Cool Particulate Regeneration
Global Clean Diesel

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Florida Polytechnic University
Brett Bailey, Global Clean Diesel
Motivation

Global Real World Emissions Reduction

Cool Particulate Regeneration (CPR)

- **Cost Saving** by Reduction in Engine and Aftertreatment Complexity, Size, and Weight.

- **Fuel Economy Improvement** - Regeneration Utilizes Unused Vehicle Kinetic Energy during Braking Conditions.

- **Real World Emissions Enhanced** - Quicker Light off of SCR Catalyst and Reduction of Particulate Number (PN#) emissions

- **Performance and Drivability** - Richer Air/Fuel Ratio Acceleration

- **Emerging Markets** - Ultra Low Cost Mechanical Engine (High Particulate Matter (PM)) and Fuel Tolerant Technology (Sulfur Tolerant) Solution


- **Future Powertrain** - Hybrid, Exhaust Energy Recovery (EER) and Stop/Start enabler. Regeneration within Engine Operation
Cool Particulate Regeneration Fundamentals

1. Filling
2. Pressurizing to Regeneration Set Point
3. Removing Particulate by Back Flushing Filter

Diesel Particulate Filter (DPF)
Inner Workings (Single Channel)

Particulate Matter (Black Smoke) Filtered

Agglomereated Particles Removed from Filter
Cool Particulate Regeneration™, CPR™

How it works

12 L storage volume will allow Particulate Matter to be stored and removed during oil change intervals. Particulate matter reintroduction into the filter during passive regeneration conditions testing is being conducted.

- Regeneration Pressure

Please View in Slide Show Mode to view animation

DOC – Diesel Oxidation Catalyst  DPF – Diesel Particulate Filter  LNT – Lean NOx Trap
CPR Demonstration Vehicle

Regeneration Valve Opened at Pressure Set Point

CPR System Installed

Closing of Volkswagen Exhaust Flapper to Initiate CPR Regeneration Pressure Buildup

CPR Regeneration Release Completed in Milliseconds

Total CPR Regeneration Completed within Seconds - System Returned to Normal Operation
Modified Jetta Hardware
Cost Reduction Enables Next Generation

Emerging Market Diesel Engine

Hybridization of the Diesel in Developed Markets for CO₂

CPR

Too Costly Poor Real World Emissions
EU LDVs Diesel Emissions Cost Ever Increasing

- Diesel Engine Costs Allowing Gasoline and Electric Vehicle traction in the market place
- CPR DPF $337
- DPF/SCR Combined ~$306
- Mechanical/Low Press Common Rail ~$337
- EGR Removal

Table ES-1 Incremental costs for LDVs meeting European standards (2010 dollars)

<table>
<thead>
<tr>
<th>ENGINE TYPE</th>
<th>VEHICLE CLASS</th>
<th>EURO 1 (BASELINE)</th>
<th>EURO 1 TO EURO 2</th>
<th>EURO 2 TO EURO 3</th>
<th>EURO 3 TO EURO 4</th>
<th>EURO 4 TO EURO 5</th>
<th>EURO 5 TO EURO 6</th>
<th>NO CONTROL TO EURO 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>4 cylinders Vd = 1.5 L</td>
<td>$142</td>
<td>$63</td>
<td>$122</td>
<td>$25</td>
<td>$10</td>
<td>--</td>
<td>$362</td>
</tr>
<tr>
<td>Gasoline</td>
<td>4 cylinders Vd = 2.5 L</td>
<td>$232</td>
<td>$3</td>
<td>$137</td>
<td>$15</td>
<td>$30</td>
<td>--</td>
<td>$417</td>
</tr>
<tr>
<td>Diesel</td>
<td>4 cylinders Vd = 1.5 L</td>
<td>$56</td>
<td>$84</td>
<td>$337</td>
<td>$145</td>
<td>$306</td>
<td>$471</td>
<td>$1,399</td>
</tr>
<tr>
<td>Diesel</td>
<td>4 cylinders Vd = 2.5 L</td>
<td>$56</td>
<td>$89</td>
<td>$419</td>
<td>$164</td>
<td>$508</td>
<td>$626</td>
<td>$1,862</td>
</tr>
</tbody>
</table>
Emerging Market Main Engine
Developed Country Hybrid Diesel

Table 5. In-cylinder control and OBD costs.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel system, common rail or extra with respect to unit injector systems</td>
<td>$750 + 10% for each successive standard</td>
</tr>
<tr>
<td>VGT (extra cost with respect to turbocharger)</td>
<td>$370</td>
</tr>
<tr>
<td>EGR system</td>
<td>$439</td>
</tr>
<tr>
<td>EGR intercooler</td>
<td>$108 ($85-130)</td>
</tr>
<tr>
<td>Full OBD</td>
<td>$425 ($350-$500)</td>
</tr>
</tbody>
</table>
Computational Fluid Dynamics (CFD) Analysis of CPR on the Volkswagen Jetta TDI
What is Florida Polytechnic University?

