New Emissions Regulations - Impact on Engine Design and Oil Formulation

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Overview of Topics

- Historical look at emissions regulations and the co-evolution of high performance diesel engines and their equally high performance lubricants
- Emission limit changes in 2002 will require new control technology - Exhaust Gas Recirculation (EGR)
- EGR - equipped engines will require new lubricants

Overview of Topics

- ASTM is working on new PC-9 category for EGR engines
- PC-9 development timing, costs, and alternatives
- Probable oil formulation impact of PC-9 tests
- Summary

Table One
U.S. EPA Diesel Engine Emission Standards

Year	1988	1991	1994	1998	2002
Unburned HC	1.3	1.3	1.3	1.3	1.3
NOx	10.7	5.0	5.0	4.0	2.0*
Carbon Monoxide	15.5	15.5	15.5	15.5	15.5
Particulate Matter	0.6	0.25	0.1	0.1	0.1

All values are measured in grams per brake horsepower-hour

* Alternate target is a total of 2.5 for combined NOx and non-methane hydrocarbons

Limits apply to engines at "end of useful life"

NOx Versus Particulate Matter Balancing Act

Reduce PM-Aggravate NOx

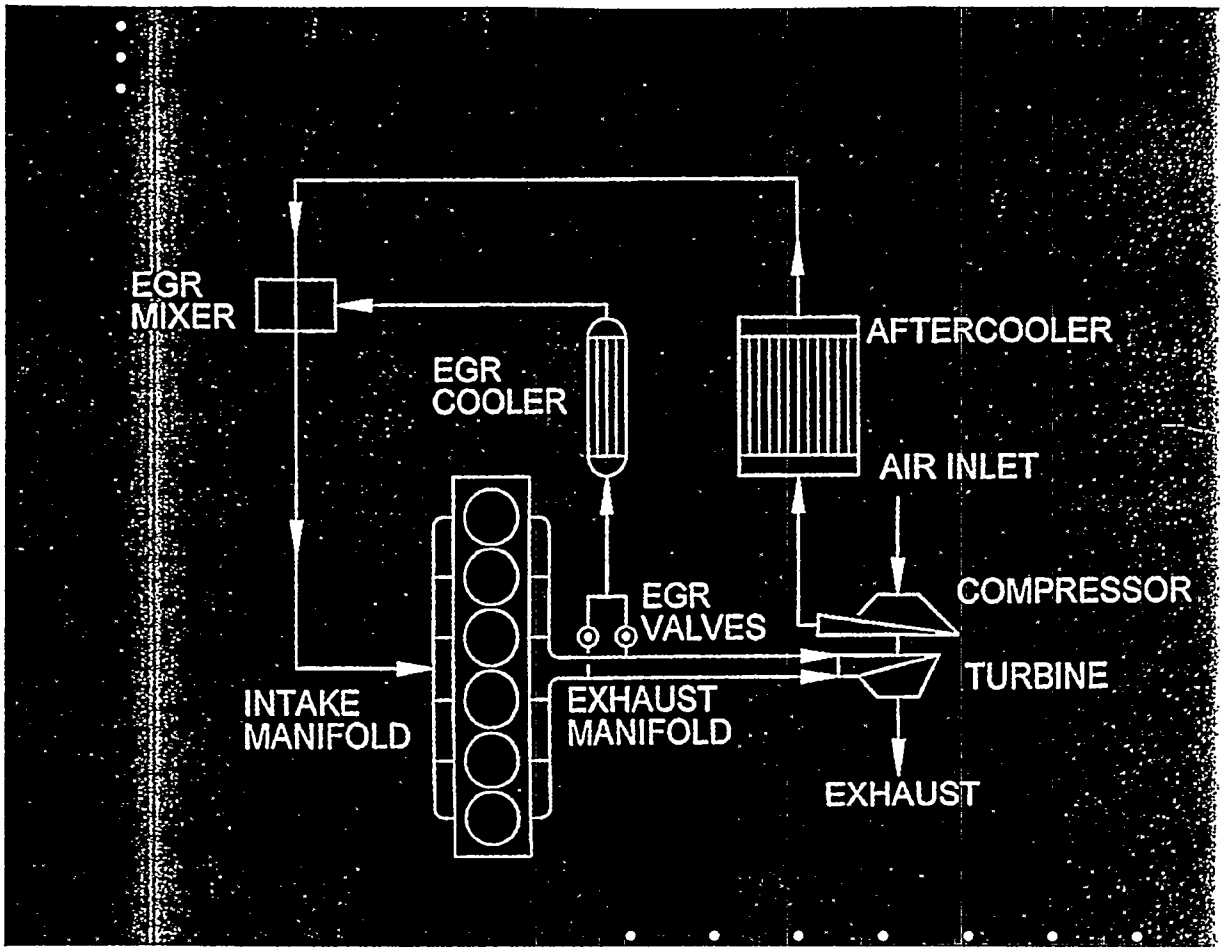
- Improved combustion
  - Inlet air swirl
  - High pressure injection
  - Advanced timing
  - Reduced crevice volume
- High peak temperature

Reduce NOx-Aggravate PM

- Less effective combustion
  - Retarded injection timing
- Lower peak temperature

New NOx Limit in October 2002

- NOx limit in EPA test cycle drops by 50%
  - Current 4.0 g/hp-h drops to 2.0 g/hp-h (or 2.5 incl HC)
- Cannot be met with existing NOx control technology
  - Beyond operational limit of retarded timing
- All engine manufacturers plan to use Exhaust Gas Recirculation (EGR) to meet 2002 NOx limits
  - EGR is expected to dramatically impact engine oil performance requirements



New Oil Category PC-9

- Anticipated performance needs of EGR-equipped engines is PC-9 driver
- Three new engine tests with EGR
  - Mack T-10 (Ring and Liner wear)
  - Cummins M11-EGR (Valve Train wear/Sludge/Filter Pressure)
  - Caterpillar 1Q (Piston Deposits)
- Performance parameters similar to CH-4 tests- T-9, M11, and 1P but using EGR
  - None of the new tests currently available

EGR...What's The Worry?

