Supplementary Information

Toward Synergetic Reduction of Pollutant and Greenhouse Gas Emissions from Vehicles: A Catalysis Perspective

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Table S1 NOx and PM limits in the standards for heavy-duty vehicles in US, EU, China, and Japan from 2000-2400

year	NOx (g/kW.h)				PM((g/kW.h)			
	China	US	EU	Japan	China	US	EU	Japan
2000		5.435	5			0.136	0.16	
2001		5.435	5			0.136	0.16	
2002		5.435	5			0.136	0.16	
2003		5.435	5			0.136	0.16	
2004		2.717	5			0.136	0.16	
2005		2.717	3.5	2		0.136	0.03	0.027
2006		2.717	3.5	2		0.136	0.03	0.027
2007		0.272	3.5	2		0.136	0.03	0.027
2008	5	0.272	2	2	0.16	0.014	0.03	0.027
2009	5	0.272	2	0.7	0.16	0.014	0.03	0.01
2010	5	0.272	2	0.7	0.16	0.014	0.03	0.01
2011	5	0.272	2	0.7	0.16	0.014	0.03	0.01
2012	5	0.272	2	0.7	0.16	0.014	0.03	0.01
2013	5	0.272	0.46	0.7	0.16	0.014	0.01	0.01
2014	5	0.272	0.46	0.7	0.16	0.014	0.01	0.01
2015	3.5	0.272	0.46	0.7	0.03	0.014	0.01	0.01
2016	3.5	0.272	0.46	0.4	0.03	0.014	0.01	0.01
2017	2	0.272	0.46	0.4	0.03	0.014	0.01	0.01
2018	2	0.272	0.46	0.4	0.03	0.014	0.01	0.01
2019	2	0.272	0.46	0.4	0.03	0.014	0.01	0.01
2020	2	0.272	0.46	0.4	0.03	0.014	0.01	0.01
2021	0.46	0.272	0.46	0.4	0.01	0.014	0.01	0.01
2022	0.46	0.272	0.46	0.4	0.01	0.014	0.01	0.01
2023	0.46	0.272	0.46	0.4	0.01	0.014	0.01	0.01
2024	0.46	0.272	0.46	0.4	0.01	0.014	0.01	0.01

Table S2 The advantages, disadvantages, and exhaust emission characteristics for vehicles using carbon-neutral fuels

	Hydrogen-fueled vehicles	Ammonia-fueled vehicles	Ammonia-hydrogen hybrid vehicles	Alcohol-fueled vehicles
Advantages	(1) zero carbon emissions, low cost, high efficiency, and low requirements for hydrogen purity. (2) mature industrial chain with low manufacturing cost.	(1) high octane rating and good anti-knock performance, suitability for operation with high compression ratios. (2) lower cost of storage and transportation than H_2. (3) no need for urea injection system.	(1) easier ignition and faster combustion than individual NH_3 fuel. (2) H_2 conveniently produced by decomposition of on-board NH_3.	(1) significant renewable and clean carbon-neutral fuel. (2) high octane rating. (3) lower levels of CO, PM, and HC compared with gasoline vehicles.
Disadvantages	(1) high storage and transportation cost. (2) requirement of urea injection system with NH_3 leakage risk.	(1) difficulties of ignition and slow combustion. (2) difficulties of simultaneously meeting the high NH_3 concentrations, low temperatures, and high N_2 selectivity.	(1) slow kinetics of electrocatalytic NH_3 to H_2. (2) requirement of high temperature pyrolysis of NH_3 to produce H_2.	(1) formaldehyde formation due to unburned methanol oxidation under oxygen-rich conditions. (2) no clear technical route for post-treatment under lean combustion condition.
Exhaust emission characteristics	(1) a large amount of NO_x emissions (~ 10,000 ppm) with N_2O. (2) high water vapor and high airspeed.	(1) multi-pollutants containing high concentration of NOx, NH_3 and N_2O. (2) insufficient low temperature activity.	(1) multi-pollutants containing high concentrations of NOx, NH_3, and N_2O. (2) insufficient low temperature activity.	(1) multi-pollutants containing NOx, CO, HC and formaldehyde. (2) narrow temperature window of CH_3OH-SCR with insufficient low temperature activity.

Appendix: The abbreviations in the manuscript

TWC: three-way catalyst

SCR: NO_x selective catalytic reduction

NSR: NO_x storage-reduction

DOC: diesel oxidation catalyst

ASC: ammonia slip catalyst

MOC: methane oxidation catalyst

DeN_2O: N_2O abatement catalyst

PNA: passive NO_x adsorber

CSC: cold start catalyst

GHGs: greenhouse gases

ICE: internal combustion engines

HC: hydrocarbons

CO: carbon monoxide

NO_x: nitrogen oxides

PM: particulate matter

GPF: gasoline particulate filter

CGPF: catalyzed gasoline particulate filter

CH_4: methane

DPF: diesel particulate filter

CDPF: catalyzed diesel particulate filter

NH_3-SCR: selective catalytic reduction of NO_x with ammonia

cc-SCR: close-coupled SCR

H_2-SCR: selective catalytic reduction of NO_x with H_2

US: the United States

EPA: Environmental Protection Agency

CARB: California Air Resources Board

EU: European Union

SI: spark ignition

CI: compression ignition

NGV: natural gas vehicles

THC: total hydrocarbons

PN: particle number

WHSC: World Harmonized Steady-state Cycle

WHTC: World Harmonized Transient Cycle

EGR: exhaust gas recirculation

EFI: electronic fuel injection

VVT: variable valve timing

AFR: air-to-fuel ratio

EHC: electrically heated catalyst

HCCI: homogeneous charge compression ignition

GCI: gasoline compression ignition

S: sulfur

P: phosphorus

cc-DOC: close-coupled DOC

MY: Model Year

NMHCs: non-methane hydrocarbon

Al_2O_3: alumina

CeO_2-ZrO_2: ceria-zirconia mixed oxides

CH_4-SCR: selective catalytic reduction of NO_x with methane

FTP: Federal Test Procedure

OC: oxidation catalyst

PGM: platinum group metals

OSMs: oxygen storage materials

AP: ambient-pressure

OSC: oxygen storage capacity

pyr-CZO: pyrochlore-phase ceria-zirconia

t-CZO: tetragonal-phase ceria-zirconia

ORR: oxygen release rate

Td: tetrahedral

C_3H_6-PROX: C_3H_6-preferential oxidation catalyst

MSI: metal-support interaction

HDCC: high dispersion-close coupling

ESC: European steady-state cycle

ZDDP: zinc dialkyldithiophosphate

HC-SCR: selective catalytic reduction of NO_x with hydrocarbons

CH_4-SCR: selective catalytic reduction of NO_x with methane

CN: cyanide

NCO: isocyanate

EFAl: extra-framework aluminum

NSC: NO_x storage capability

SOF: solvent organic fraction

PVA: polyvinyl alcohol

BEA: β-zeolite

SACs: single-atom catalysts

3DOM: three-dimensionally ordered microporous

DRC: degree of relative contact

TMO: transition metal (Mn, Fe, Co, Ni, Cu) oxide

SOC: surface composite oxides

CNG-LCV: natural gas light commercial vehicles

NH_3-SCO: selective catalytic oxidation of NH_3

SMSI: strong metal-support interaction

-HNO: imide

-N_2H_4: hydrazine

i-SCR: internal selective catalytic reduction

MvK: Mars-van Krevelen

DFT: density functional theory

L-H mechanism: Langmuir-Hinshelwood mechanism

E-R mechanism: Elecy-Rideal mechanism

Pd/CZO: Pd/CeO_2-ZrO_2