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Comparative Study on Regulated Emissions and Size-resolved Particle Emissions from Light-duty Truck Equipped with Common Rail Direct Injection Diesel and Turbocharged LPG Direct Injection Engine under Various Vehicle Test Conditions

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INTRODUCTION

➢ "Global warming issue"
; CO_2 reduction should be carried out
- In Korea, CO_2 reduction in transportation
  - "2030 GHG reduction plan"; 5.2 million ton ↓
- Including electrification, F/E improvement ↑
  - Diesel and gasoline direct injection (GDI) engine have become popularized

➢ "Urban area air quality issue"
; Need for improvement on NO_X and PM
- Diesel-NO_X and GDI-PM emission problem
  - Light-duty trucks (LDTs) are seriously affected
- The Korean Government's announcement
  - "Special Act on Fine dust reduction and management"; deregulation on LPG vehicle

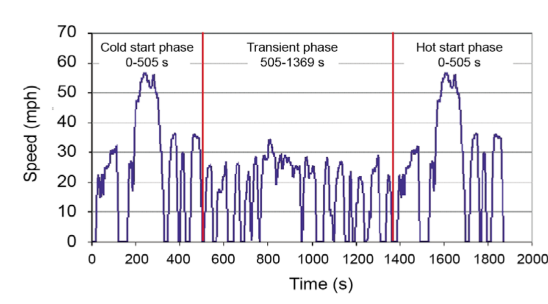
➢ "Use of alternative fuel issue"
; Liquefied petroleum gas (LPG or Autogas)
- Superior vaporization characteristics
  - Overcoming the direct injection disadvantage
- 『Turbocharged LPG direct injection (T-LPDi)』
  - Goal: CO_2/NO_X/PM simultaneous reduction

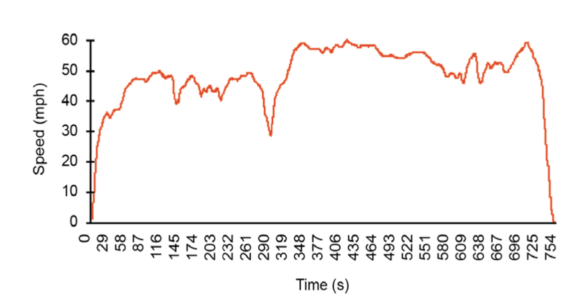
RESEARCH METHOD

➢ Under various vehicle test conditions, $CRDI_{(Diesel)}$-$T\text{-}LPDi_{(LPG)}$ comparative study

US Federal and California, FTP-75	
Distance/time	11.04 mi (17.77 km) / 2,475 (1874+600) sec
Avg./Max. speed	21.19 mph (34.2 km/h) / 56.68 mph (91.2 km/h)

US Federal and California, HWFET	
Distance/time	10.26 mi (16.50 km) / 765 sec
Avg./Max. speed	48.30 mph (77.7 km/h) / 59.91 mph (96.4 km/h)



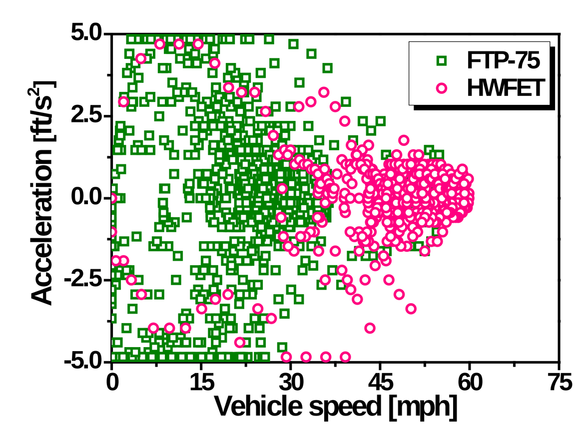


Source: Delphi Technologies, Worldwide Emissions Standards, Passenger Cars & Light Duty Vehicles