The combustion process:

- In the textbook
  - $C_xH_y + O_2 \Longrightarrow CO_2 + H_2O + \text{Heat}$
- In the real world
  - $\text{Fuel} + \text{Air} \Longrightarrow CO_2 + H_2O + \text{Heat} + CO + HC + NO_x + SO_x + \text{Particulate Matter} + ??$
  - At high temperatures not a problem
- Cooled EGR condenses nitric and sulfuric acids
  - Recirculated into engine power assembly

PC-9 Is Not Just Three New Tests

Current engine test proposal to define PC-9:

– Mack T-10	New test - $65,000
– Cummins M11-EGR	New test - $85,000
– Caterpillar 1Q	New test - $60,000
– Caterpillar 1N	CG-4 test - $22,000
– Mack T-8E	CH-4 test - $43,000
– John Deere JDQ-78A	New test - $60,000
– RFWT	CH-4 test - $12,000
– EOAT	CH-4 test - $ 7,000

Total, one time pass = $354,000

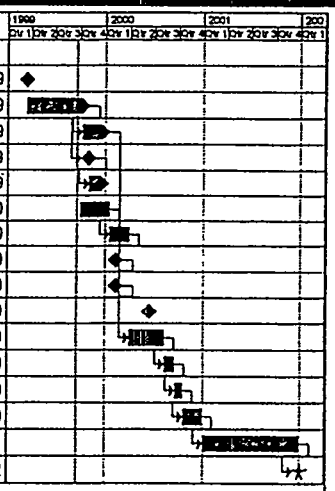
PC-9 Costs

- One time pass in just HD tests > $350,000
- Add in PCMO test costs > $500,000
  - To approve one core data set in one viscosity grade
  - Engine tests only - slight increase to include bench tests
- If testing volume is similar to CH-4 experience, PC-9 reformulation cost could approach $40 million
  - Reduced by about $3,000,000 if Sequence IIIF could be substituted for JDQ-78A

Summary of Events Required for PC-9 Licensing

Brent Shoffner 9/21/99

ID	Task Name	Start	Finish
1			
2	Define PC-9 Performance Parameters	3/16/99	3/16/99
3	Design Prec. Mtx. Finalized	3/17/99	10/7/99
4	PC-9 Funding MOU Signed	10/8/99	12/20/99
5	Designate Base Stocks for Prec. Mtx.	11/1/99	11/1/99
6	Select additive suppliers for Prec. Mtx.	11/2/99	12/15/99
7	Identify Test Oils (with validation)	10/1/99	1/17/00
8	Blend Prec. Mtx. Oil Formulations	1/18/00	3/29/00
9	Final Acceptance of New Engine Tests *	2/9/00	2/9/00
10	Final Acceptance of Test Parameters	2/9/00	2/9/00
11	PC-9 Demonstration Oil Is Validated	6/15/00	6/15/00
12	PC-9 Precision Matrix Testing	3/30/00	8/9/00
13	Precision Matrix Data Analysis	8/10/00	9/15/00
14	HDEOCP Post Matrix Test Acceptance	9/18/00	10/17/00
15	Finalize Pass/Fail Criteria (Sub B Mtg)	10/18/00	12/29/00
16	New Product Development	1/1/01	12/31/01
17	API Licensing Allowed	1/1/02	1/1/02



* Acceptance of each engine test (by HDEOCP) for discrimination and preliminary precision prior to starting the precision matrix. What is the criteria? Minimum of one test on 1005-1 and one on a prototype PC-9 oil?

PC-9 Alternatives

- Past history suggests PC-9 will not be developed in time for a January 1, 2002 API first licensing
- EPA emission deadline is firm
  - EGR required to meet NOx limits
  - New oils required to protect engines
- OEM specifications already exist
  - Mack has EO- X oil approval lists
  - Cummins has CES 200XX oil specifications
  - Will be upgraded as required to protect engines

PC-9 Oil Formulation Implications

- EGR and its attendant acid formation will stress the acid neutralization capability of oils
  - More TBN?
  - More or less reactive TBN?
  - A balance of both?
- Increased soot loading with PC-9 tests will require increased dispersant potency
- High soot also leads to wear concerns
  - Possible need for high anti-wear treats at odds with low phosphorus / catalyst compatibility for light duty oils

Continued Formulation Implications

- "Backward compatibility" has always been a key part of the API oil category system
  - Newer / higher quality oils can be recommended for use in engines which originally called for lower categories
- Potential need for higher TBN/SASH oils to meet PC-9 performance could cause difficulties
  - The 1P test in CH-4 is very difficult for high SASH oils
- Industry guidance is that protection of EGR engines outweighs backward compatibility

Summary

- EPA emission regulations reduce NOx in 2002
- New limits will require EGR
- EGR will recirculate acids into the engine
- PC-9 under development for EGR engines
  - Many tests / high cost to reformulate

Summary

- Very tight time schedule, delay likely
  - OEM's will do whatever is required to protect engines
- PC-9 oils expected to differ significantly from current CH-4/SJ formulations

Summary (continued)

- Although the development process will be difficult, it is likely that the combination of EGR-equipped engines and PC-9 quality lubricants will successfully continue the historic co-evolution of high performance diesel engines and their equally high performance oils.