- Established in 2014 and regionally accredited in 2017, Florida Polytechnic University is a science, technology, engineering, and mathematics (STEM) focused university.

- Florida Polytechnic University has a IBM Supercomputer which was utilized in unison with Converge Science CFD to complete this project.
Background

- The success of GCD’s marketing demonstrations put the project on hold until May of 2018. GCD’s success, in the Indian market, shifted the focus to low speed operation.
- Limited testing, under Indian low load, demonstrated a build up of backpressure.
- CFD analysis of the Jetta’s CPR began in the summer of 2018 to gain a better understanding of CPR regeneration.
- The CFD analysis revealed that the regenerations were suffering from several flow issues.
Flow Challenges

• Design modifications were limited by packaging constraints
• The off center engine exhaust outlet creates a bias to one side of the filter during reverse flow.
Flow Challenges

- Design modifications were limited by packaging constraints
- The off center engine exhaust outlet creates a bias to one side of the filter during reverse flow.
- The bottom of DPF is close to the exhaust which restricts the flow to the right creating a left flow bias.
Flow Challenges

- Design modifications were limited by packaging constraints.
- The off center engine exhaust outlet creates a bias to one side of the filter during reverse flow.
- The bottom of DPF is close to the exhaust which restricts the flow to the right creating a left flow bias.
- Additionally, his lip further restricts flow on the right side.
Our Solutions

• Thus, given the previously stated design challenges, simply attaching a CPR system to the Jetta does not achieve our development goal.

• The CFD simulations suggest that certain parts of the filter receive less flow than others, reducing the effectiveness of regeneration.

• We propose a 20% reduction of filter volume and a slight design modification to allow for more uniform flow.
Our Solutions (cont.)

Before

Filter length reduced by 46 MM

After

Lip length reduced by 13 MM
Our Solutions (cont.)

• With this new filter design modeled and simulated, we’ve addressed two solutions that represent two opposites sides of a spectrum. These two being with no vacuum and with a vacuum. However many possible solutions exist within these two bounds.

• Solution 1: Simply increase the regeneration pressure.

• Solution 2: Pull a vacuum, in the storage tank, to keep regeneration pressures low.
Solution 1
(no vacuum)

• A 17 liter storage tank and a 66 mm Poppet valve were mounted to the top of the oxidation catalyst.
Solution 1
(no vacuum)

• Then, the butterfly valve, already installed for EGR, was closed to pressurize the system (not including the 17 liter tank) to 240 kPa gauge.
No Vacuum Results
No Vacuum Results
No Vacuum Results
Solution 1 (no vacuum) Conclusion

• The particle traces demonstrate a successful regeneration in 1.26 s.
• The system takes exactly 1.16 s to build up pressure.
• The system takes 0.1 s to complete the regeneration.
Solution 1 (no vacuum) Conclusion

Advantages:
• Very simple
• Low cost
• Effective

Disadvantages:
• Requires higher regeneration pressure

We envision this solution being used on everyday cars and large vehicles.
Solution 2
(vacuum)

- The design is identical, the system was pressurized (not including the 17 litre tank) to 124 KPA. Then, the pressure in the 17 litre tank and the Poppet value was brought down to -69 KPA.
Vacuum Results
Vacuum Results
Solution 2 (vacuum) Conclusion

- The flow is mostly uniform and the particle traces demonstrate a successful regeneration in 0.5 s.
- The system takes 0.4 s to build up pressure.
- The system takes 0.1 s to complete the regeneration.
Solution 2 (vacuum) Conclusion

Advantages:
• Better distribution of flow
• Faster regeneration

Disadvantages:
• More complex
• More expensive

We envision this solution being used on luxury cars where efficiency is important and cost is not as much of an issue.
Final Thoughts On CFD

• We overcame the challenges and with CFD we were able to demonstrate it is possible to implement CPR in the Volkswagen Jetta TDI.

