Stoichiometric Gasoline HCCI:

Control, Efficiency, Catalysts, and Cetane Improvers

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Background

- Negative valve overlap variable valve actuation (NVO VVA) with no throttling can produce low NOx and good efficiency in low to mid load range and mid speed range for gasoline engines
- Combustion phasing and stability is controlled by exhaust valve closing angle (EVCA), which controls amount of EGR and recompression heating of cylinder
- This type of engine normally runs slightly lean, but should be able to run stoichiometric
- Stoichiometric operation enables three way catalysts (TWC) and assists mode transitions to conventional combustion with high or low EGR
- Fully flexible engines should be able to achieve HCCI, PCCI, lean burn, and conventional combustion, giving engine designer more options and allowing mode switching
  - Should I say 'partially stratified HCCI' instead of 'PCCI' when referring to gasoline engines?

Purpose of research

- Evaluate ability of negative valve overlap gasoline HCCI engine to maintain stoichiometric combustion and evaluate
  - Control
  - Efficiency
  - Effectiveness of TWC for emissions control
  - Effect of catalyst aging
  - Effectiveness of cetane improvers for ignition control
- Note that we have not answered all the questions, so I will ask a few during this presentation
- Research supported by DOE fuels program. Steve Goguen, Kevin Stork, and Dennis Smith are team leaders at DOE.

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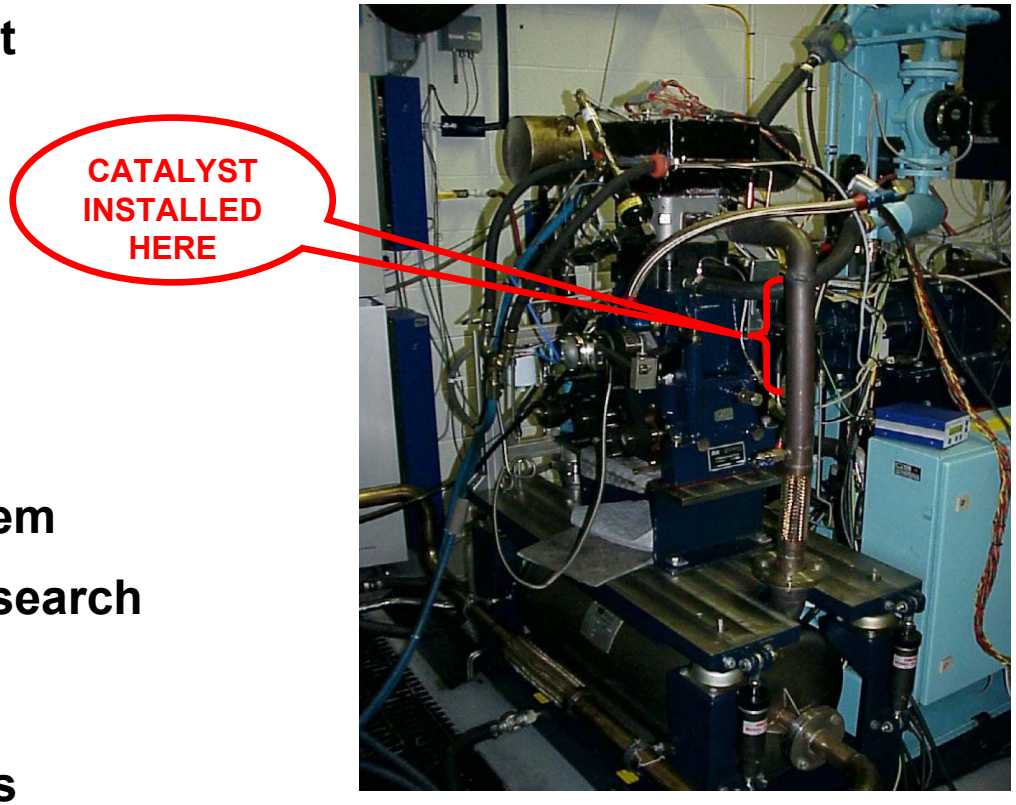
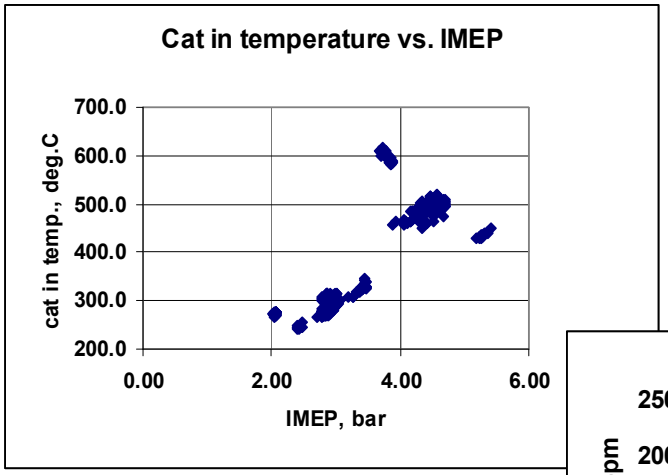
The engine

