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Quantitative estimation of the impact of ash accumulation on diesel particulate filter related fuel penalty for a typical modern on-road heavy-duty diesel engine

Jun Zhang[a], Victor W. Wong[b], Shijin Shuai[a,*], Yu Chen[b], Alexander Sappok[b]

[a] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, China
[b] Sloan Automotive Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

HIGHLIGHTS

- DPF model considering ash effects is built and validated.
- Quantitative analysis on the impact of ash on DPF related engine fuel penalty.
- DPF ash induced fuel penalty typically ranges from 0.02% to 0.42%.
- DPF lifetime fuel penalty can be reduced by ash cleaning interval optimization.
- Fuel saving potential of DPF ash management typically ranges from 0.22% to 0.69%.

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ABSTRACT

Fuel saving and emission reduction are big challenges in the development of diesel engines. Diesel particulate filters (DPF) can effectively reduce particulate matter (PM) emissions of diesel engines but negatively affect the engine fuel economy. Some previous studies have been conducted to investigate the effects of DPFs on engine fuel economy, however, nearly all previous studies have neglected the impact of ash accumulation on DPF related fuel penalty. This work aims to quantitatively estimate the impact of ash accumulation on DPF related fuel penalty for a typical modern on-road heavy-duty diesel engine. For this purpose, a one-dimensional full-size DPF model considering ash effects was built and validated in this work, and an engine bench test was conducted to evaluate the effects of exhaust backpressure on engine fuel consumption. An estimation method for the quantitative evaluation of the impact of ash accumulation on DPF related engine fuel penalty was proposed based on the model and experimental data. Subsequently, the impact of ash accumulation on DPF lifetime fuel penalty as well as the potential of fuel saving by DPF ash management for a typical modern on-road heavy-duty diesel engine were quantitatively analyzed. In addition, the effects of engine-out PM emission concentration and DPF maximum soot loading prior to regeneration on the impact of ash accumulation on DPF lifetime fuel penalty and the fuel saving potential of DPF ash management are investigated with the estimation method. The results showed that the DPF ash induced fuel penalty ranged from 0.02% to 0.42% for the typical modern on-road heavy-duty diesel engine studied in this work, and the DPF lifetime fuel penalty could be reduced by optimizing the DPF ash cleaning interval. The fuel saving potential of DPF ash management ranged from 0.22% to 0.69% for all the cases studied in this work, which has the similar magnitude to some specific individual applications such as engine friction reduction, lowering accessory losses, or pumping optimization. Both the DPF ash induced fuel penalty and the fuel saving potential of DPF ash management are increasing with the rise of engine-out PM emission concentration no matter the DPF control strategy is implemented without or with ash correction, while the DPF maximum soot loading prior to regeneration showed little effects on the ash induced fuel penalty and the fuel saving potential of DPF ash management.

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[*] Corresponding author.
E-mail address: sjshuai@tsinghua.edu.cn (S. Shuai).

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Nomenclature

Abbreviations

BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
C	carbon
CO	carbon monoxide
CO_2	carbon dioxide
cspi	channels per square inch
DOC	diesel oxidation catalyst
DOE	Department of Energy
DPF	diesel particulate filter
ETC	European transient cycle
NEDC	New European Driving Cycle
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
O_2	oxygen
OEM	original engine manufacturer
PM	particulate mater
S	solid state
SCR	selective catalytic reduction
SV	space velocity
US	United States
WHSC	world harmonized stationary cycle