Base CRDI diesel LDT test

Same vehicle test after T-LPDi engine installation (using commercial LPG LDT)

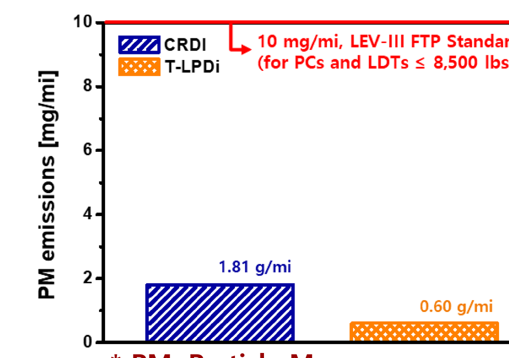
CO_2/NO_X/PM emission comparative study

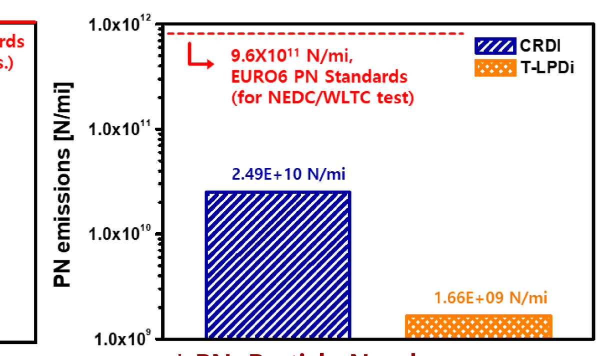


* FTP-75
: Federal Test Procedure; City mode
* HWFET
: Highway Fuel Economy Test

PARTICULATE EMISSIONS ANALYSIS

Particle Mass and Number Emissions under FTP-75

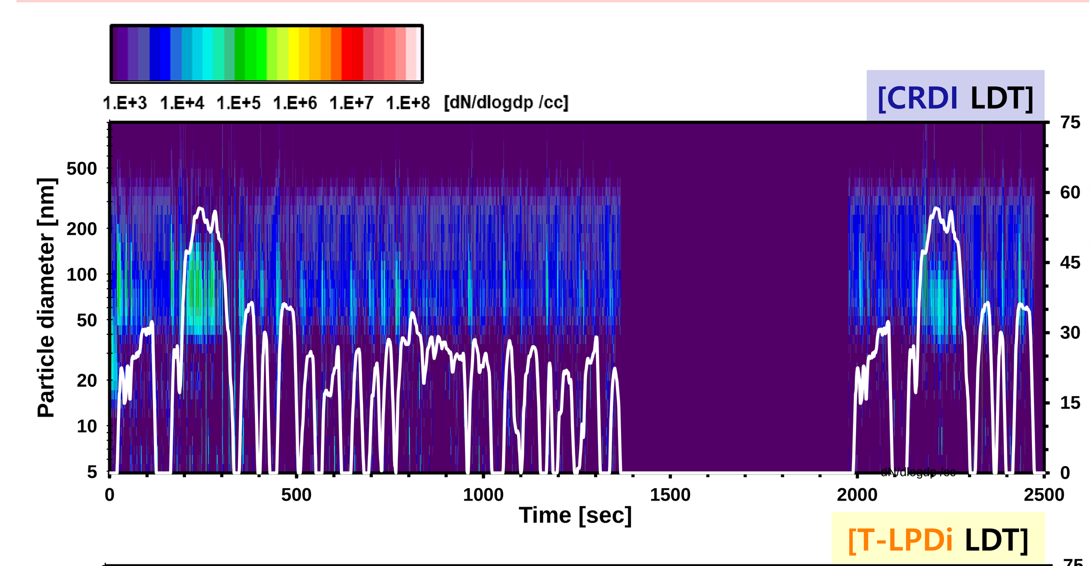


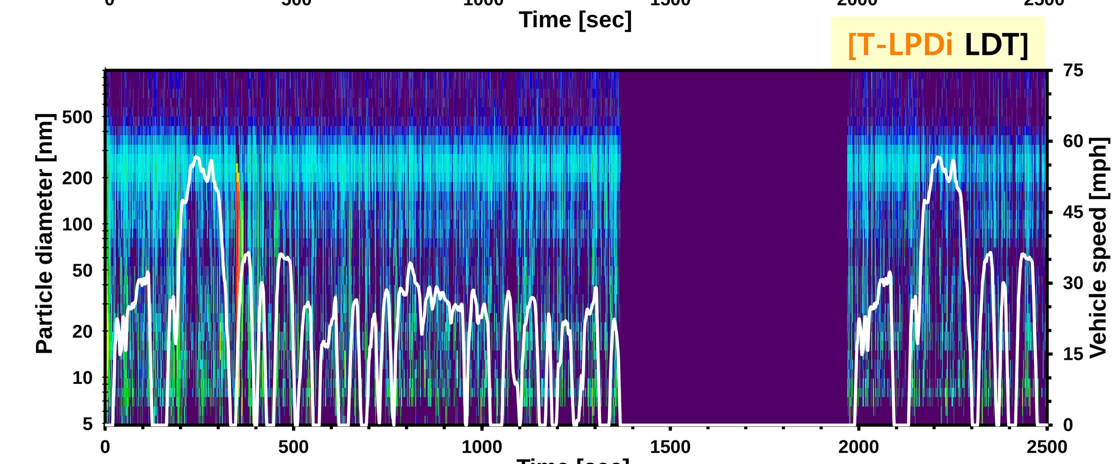


* PM: Particle Mass
* PN: Particle Number

- Korea and US regulations for LDTs have PM standard only (unlike EU)
- With DPF, CRDI LDT's PM/PN emissions significantly ↓
- T-LPDi LDT's PM and PN emissions ↓ compared to CRDI
  - ➢ It may be because of superior vaporization characteristics of LPG
- What if future regulations are including sub-23 nm particles?
  - ➢ PN emission analysis by size should be carried out