- AVL single cylinder HCCI engine
  - Located in Plymouth, MI
  - Used under subcontract
- Engine parameters
  - 3 valve hemi head
  - Sturman VVA system
  - 487 cc, 11.34 CR, NA
  - Spark, no spark
  - PFI and DI
  - Open loop control system
- Widely used in previous research
  - ORNL
    - Spark HCCI
    - Gasoline fuel effects
    - Non-linear dynamics analysis and control of combustion
  - CRC AVFL13 fuel effects

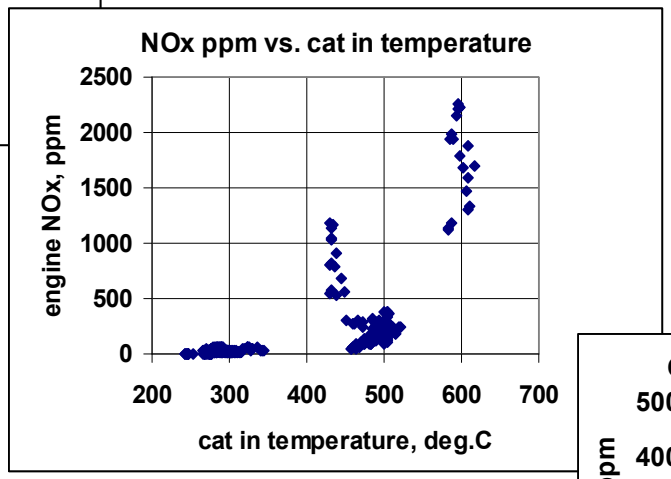


Operating characteristics of engine (all data)

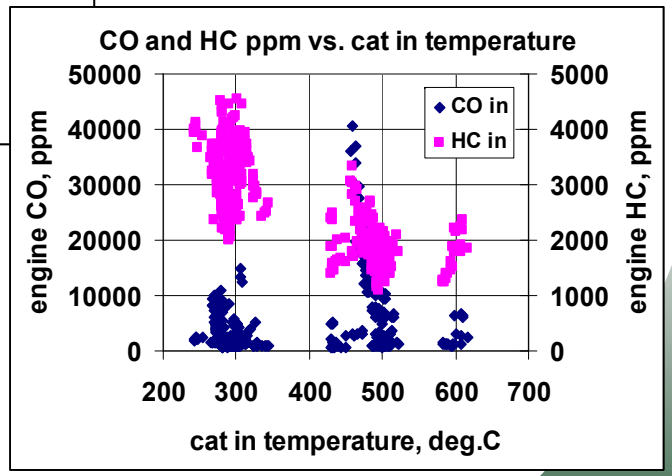


Low cat temperatures at low loads (due to single cylinder engine or inherent to HCCI?)

High NOx at higher cat temperatures (reduced levels of retained exhaust)



High HC at light load



IT LOOKS LIKE SOME FORM OF CATALYST WILL BE NEEDED FOR ALL OPERATING POINTS

Three way catalyst used

- Supplied by Catalytic Solutions (Oxnard, CA)
  - 2005 model year release production catalyst
    - Pt/Pd/Rh = 8/50/8 g/ft3
    - Base-metal promoter package
    - High-Zr OSM, alumina support
    - Two-layer construction
    - 600 cpsi
- 2” x 6” cores
  - 0.63 catalyst volume to engine displacement ratio
  - Installed about 12” downstream from cylinder head
  - Catalysts run in two conditions
    - Un-aged – as received
    - Aged – 24 hours at 1000 deg.C in argon + 10% H2O
      - Later identified as a severe oxidation aging condition
      - We did not ‘reactivate’ PGM after oxidation
- Special thanks to Steve Golden and Svetlana Iretskaya of Catalytic Solutions for catalyst samples and advice