• These solutions were also capable of no passive regeneration conditions with a minor design change of the filter.

• The CPR regeneration is quick and efficient requiring no thermal active regeneration.
Cool Particulate Regeneration
Unsteady 1D Code

Quickly Research and Develop new CPR system demonstrations
## CPR 1D Modeling Tests

<table>
<thead>
<tr>
<th>Test #</th>
<th>RegenP</th>
<th>Valve</th>
<th>Tank</th>
<th>RevDist</th>
<th>Delta P</th>
<th>Annulus Required</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kPa</td>
<td>mm</td>
<td>l</td>
<td>kPa</td>
<td>l</td>
<td></td>
</tr>
<tr>
<td>Test 1</td>
<td>240</td>
<td>46</td>
<td>10.2</td>
<td>0.164</td>
<td>17.15</td>
<td>Y</td>
</tr>
<tr>
<td>Test 2</td>
<td>340</td>
<td>46</td>
<td>10.2</td>
<td>0.22</td>
<td>33.4</td>
<td>Y</td>
</tr>
<tr>
<td>Test 3</td>
<td>340</td>
<td>46</td>
<td>15.4</td>
<td>0.269</td>
<td>58</td>
<td>Y</td>
</tr>
<tr>
<td>Test 4</td>
<td>240</td>
<td>66</td>
<td>15.4</td>
<td>0.1843</td>
<td>24</td>
<td>Y</td>
</tr>
<tr>
<td>Test 5</td>
<td>340</td>
<td>66</td>
<td>15.4</td>
<td>0.269</td>
<td>58</td>
<td>?</td>
</tr>
<tr>
<td>Test 6</td>
<td>340</td>
<td>66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Test 1 Baseline Arrangement
240kPa (20psi) 10.2l (2.75gal) Holding
46mm Regen Valve

Base Holding Tank Size (10L)
Regeneration through an Annulus Design
Annulus Design or Outlet between DOC and DPF required for low Loads

- 0.164 m reverse flow distance
- 17.2kPa Delta P pressure
- 9 m/s reverse flow velocity
- 86% reversed flowed out of the filter
Test 2 Baseline Arrangement with Increased Pressure
340kPa (35psi) 10.2l (2.75gal) Holding
Base Holding Tank Size (10L)
Regeneration through an Annulus Design
Test 3 340kPa (35psi) 15.4l (4gal) Holding
Base Holding Tank Size (10L)
Regeneration through an Annulus Design
Test 4 240kPa (20psi) 10l Holding

Base Holding Tank Size (10L)

Regeneration through an Annulus Design
Test 5 240kPa (20psi) 15.4l Holding
Base Holding Tank Size 15.4L (4 gal)
Baseline Test 6 340kPa (35psi) Regen Pres

66mm Regeneration Valve Diameter
15.4 (4 gal) Holding Tank
Baseline 340kPa (35psi) Regen Pres

66mm Regeneration Valve Diameter

20.6 (5.5gal) Holding Tank
Baseline 140kPa (20psi) Regen Pres

46 & 66mm Regeneration Valve Diameters

10.3L, 12.8, 15.4 (2.75, 3.4, & 4 gal) Holding Tank
DPF Length

DPF+DOC Length

DPF+DOC+ Length

Lnth=8  - 10.3l (2.7gal) Tank
Lnth=10 - 15l (3.4 gal) Tank
Lnth=12 - 15l (4gal) Tank

Regen 46mm

Regen 66mm

Cumulative Reverse Flow Distance

X: 0.4593, Y: -0.1607
X: 0.4612, Y: -0.1769
X: 0.4627, Y: -0.191
Conclusions

- Retrofitting of millions of Volkswagen Jetta TDI and similar vehicles is possible
  - Power, Response, Emissions, and Efficiency can be achieved
- 3D Modeling Demonstrating Flow Concerns
- 1D Modeling Demonstrating Need for Reduced Translation Distance
India Bharat VI Emissions
Opportunity for Ford Motor Company

- India is a double digit growth market for Ford. It is a cost driven market requiring simple maintenance.
- Thermal Regeneration Expected to be Challenged by Low Speeds and Start/Stop Operation of India
- Success in India Replicated in Europe and US Diesel Hybrids