Size-resolved Particle Number Emissions under FTP-75





- PN emissions were increased under transient operation such as engine cold-start and acceleration/deceleration condition
- CRDI LDT's real-time PN concentrations were lower than T-LPDi LDT's under almost entire driving duration
  - ➢ Considering above PN emissions and exhaust flow rate of both vehicles, T-LPDi LDT's PN concentration ↑ but total PN ↓
- CRDI LDT's PN size distribution showed a singular peak point around 100 nm (accumulation mode particles)
- On the other hand, under T-LPDi LDT test, there were multiple peak points that include nuclei/accumulation particles
- These can be improved by further optimizations as mentioned before

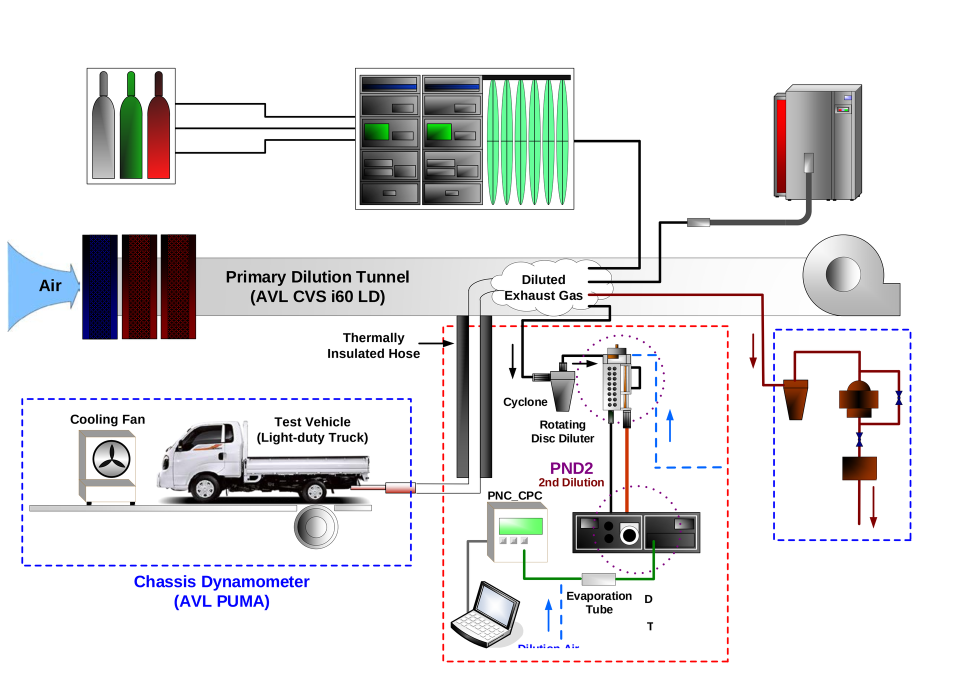
Source : D. B. Kittelson (1998), ENGINES AND NANOPARTICLES: A REVIEW, *J. Aerosol Sci.* 29, 575-588