The fuels

- **Indolene**
  - **97.0 RON, 88.8 MON, 8.2 sensitivity**
- **Indolene + 3000 ppm di-tert butyl peroxide (DTBP)**
  - **93.0 RON, 88.8 MON, 4.2 sensitivity**
- **Indolene + 3000 ppm ethyl hexyl nitrate (EHN)**
  - **90.8 RON, 84.6 MON, 6.2 sensitivity**

- **Special thanks to Paul Richards of Innospec for discussion and samples of cetane improvers**

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Modeling of data set

- Independent variables are RPM, fuel pulse width, EVCA, MAP, RON, sensitivity, and added N (from EHN)
- Used PCA and built model into simulator format for ease of use
  - Simulator used to 'repeat' experiments for parametric studies
- Model is first order with interactions and dependent variables transformed as logs
  - 18 eigenvectors, 25 terms each
- Catalyst light-off and lambda effects required special functions
  - Logistic function for HC and CO
  - Log normal (right skewed) for NOx
- Modeling work by Robert W. Crawford of Rincon Ranch Consulting

Dependent variables

Model	R2
ISFC	0.80
NOx	0.98
IMEP	0.99
Lamda	0.86
CA1090	0.75
MFB10	0.86
MFB50	0.85
MFB90	0.62
Noise	0.91
dPdCA	0.88
COVPct	0.91
HC	0.88
CO	0.63
cat T	1.00

Control of engine for Stoichiometric HCCI

- Engine is 'nominally' stoichiometric, but generally slightly lean
- It was very difficult to control to exact stoichiometric operation
  - Engine has open loop control
  - Unstable operation at lambda = 1 with high COV, CO, and HC
  - Some uncertainty about catalyst condition due to over-temperature events
  - Melted 3 catalysts during program by lean operation after rich misfire
- Required multiple modes to cover desired catalyst operating conditions
  - 8 different speed / fueling combinations
  - Spark assist required for some conditions
  - Mostly PFI, but DI required for some conditions
  - EVCA ranged from 232 to 342 ATDC
  - Use of throttle
- No single mode was able to cover a wide operating range
- Throttle and fuel additives were used to open up normal relationships between EVCA, lambda, and MFB50

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Operating ranges achieved

- Managed to cover a wide range of operating conditions
  - IMEP: 2.0 to 5.4 bar
  - 1600 and 2400 rpm
  - IMP: 1.0 to 0.5 bar absolute
  - Lambda: 0.88 to 1.25
  - MFB50: 0 to 13 ATDC
  - Cat in Temperature: 240 to 620 deg.C
  - NOx: 0.5 to 2260 ppm
- Experiment evolved as we went
  - It was more difficult to cover this range than we expected
  - 568 data points, consisting of pockets of data with very wide spaces in between and very non-orthogonal
  - Some conditions exhibited high COV and/or drifting
  - Difficult to model the data
  - Plus, TWC catalyst behavior is also inherently non-linear