BS VI Emissions – RDE w/ India Low Speed
Low Cost by Potential Removal of HP CRD, EGR, DOC, SCR Substrate, and ASC Catalyst
Hybrid, Start-Stop, Exhaust Energy Recovery Compatible
Fuel Economy Improvement Operation with BS IV Fuel and Oil and Biodiesel
Ash Maintenance Eliminated or Reduced
Unsustainable PGM Reduced or Eliminated
Class Leading Performance – Power and Drivability
Please Contact for Additional Information

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Email: brett.bailey@ivhco.com
Web: www.ivhco.com
240kPa Slightly Oversized Settling Tank

Baseline without Vacuum

17 L (4.5 Gal) Tank

46mm Valve
Demonstration of Acceptable EU Retrofit 240kPa Slightly Oversized Settling Tank Plugging of Filter and CPR Adaptability

17 L (4.5 Gal) Tank
46mm Valve
250kPa (35psi) Regen Pres

46 & 66mm Regeneration Valve Diameters

10.3L, 12.8, 15.4 (2.75, 3.4, & 4 gal) Holding Tank
250kPa (35psi) Regen Pres
46 & 66mm Regeneration Valve Diameters
10.3L, 12.8, 15.4 (2.75, 3.4, & 4 gal) Holding Tank
240kPa Regen Press

46mm Regen Valve Dia

Parametric Study of Settling tank Size
Cumulative Reverse Flow Distance

4 gal settling tank 35psi Regen Press

-0.18
-0.16
-0.14
-0.12
-0.1
-0.08
-0.06
-0.04
-0.02
0.43 0.435 0.44 0.445 0.45 0.455 0.46 0.465

Time [sec]

Reverse Flow Distance [m]
Cumulative Reverse Flow Distance

Time [sec]

Reverse Flow Distance [m]

Cumulative Reverse Flow Distance

T11, VlvA=2.58, Lnth=12

X: 0.495
Y: -0.1836

X: 0.4944
Y: -0.1858

X: 0.4993
Y: -0.1754

T11, VlvA=2.58, Lnth=12
regen=0.4576

T11, VlvA=2.58, Lnth=12
regen=0.45781

T11, VlvA=2.58, Lnth=12
regen=0.45716
240kPa 10l Holding

Base Holding Tank Size (12L)
240kPa 15l Holding

46mm Regeneration valve
220kPa 15l Holding
300kPa 15l Holding
Pressure Profile

- P100, VlvA=1.8, Lnth=16.5  regen =0.36
- P9, VlvA=1.8, Lnth=16.5  regen =0.36
- P100, VlvA=2.56, Lnth=16.5  regen =0.36
- P9, VlvA=2.56, Lnth=16.5  regen =0.36
- P100, VlvA=3.32, Lnth=16.5  regen =0.36
- P9, VlvA=3.32, Lnth=16.5  regen =0.36
- P100, VlvA=4.08, Lnth=16.5  regen =0.36
- P9, VlvA=4.08, Lnth=16.5  regen =0.36
- P100, VlvA=1.8, Lnth=20.5  regen =0.36
- P9, VlvA=1.8, Lnth=20.5  regen =0.36
- P100, VlvA=2.56, Lnth=20.5  regen =0.36
- P9, VlvA=2.56, Lnth=20.5  regen =0.36
- P100, VlvA=3.32, Lnth=20.5  regen =0.36
- P9, VlvA=3.32, Lnth=20.5  regen =0.36
- P100, VlvA=4.08, Lnth=20.5  regen =0.36
- P9, VlvA=4.08, Lnth=20.5  regen =0.36
- P100, VlvA=1.8, Lnth=24.5  regen =0.36
- P9, VlvA=1.8, Lnth=24.5  regen =0.36
- P100, VlvA=2.56, Lnth=24.5  regen =0.36
- P9, VlvA=2.56, Lnth=24.5  regen =0.36
- P100, VlvA=3.32, Lnth=24.5  regen =0.36
- P9, VlvA=3.32, Lnth=24.5  regen =0.36
- P100, VlvA=4.08, Lnth=24.5  regen =0.36
- P9, VlvA=4.08, Lnth=24.5  regen =0.36
- P100, VlvA=1.8, Lnth=28.5  regen =0.36
- P9, VlvA=1.8, Lnth=28.5  regen =0.36
- P100, VlvA=2.56, Lnth=28.5  regen =0.36
- P9, VlvA=2.56, Lnth=28.5  regen =0.36
delta Pressure Profile

-20
-15
-10
-5
0
5
10

0.36 0.37 0.38 0.39 0.4

delta Pressure [kPa]