EXPERIMENTAL SETUP

Specification of Test Engines and Vehicles

	CRDI (Diesel)	T-LPDi (LPG)
Engine Type	Turbocharged In-line 4	Turbocharged In-line 4
Displacement	2,497 cc	2,359 cc
Fuel Type	Diesel	LPG
Injection Type	Common rail direct injection (CRDI)	Stoichiometric direct injection (DI)
Charge Type	Single WGT	Single WGT
Aftertreatment	NO_X storage catalyst (NSC) + Diesel particulate filter (DPF)	Three way catalyst (TWC) only
Transmission	6-speed M/T	6-speed M/T
Max. Torque	26.5kgf.m @ 1500~ rpm	26.5kgf.m @ 1,500~ rpm
Max. Power	133 PS @ 3800 rpm	170 PS @ 5,000 rpm

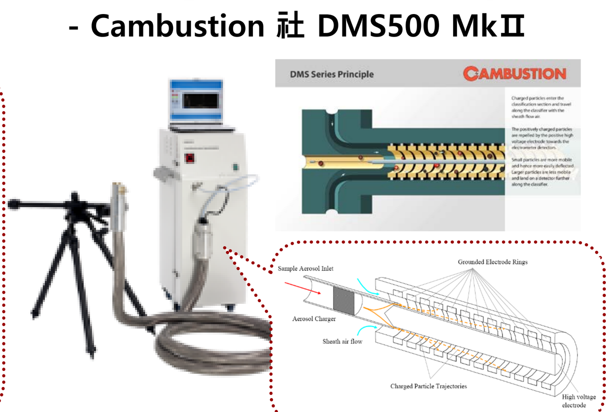
Schematic Diagram of Vehicle Test



Specification and Description of Experiment Apparatus

[Gas Analyzer]
- AVL 社 AMA i60

[Fast Engine Particulate Analyzer]
- Cambustion 社 DMS500 MkⅡ



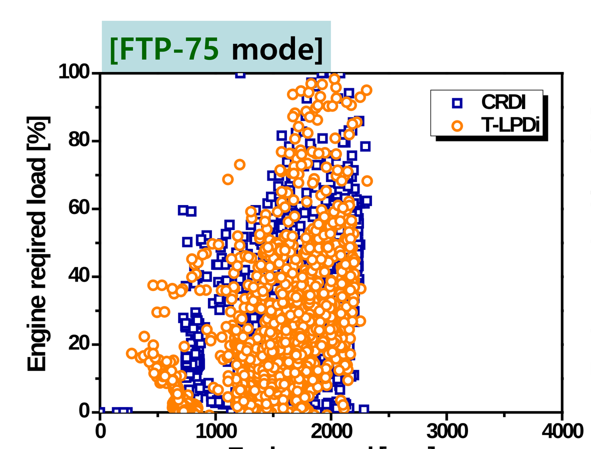
- Non-dispersive infrared (NDIR)
- Infrared → CO_2 4.3μ absorption
- Following Lambert Beer's Law, CO_2 concentration is detected