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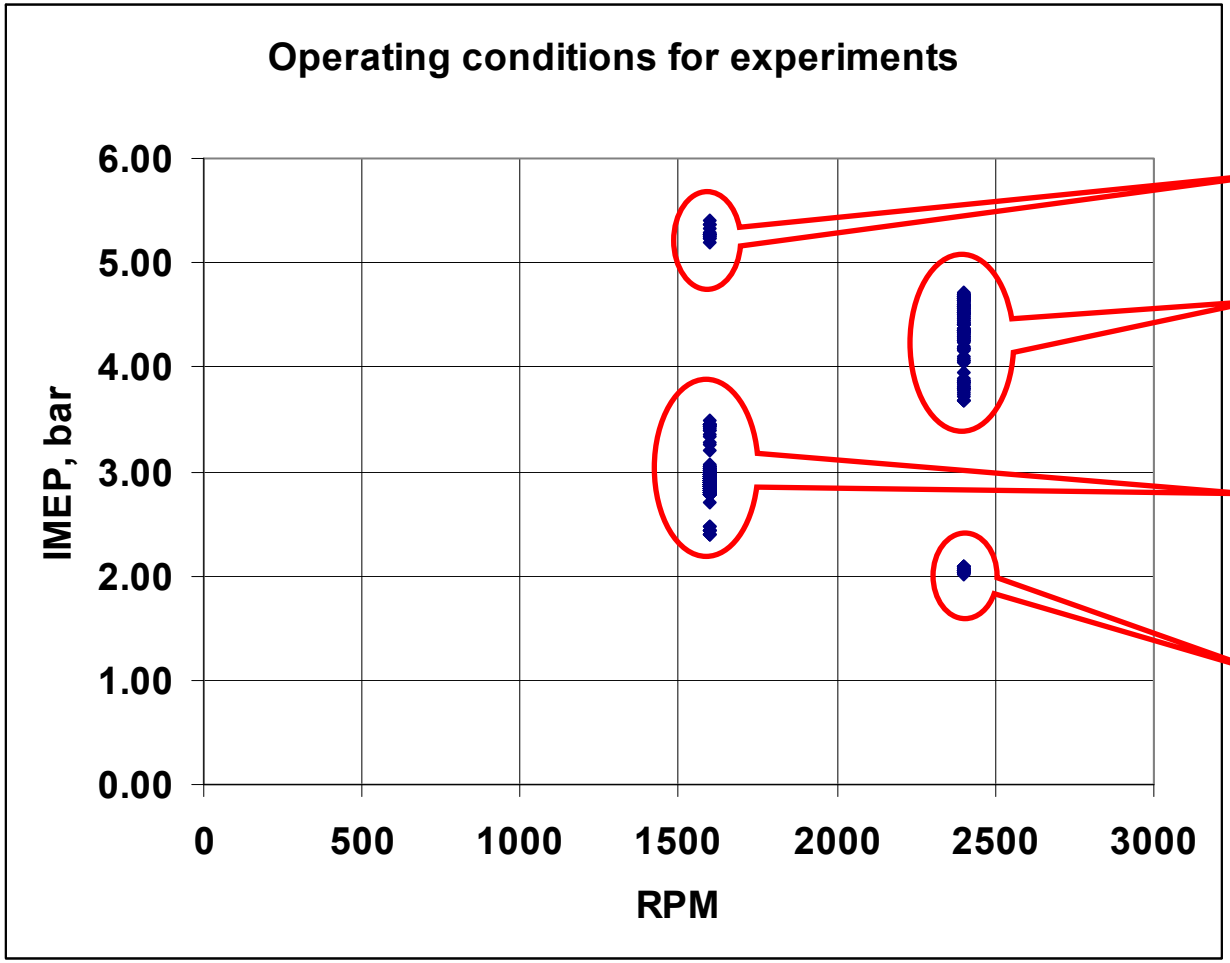
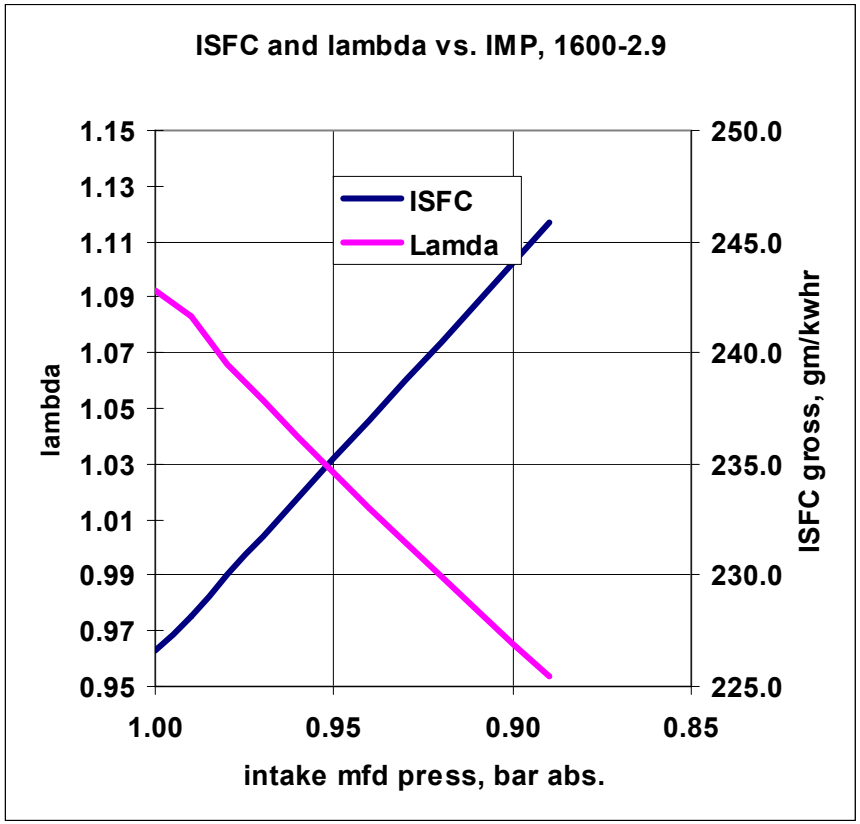
Experimental design evolved as we searched for temperatures and stable operation, burned up catalysts, and used up budgeted cell hours