Time [sec]
Reverse Flow Distance [m]

Cumulative Reverse Flow Distance

Time [sec]

T11, VlvA=1.8, Lnth=8.5  t = 0.36
T11, VlvA=2.56, Lnth=8.5  t = 0.36
T11, VlvA=3.32, Lnth=8.5  t = 0.36
T11, VlvA=4.08, Lnth=8.5  t = 0.36
T11, VlvA=1.8, Lnth=12.5  t = 0.36
T11, VlvA=2.56, Lnth=12.5  t = 0.36
T11, VlvA=3.32, Lnth=12.5  t = 0.36
T11, VlvA=4.08, Lnth=12.5  t = 0.36
T11, VlvA=1.8, Lnth=16.5  t = 0.36
T11, VlvA=2.56, Lnth=16.5  t = 0.36
T11, VlvA=3.32, Lnth=16.5  t = 0.36
T11, VlvA=4.08, Lnth=16.5  t = 0.36
T11, VlvA=1.8, Lnth=20.5  t = 0.36
T11, VlvA=2.56, Lnth=20.5  t = 0.36
T11, VlvA=3.32, Lnth=20.5  t = 0.36
T11, VlvA=4.08, Lnth=20.5  t = 0.36
T11, VlvA=1.8, Lnth=24.5  t = 0.36
T11, VlvA=2.56, Lnth=24.5  t = 0.36
T11, VlvA=3.32, Lnth=24.5  t = 0.36
T11, VlvA=4.08, Lnth=24.5  t = 0.36
T11, VlvA=1.8, Lnth=28.5  t = 0.36
T11, VlvA=2.56, Lnth=28.5  t = 0.36
T11, VlvA=3.32, Lnth=28.5  t = 0.36
T11, VlvA=4.08, Lnth=28.5  t = 0.36

X: 0.4016
Y: -0.2205
Reverse Flow Distance [m]

Cumulative Reverse Flow Distance

X: 0.4016
Y: -0.2205

X: 0.3998
Y: -0.2089

X: 0.3977
Y: -0.1948

X: 0.3953
Y: -0.1775

X: 0.3919
Y: -0.1556

X: 0.3878
Y: -0.1268
%Specify the complete path where the executable is located
path_exe = 'C:\Program Files (x86)\GFSSP701\';
%Specify the complete path where the case files are located
%Files required in the directory include:
%[case]IN.dat,ExhBrake.dat,RegenValve.dat,
path_case = 'C:\Users\brett\Desktop\1dCode\Jetta1DMod2\';
name_case = 'Jetta220kPa4inafterDPF'; %name of the case, used to generate file names
Run_steady = 1; %Do you want to perform a steady simulation? 0=No 1=Yes
Run_unsteady = 1; %Do you want to perform an unsteady simulation? 0=No 1=Yes % if both steady and unsteady simulations are performed, the steady % simulation will occur first.

%OUTPUT OPTIONS
SIoutput = 1; %set to 0 for english units on plots, or 1 for SI
PressurePlot = [100,9]; % enter the NODE numbers for the pressures you want to plot
VelPlot = [70]; % enter the BRANCH numbers for the velocities you want to plot
MFPlot = [70]; % enter the BRANCH numbers for the mass flows you want to plot
dPPlot = [70]; % enter the BRANCH numbers for the Pressure Difference you want to plot
DistRevF = [70]; % enter the BRANCH numbers for the reverse flow distance you want to plot
TargetPressure = 220; %kPa %note: set in kPa for SIoutput=1, in psi for SIoutput=0
dP = 1.0; %kPa %accuracy desired for target pressure match, set to high number to skip
tGuessSav = 0.36; % initial guess for regen valve timing
FNode = 3; % please enter the node entry position for the intereated pressure, i.e. 3 = third entry in pressure output

%Note: these inputs are in english units
Variable = 'VlvA'; %specify for output labeling
Rangel = [1.8:0.76:4.08];

Variable2 = 'Lnth';
Range2 = [8.5:4:28.5]; % currently set to valve area
Volkswagen Jetta DPF Outlet
2011 Volkswagen Jetta Sportwagen Emissions System
Cool Particulate Regeneration™, CPR™
How it works

12 L storage volume will allow Particulate Matter to be stored and removed during oil change intervals. Particulate matter reintroduction into the filter during passive regeneration conditions testing is being conducted.