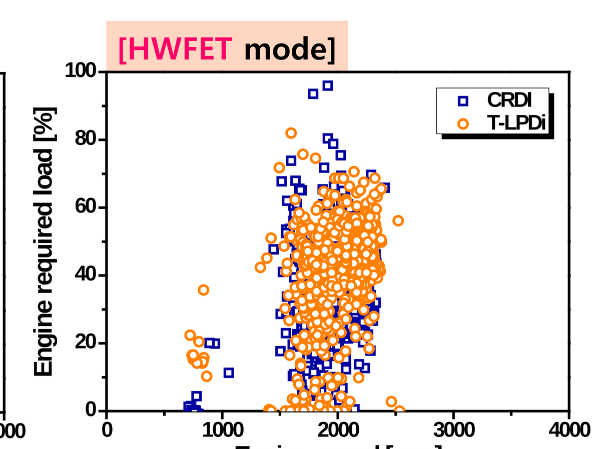
- Diffusion charging (DC)
- Positive charge of particles → negative charge detector
- Inertia ↔ Electric mobility

Source: National Institute of Environmental Research (NIER) of Korea
Cambustion Ltd., Fast Engine Particulate Analyzer, DMS500 Instrument Principle

ENGINE OPERATION ANALYSIS

Engine Speed-Load Characteristics under Vehicle Test

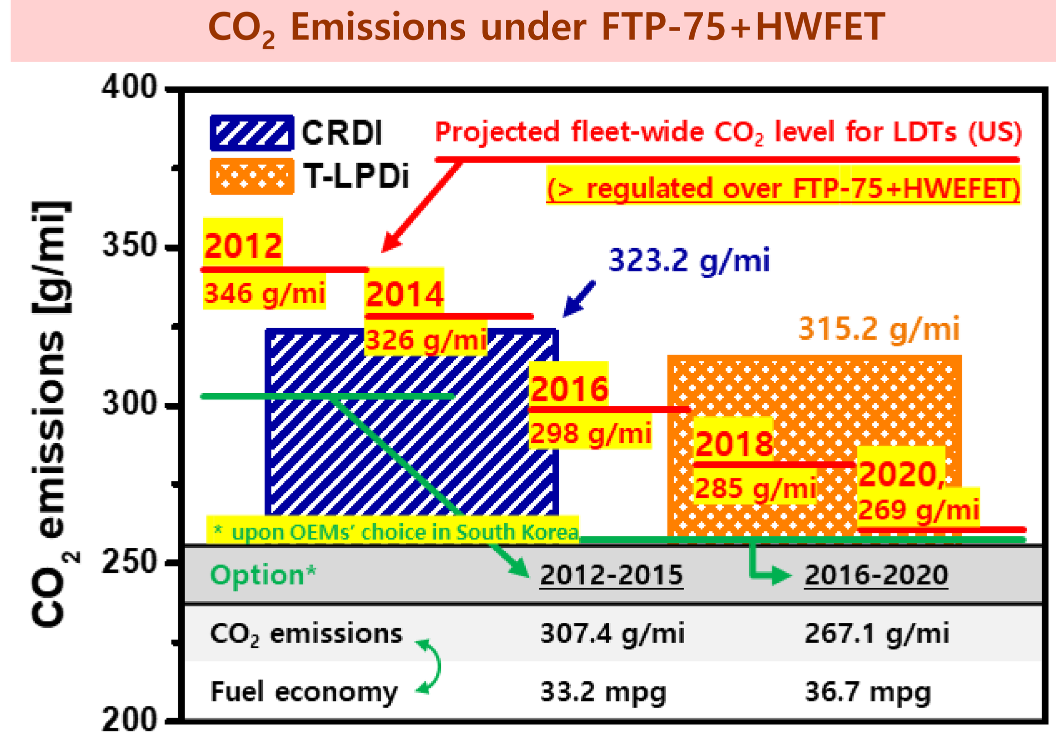




- Engine speed-load maps of both LDTs showed similar pattern
  - ➢ Equivalent torque performance from 1,500 rpm of engine speed
  - ➢ Comparable speed-load characteristics even during acceleration
- Engine operating points can be optimized by further improvements
  - ➢ Ex.) T-LPDi LDT dedicated transmission, differential gear, etc.