Symbols

A_1	free inlet channel cross section (m^2)
A_2	free outlet channel cross section (m^2)
A_s	surface of the solid part of the DPF (m^2)
BFP	backpressure fuel penalty (%)
$\overline{BFP}$	cycle averaged backpressure fuel penalty (%)
c_{O_2}	oxygen concentration in the exhaust gas ($kmol/m^3$)
c_p	specific heat of the exhaust gas (kJ/(kg·K))
$c_{p,s}$	specific heat of the DPF solid phase (kJ/(kg·K))
d	vehicle driving distance (km)
d_1	diameter of the DPF inlet/outlet channel (m)
E_f	activation energy of the denominator term of f_{CO} (kJ/kmol)
E_i	activation energy of reaction i (kJ/kmol)
F_1	friction coefficient in the inlet channel (–)
F_2	friction coefficient in the outlet channel (–)
FC	engine fuel consumption rate (kg/h)
f_{CO}	temperature dependence factor (–)
GSA	geometry surface area for DPF inlet and outlet channels (m^2/m^3)
H_u	lower heating value of the diesel fuel (kJ/kg)
$\boldsymbol{K}$	anisotropic heat conduction matrix (W/(m·K))
k_{ac}	permeability of the ash cake (m^2)
k_f	exponential factor of the denominator term of f_{CO} (–)
k_h	gas-solid heat transfer coefficient ($W/(m^2 \cdot K)$)
k_i	Arrhenius frequency factor of reaction i (variable)
k_{sc}	permeability of the soot cake (m^2)
k_{sd}	permeability of the soot depth layer (m^2)
k_w	permeability of the wall (m^2)
$l_{ash-plug}$	length of the ash plug (m)
l_{eff}	effective filtration length (m)
l_{plug}	length of the DPF inlet/outlet plug (m)
$\dot{m}_{exhaust}$	engine exhaust mass flow rate (kg/h)
$\dot{m}_{fuel}$	fuel injection rate (kg/h)
M_j	molar mass of the species j (kg/kmol)
M_k	molar mass of the species k (kg/kmol)
$\vec{n}$	normal vector to the surface of the DPF solid part (–)
p_1	pressure in the inlet channel (Pa)
p_2	pressure in the outlet channel (Pa)
p_{out}	pressure at the filter outlet (Pa)
Δp_{ac}	pressure loss of the ash cake (Pa)
Δp_{DPF}	DPF overall pressure drop (Pa)
Δp_{eff}	pressure loss over the effective filter length (Pa)
Δp_{inl}	pressure loss at the filter inlet (Pa)
Δp_{out}	pressure loss at the filter outlet (Pa)
$\Delta p_{plug,inl}$	pressure loss over the DPF inlet plug (Pa)
$\Delta p_{plug,out}$	pressure loss over the ash plug and DPF outlet plug (Pa)
Δp_{sc}	pressure loss of the soot cake (Pa)
Δp_{sd}	pressure loss of the soot depth layer (Pa)
Δp_w	pressure loss of the wall (Pa)
q_f	reaction order of the denominator term of f_{CO} (–)
r	total number of reactions (–)
R	universal gas constant (kJ/(kmol·K))
RFP	regeneration fuel penalty (%)
$\overline{RFP}$	cycle averaged regeneration fuel penalty (%)
$\dot{r}_i$	reaction rate of reaction i ($kmol/(m^3 \cdot s)$)
s	total number of species (–)
S_1	wet perimeter of the free inlet channel (m)
S_2	wet perimeter of the outlet channel (m)
S_r	energy source term of the chemical reactions (W)
T_g	exhaust gas temperature (K)
$t_{loading}$	DPF loading time (s)
$t_{regeneration}$	DPF regeneration time (s)
T_s	DPF solid temperature (K)
ΔT	the difference between the target temperature and the actual temperature at DPF inlet (K)
V	DPF volume (m^3)
v_1	velocity in the inlet channel (m/s)
v_2	velocity in the outlet channel (m/s)
$v_{i,j}$	the stoichiometric coefficient of the species k in reaction j (–)
$v_{i,k}$	the stoichiometric coefficient of the species k in reaction i (–)
v_{inl}	velocity at the filter inlet (m/s)
v_{out}	velocity at the filter outlet (m/s)
V_s	solid volume part of the DPF (m^3)
v_w	wall velocity (m/s)
v_{w1}	wall velocity in the inlet channel (m/s)
v_{w2}	wall velocity in the outlet channel (m/s)
$w_{g,k}$	mass fraction of the species k (kg/kg)
y_g	mole fraction (mol/mol)

Greek letters

α	ash content of the lubricant oil (%)
δ_{ac}	height of the ash cake (m)
δ_{sc}	height of the soot cake (m)
δ_{sd}	height of the soot depth layer (m)
δ_w	thickness of the filter wall (m)
μ	gas viscosity (Pa·s)
ρ_1	gas density in the inlet channel (kg/m^3)
ρ_2	gas density in the outlet channel (kg/m^3)
ρ_g	exhaust gas density (kg/m^3)
ρ_{inl}	gas density at the filter inlet (kg/m^3)
ρ_{out}	gas density at the filter outlet (kg/m^3)
ρ_s	DPF solid density (kg/m^3)
φ	DPF channel shape factor (–)
ζ_{inl}	pressure loss coefficient at the filter inlet (–)
ζ_{out}	pressure loss coefficient at the filter outlet (–)