- Regeneration Pressure

Please View in Slide Show Mode to view animation

DOC – Diesel Oxidation Catalyst  DPF – Diesel Particulate Filter  LNT – Lean NOx Trap
Table 4-17: Estimated costs of emission control technologies for European diesel LDV, V_d > 2.0 L

<table>
<thead>
<tr>
<th>REGULATION</th>
<th>EURO 1</th>
<th>EURO 2</th>
<th>EURO 3</th>
<th>EURO 4</th>
<th>EURO 5</th>
<th>EURO 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>REGULATED POLLUTANTS</td>
<td>(NO_x, HC/PM/CO)</td>
<td>(NO_x, HC/PM/CO)</td>
<td>(NO_x, PM/CO)</td>
<td>(NO_x, NO_x/CO)</td>
<td>(NO_x, NO_x/PM/CO)</td>
<td>(NO_x/PM/CO)</td>
</tr>
<tr>
<td>EMISSION LEVELS, g/km</td>
<td>1.13/0.36/0.17</td>
<td>0.70/0.08/0.11</td>
<td>0.55/0.05/0.14</td>
<td>0.25/0.02/0.05</td>
<td>0.38/0.005/0.15</td>
<td>0.89/0.0045/0.15</td>
</tr>
</tbody>
</table>

1. Aftertreatment systems

- Assuming a 4-cyl engine, V_d = 2.5 liters

<table>
<thead>
<tr>
<th>Technology</th>
<th>EURO 1</th>
<th>EURO 2</th>
<th>EURO 3</th>
<th>EURO 4</th>
<th>EURO 5</th>
<th>EURO 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of aftertreatment systems (h)</td>
<td>$60</td>
<td>$119</td>
<td>$414</td>
<td>$578</td>
<td>$686</td>
<td>$830</td>
</tr>
</tbody>
</table>

2. Fixed costs (R&D, tooling, certification)

<table>
<thead>
<tr>
<th></th>
<th>EURO 1</th>
<th>EURO 2</th>
<th>EURO 3</th>
<th>EURO 4</th>
<th>EURO 5</th>
<th>EURO 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$26</td>
<td>$25</td>
<td>$51</td>
<td>$51</td>
<td>$51</td>
<td>$51</td>
</tr>
</tbody>
</table>

3. Total cost of emission control tech (3+4)

<table>
<thead>
<tr>
<th></th>
<th>EURO 1</th>
<th>EURO 2</th>
<th>EURO 3</th>
<th>EURO 4</th>
<th>EURO 5</th>
<th>EURO 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$56</td>
<td>$145</td>
<td>$564</td>
<td>$728</td>
<td>$1,356</td>
<td>$1,862</td>
</tr>
</tbody>
</table>

(a) Cost of rotary pump, HFFI pump, valves, common rail, and injectors. 50% of cost is charged to non-CO_2 regulated emissions.
(b) Single stage turbocharging assumed. 50% of cost is charged to non-CO_2 regulated emissions.
(c) Single loop EGR. 50% of cost is charged to non-CO_2 regulated emissions.
(d) Maximization of fuel economy and minimization of emissions by fuel injection strategies, air management, turbo, EGR.
(e) Research and development focused on improving combustion (fuel efficiency and emissions) through modeling (CFD) and experiments.
(f) See diesel aftertreatment detail.
(g) SCR cost includes the cost of dosage unit and tank. NH_3 slip catalyst included. NO_x sensor and H_2 catalyst not included in cost.
(h) The cost of aftertreatment systems includes a minimum of devices for control of HC, CO, PM and NO_x. The cost presented may vary depending on specific engine applications.
<table>
<thead>
<tr>
<th>DIESEL</th>
<th>4-CYL OR Vd=2.5 LITERS</th>
<th>6-CYL OR Vd=2.5 LITERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>REGULATION</td>
<td>TIER 2 BIN 5</td>
<td>TIER 2 BIN 5</td>
</tr>
<tr>
<td>INTRODUCTION YEAR</td>
<td>2009</td>
<td>2009</td>
</tr>
<tr>
<td>REGULATED POLLUTANTS</td>
<td>(NOₓ/PM/CO)</td>
<td>(NOₓ/PM/CO)</td>
</tr>
<tr>
<td>EMISSION LEVELS, G/KM</td>
<td>0.04/0.006/2.5</td>
<td>0.04/0.006/2.5</td>
</tr>
</tbody>
</table>