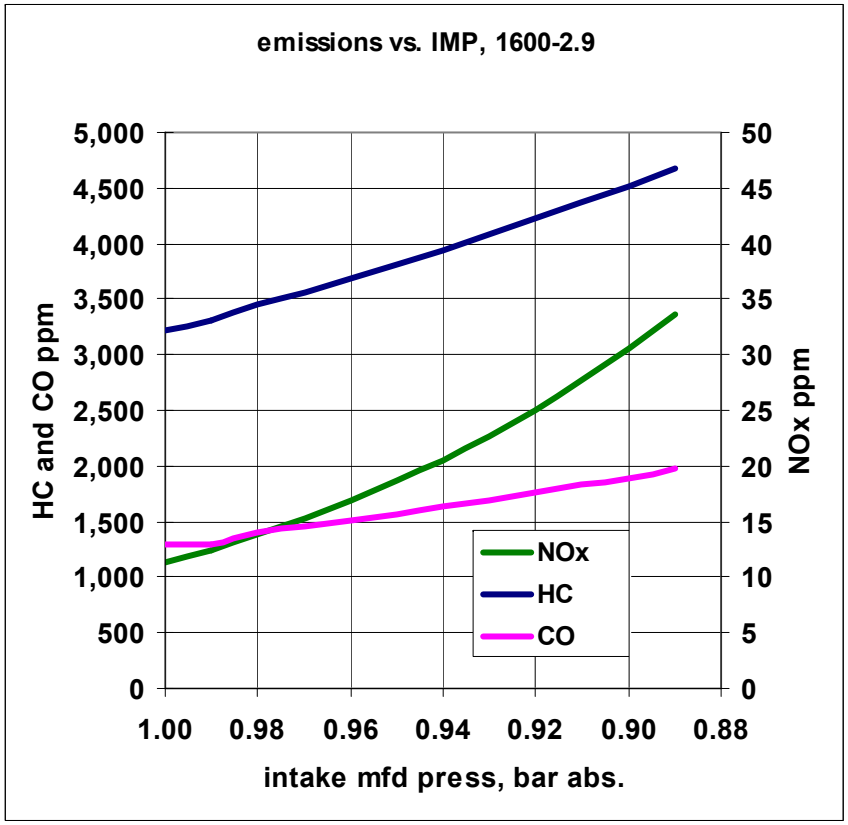


FUEL - CAT COMBOS

- DTBP - aged
- Indolene - un-aged
  DTBP - aged
- Indolene - un-aged
  Indolene - aged
  EHN - un-aged
  DTBP - un-aged
- Indolene - un-aged

