- Turbocharger
- Intake Valve
- EGR Valve
Strategy for improving fuel economy in diesel engines

- Develop low end torque and highly responsive air management systems
- Define cost effective aftertreatment systems based on engine and vehicle boundary conditions

- Low inertia, low friction
  - Highly responsive turbocharger

- High pressure fuel injection system (> 2000 bar)

- Dual loop EGR System
  - HP + LP EGR system

- Exhaust aftertreatment system
  - (DPF, LNT, SCR systems)

- Friction reduction / Thermal Management systems

Source: Toyota
Renault & Cummins — Diesel HCCI/PCCI

- Renault VelSatis (HCCI w. NADI™ Concept)
  - 4 cylinder, light-duty direct injection Diesel engine
  - 2.2 litre (87 mm bore and 92 mm stroke)
  - Combustion chamber designed for NADI concept
  - Compression ratio of 14:1

- Developed by IFP with Faurecia and Valeo
  - Redefinition of the air and EGR loop with dedicated cooling circuit using low temperature water and EGR exchanger bypass

Reference: KAIST Engine Laboratory
Future Diesel Engine Technology

- After treatment system (LNT/SCR) & fuel efficiency
- High pressure injection system (>2000 bar)
- Advanced combustion (LTC, dual fuel)
- Smart engine thermal management with exhaust gas
- Friction reduction
- VVA (CVVT w/wo VVL)
- Enhancing transient control logic (Air system + T/C + EGR) In-cylinder based / Model based control
- Hybrid EGR (HP + LP), intercooler efficiency
- Low compression ratio (14~16)
- Waste heat recovery

Emissions
- After treatment
- Hybrid EGR
- VVA (CVVT/CVVL)
- High press injection
- Advanced combustion

Fuel economy
- VVA (CVVT/CVVL)
- Advanced combustion
- thermal management
Future Outlook of ICE’s Evolution (48V System)

- Synergies between Hybrid and combustion engine enable further fuel economy / emission benefits
- Transient response and torque assist functionality
- Reduce emission through shaving of dynamic torque peaks

Schematic of 48V System

Synergies between Hybrid and combustion engine enable further fuel economy / emission benefits

Transient response and torque assist functionality

Reduce emission through shaving of dynamic torque peaks

12V → 48V

Transmission

Combustion Engine

Functionality ICE

Electrification

Functionality Powertrain

6th gear full load acceleration

-28% -11%

Transmit response and torque assist functionality

Reduce emission through shaving of dynamic torque peaks

Synergies between Hybrid and combustion engine enable further fuel economy / emission benefits

Transient response and torque assist functionality

Reduce emission through shaving of dynamic torque peaks

12V → 48V

Transmission

Combustion Engine

Functionality ICE

Electrification

Functionality Powertrain

6th gear full load acceleration

-28% -11%
Strategies for Emission and Fuel Economy Regulation

**Combustion**
- High pressure Injection
- Multi-Stage Injection
- Lean Burn
- Alternative Fuel (CNG, LPG, Ethanol)
- HCCI
- Gasoline Direct Injection

**Down Sizing**
- Turbo / Super Charger
- Gasoline Direct Injection

**Engine Control & Valve System**
- Idle Stop Go (ISG)
- Coasting Function
- Cylinder Deactivation (CDA)
- CVVT / CVVL
- Atkinson Cycle

**Eco-Friendly**
- Electric Vehicle (EV)
- Hybrid Electric Vehicle (HEV)
- Fuel Cell Electric Vehicle (FCEV)

**After Treatment**
- LNT (Lean NOx Trap)
- SCR (Selective Catalytic Reduction)
- DPF / GPF (Particulate Filter)
- DOC (Diesel Oxidation Catalyst)
- TWC (Three Way Catalyst)
Success Factor of EV(1) – decrease of battery cost

- Battery cost gradually decreased due to increase of EV sales volume

Li Battery Cost
[$/kWh], 2010~2016

Li Battery Cost and Energy Density

Source: Bloomberg New Energy Finance, 2017

Source: Global EV Outlook 2017, IEA
Success Factor of EV(2) – Subsidy system by government

- Sales volume of BEV in China and USA

- China and the United States are leading the global electric vehicle market.

- China is implementing mandatory new energy vehicle credits, electric vehicle subsidy policies, and limiting the issuance of internal combustion vehicle license plates to control the supply of battery electric vehicles.

- Inclusion: plug-in hybrids

- Sources: InsideEVs, CAAM

- China and US electric vehicle sales volume chart

- The Chinese and American electric vehicle market share chart.
Expected Global Sales Volume of FCEV

<table>
<thead>
<tr>
<th>Country</th>
<th>’18 10</th>
<th>(DOE, 2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>5,715</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>3,359</td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>926</td>
<td></td>
</tr>
<tr>
<td>Korea</td>
<td>794</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10,795</strong></td>
<td></td>
</tr>
</tbody>
</table>

< Proprietary technologies in Hyundai >

< Prospective number of Korea >

Source: 현대자동차 수소 연료전지, NH 투자증권 리서치 본부
Roadmap of Japan

**Phase 1:**
- Installation of Fuel Cell
- 2009: Residential FC, 2014: FCV
- 2017: Stationary FC
- Around 2020:
  - FCV fuel cost ≤ HEV fuel cost
  - 40,000 FCVs, 160 HRSs
- Around 2025:
  - FCV in main market segment
  - FCV cost competitive ≥ HEV
  - 200,000 FCVs, 320 HRSs

**Phase 2:**
- H2 Power Plant/Mass Supply Chain
- Accelerate RD&D
- Realize reasonable H2 Price
- 2nd half of 2020's:
  - H2 Cost (CIF): JPY 30/Nm^3
  - Enhance Supply Chain in Japan

**Phase 3:**
- CO2-free Hydrogen
- Planned R&D based on the outlook for the hydrogen supply system
- Around 2040:
  - Full Scale CO2-free H2 (w/ Renewable Energy, CCS, etc)

**Expected Global Hydrogen Station:**
- **Northeastern US:** 250 HRS by 2027
- **China:** 1,000 HRS by 2030
- **South Korea:** 310 HRS by 2022
- **California:** 100 HRS by 2020
- **EU:**
  - 1,150 HRS by 2030 (UK)
  - 150 HRS by 2020 (Scandinavia)
  - 400 HRS by 2023 (Germany)
  - 820 HRS by 2030 (Other)

**Source:** Hydrogen Energy Navi, 2019

*HRS: Hydrogen Refueling Station

참고자료: 환경부, 미국 에너지부 보고서(2018), IHS