1. A/F control & engine-out emission
   - Assuming 4-cyl, Vd=2.0L
     - Fuel system - 50% of cost (a) $420
     - Turbocharger - 50% of cost (b) $150
     - Intercooler - 50% of costs (b) $32
     - VGT (extra cost) - 50% of costs (b) $50
     - EGR valves (c) $38
     - EGR cooling system (c) $58
   - Assuming 6-cyl, Vd=3.0L
     - Fuel system - 50% of cost (a) $459
     - Turbocharger - 50% of cost (b) $155
     - Intercooler - 50% of costs (b) $30
     - VGT (extra cost) - 50% of costs (b) $60
     - EGR valves (c) $38
     - EGR cooling system (c) $66

2. Aftertreatment systems
   - Diesel oxidation catalyst (DOC) (f) $78 $116
   - Diesel particulate filter (DPF) (f) $332 $468
   - Lean NOₓ trap (LNT) (f) $413 ($602)*
   - Selective catalytic reduction (SCR) (f, g) - $633**
   - Cost of aftertreatment systems (h) $823 $1,217

3. Total cost of hardware [1+2]
   - Vd=2.0 L $1,659 $2,035
   - Vd=3.0 L

4. Fixed costs (R&D, tooling, certification)
   - $51 $51

5. Total cost of emission control tech. [3+4]
   - Vd=2.0 L $1,610 $2,086
   - Vd=3.0 L

* Note: Cost numbers in parenthesis are informative, not added to final cost summation.
** SCR catalyst cost calculated with SVR corresponding to US requirements (SVR=2.0).
(a) Cost of rotary pump, HFP, pump, valves, common rail, and injectors. 50% of cost is charged to non-CO₂ regulated emissions.
(b) Single stage turbocharging assumed. 50% of cost is charged to non-CO₂ regulated emissions.
(c) Single loop EGR. 50% of cost is charged to non-CO₂ regulated emissions.
### Table 4-18 Estimated costs of emission control technologies for diesel passenger cars under US Tier 2-Bin 5 emission levels

<table>
<thead>
<tr>
<th>DIESEL</th>
<th>4-CYL OR Vd&lt;2.5 LITERS</th>
<th>6-CYL OR Vd&gt;2.5 LITERS</th>
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<tr>
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#### 1. A/F control & engine-out emission

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<tbody>
<tr>
<td>Fuel system - 50% of cost (a)</td>
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</tr>
<tr>
<td>Turbocharger - 50% of cost (b)</td>
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<td>$155</td>
</tr>
<tr>
<td>Intercooler - 50% of costs (b)</td>
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<td>$39</td>
</tr>
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<td>$66</td>
</tr>
<tr>
<td>Engine mapping and tuning (d)</td>
<td>R&amp;D</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Improvements on combustion chamber &amp; nozzle geometry (e)</td>
<td>R&amp;D</td>
<td>R&amp;D</td>
</tr>
</tbody>
</table>

#### 2. Aftertreatment systems

<table>
<thead>
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<th>Vd=3.0 L</th>
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<td>-</td>
<td>$633**</td>
</tr>
<tr>
<td>Cost of aftertreatment systems (h)</td>
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<td>$1,217</td>
</tr>
</tbody>
</table>

#### 3. Total cost of hardware [1+2]

- Vd=2.0 L: $1,559
- Vd=3.0 L: $2,035

#### 4. Fixed costs (R&D, tooling, certification)

- $51

#### 5. Total cost of emission control tech. [3+4]

- Vd=2.0 L: $1,610
- Vd=3.0 L: $2,086

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** SCR catalyst cost calculated with SVR corresponding to US requirements (SVR=2.0).

(a) Cost of rotary pump, HPFI pump, valves, common rail, and injectors. 50% of cost is charged to non-\(\text{CO}_2\) regulated emissions.

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(c) Single loop EGR. 50% of cost is charged to non-\(\text{CO}_2\) regulated emissions.
Packaging Space

Valve Size

<table>
<thead>
<tr>
<th>Low</th>
<th>High</th>
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</thead>
<tbody>
<tr>
<td>Low</td>
<td>Retrofit</td>
</tr>
<tr>
<td></td>
<td>Compact &amp; Luxury Vehicle</td>
</tr>
<tr>
<td></td>
<td>Commercial</td>
</tr>
</tbody>
</table>

Vacuum Assist

Higher Backpress

Vacuum Assist