Throttling effect on NVA engine

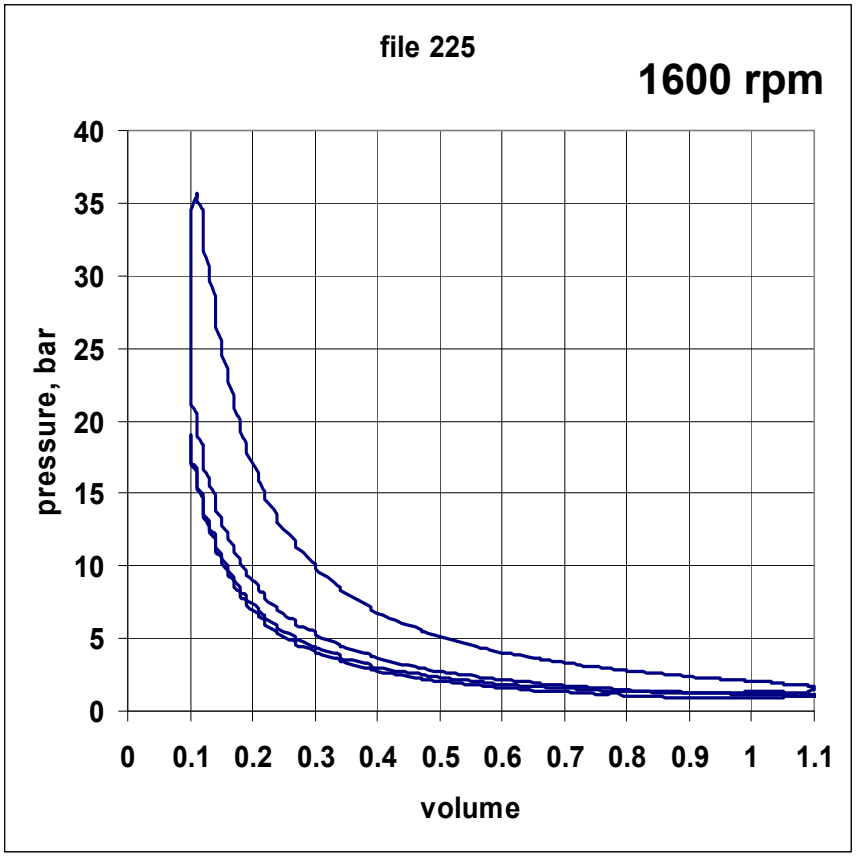


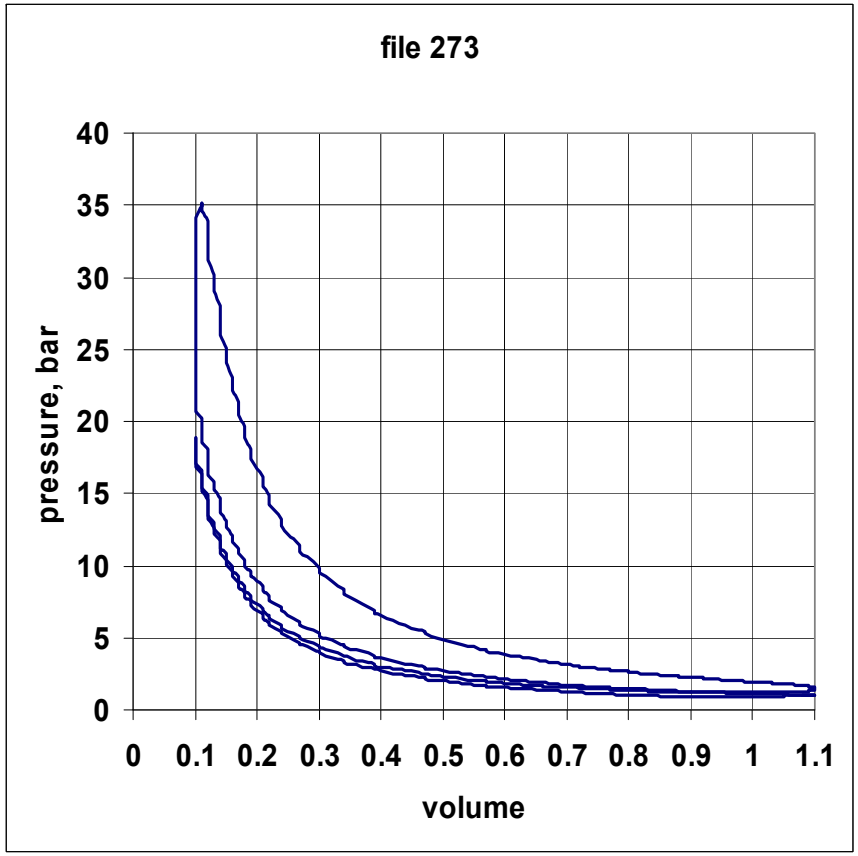


Throttling decreases lambda, increases ISFC, and increases emissions

(Gross = net + pumping and pumping is negative for NA operation)