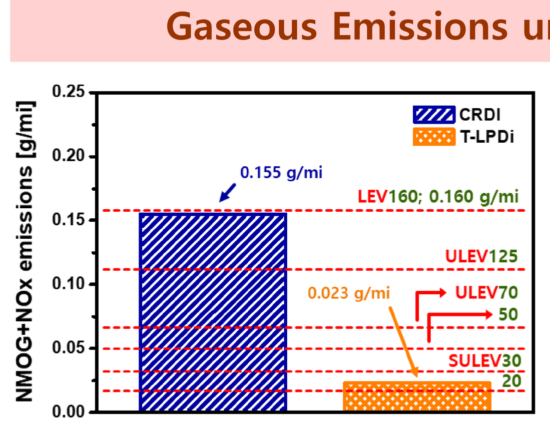
GASEOUS EMISSIONS ANALYSIS

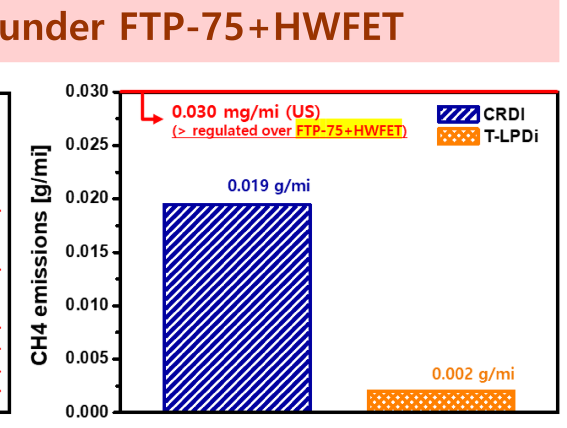
CO_2 Emissions under FTP-75+HWFET



- CO_2 emissions from T-LPDi (315.2 g/mi) ↓ than CRDI (323.2 g/mi)
  - ➢ ∵ Atk. + Turbo. + DI system with LPG of which evaporation & LHV ↑
- However, Korea's CO_2 target is much lower than those emission levels
  - ➢ Further GHG reduction roadmap should be necessary

Gaseous Emissions under FTP-75+HWFET





- Other gaseous emissions from T-LPDi LDT were significantly ↓
- T-LPDi LDT can achieve US LEV-III SUELV standard
  - ➢ ∵ Gaseous fuel + stoichiometric operation + TWC strategy

CONCLUSION AND DISCUSSION

■ Summary and Conclusion

Ⅰ. Efforts on improving fuel economy and urban air quality (NO_X, PM, etc.) are equally important.

Ⅱ. T-LPDi engine concept showed a capability on reducing CO_2/NO_X/PM simultaneously.

Ⅲ. There are both need and room for further improvements on internal combustion engines.

FTP-75	CO_2 [g/mi]	Reduction [%]	PM [mg/mi]	Reduction [%]
CRDI	341.4	-	1.81	-
T-LPDi	357.3	+4.7	0.60	66.9

HWFET	CO_2 [g/mi]	Reduction [%]	PM [mg/mi]	Reduction [%]
CRDI	303.5	-	0.87	-
T-LPDi	267.8	-11.8	0.32	63.2

■ Discussion

Ⅰ. This research can help overview LDTs' exhaust emission performances with LPG fueled DI engine technology.

Ⅱ. Since LDTs have an influence on environments more than passenger cars, highly efficient and ecofriendly powertrain systems are necessary.

Ⅲ. As an alternative, the T-LPDi scheme can be useful not only for LDTs but also for various passenger/commercial vehicle applications.

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