Very moderate throttling increases pumping losses

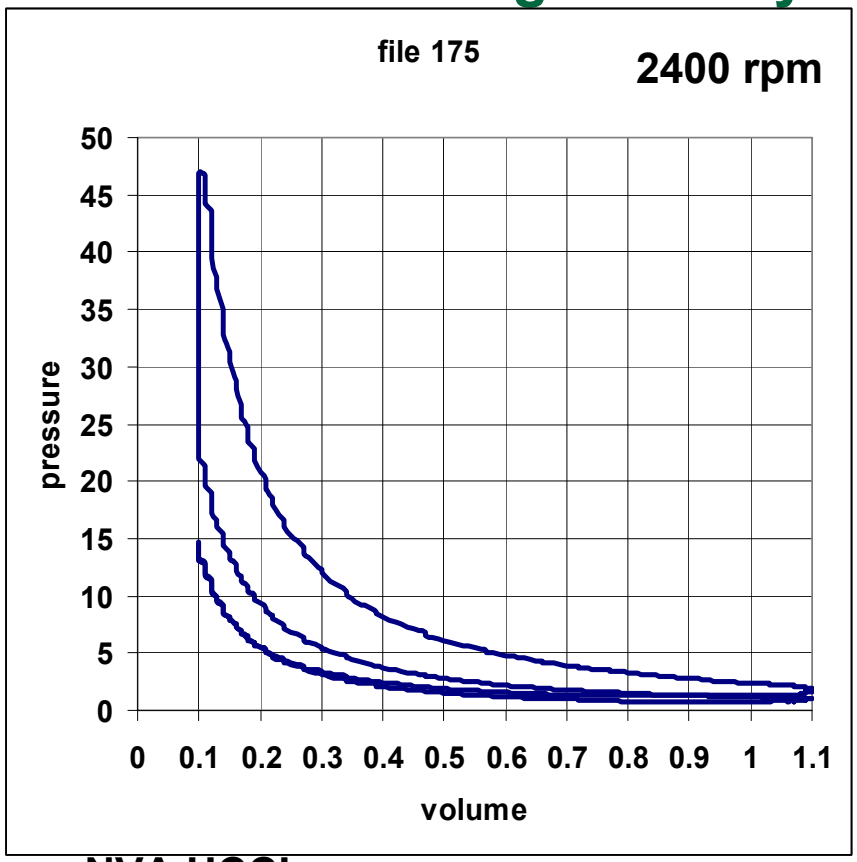


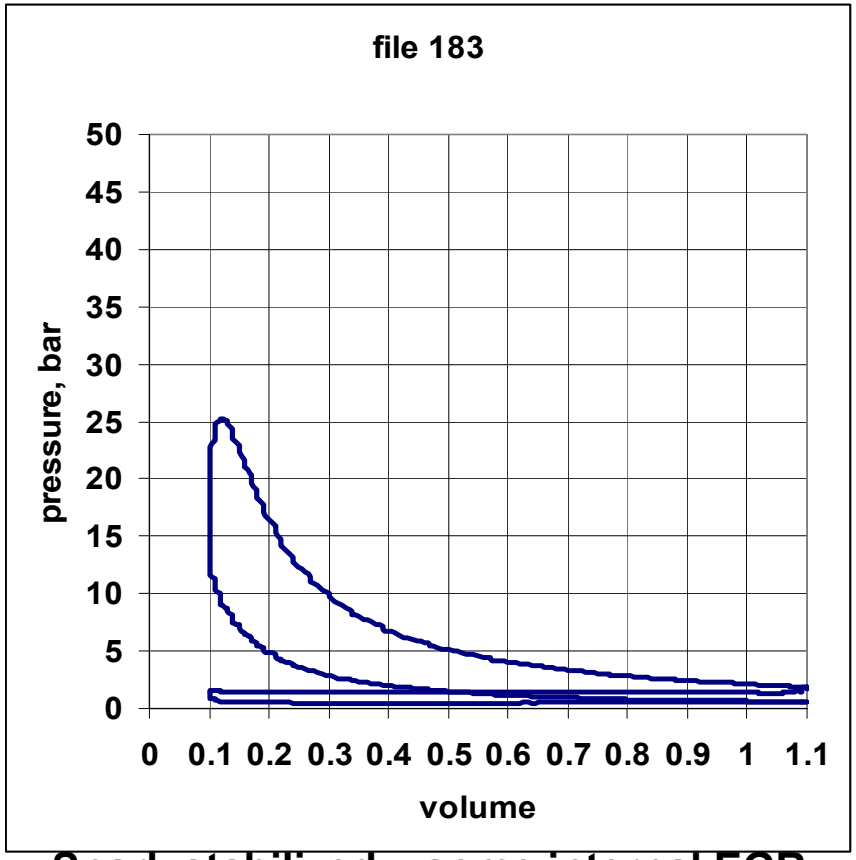


NVA HCCI
3.0 bar IMEPg, -0.30 bar pumping
220 gm/kwhr ISFC
1.0 bar IMPa
248 EVCA
11 ppm NOx
1.09 lambda

NVA HCCI
2.8 bar IMEPg, -0.34 pumping work
237 gm/kwhr ISFC
0.98 bar IMPa
251 EVCA
14 ppm NOx
1.05 lambda

Increased throttling continues to hurt ISFC and significantly alters combustion

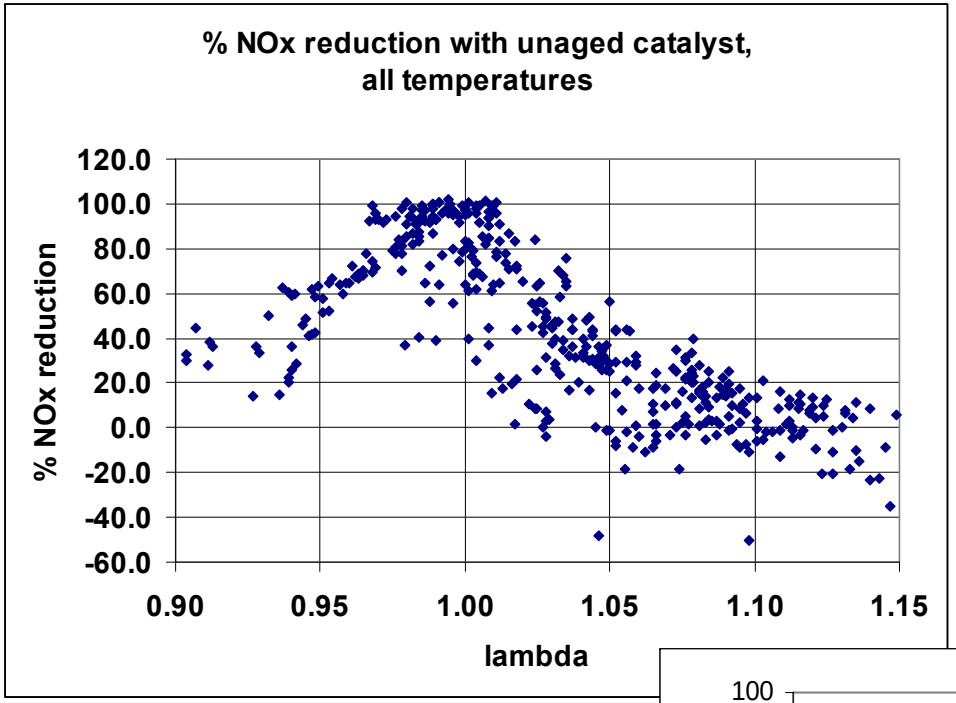




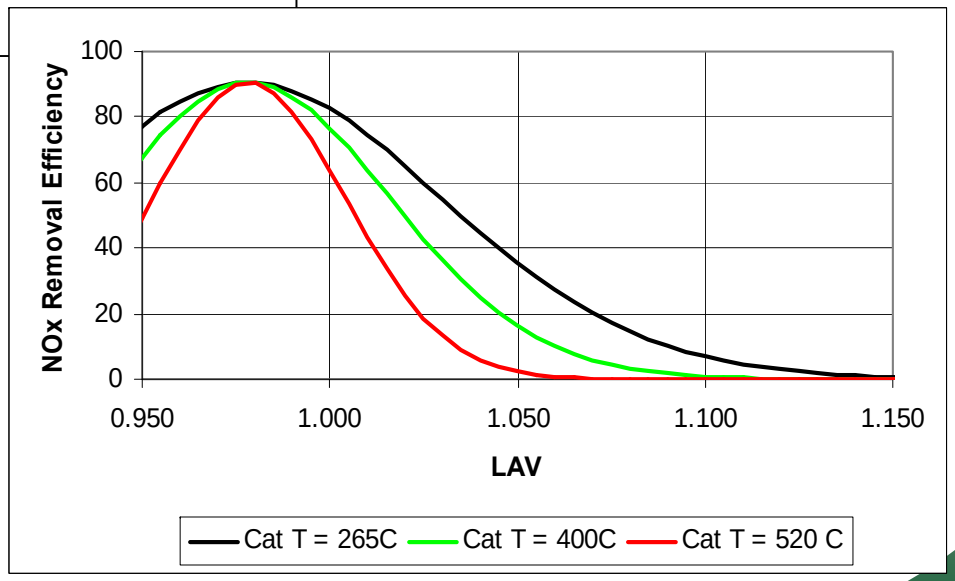
NVA HCCI
4.4 bar IMEPg, -0.36 pumping work
223 gm/kwhr ISFC
1.0 bar IMPa
274 EVCA
284 ppm NOx
1.00 lambda

Spark stabilized – some internal EGR
3.8 bar IMEPg, -0.89 pumping work
251 gm/kwhr ISFC
0.5 bar IMPa
342 EVCA
1660 ppm NOx
1.00 lambda

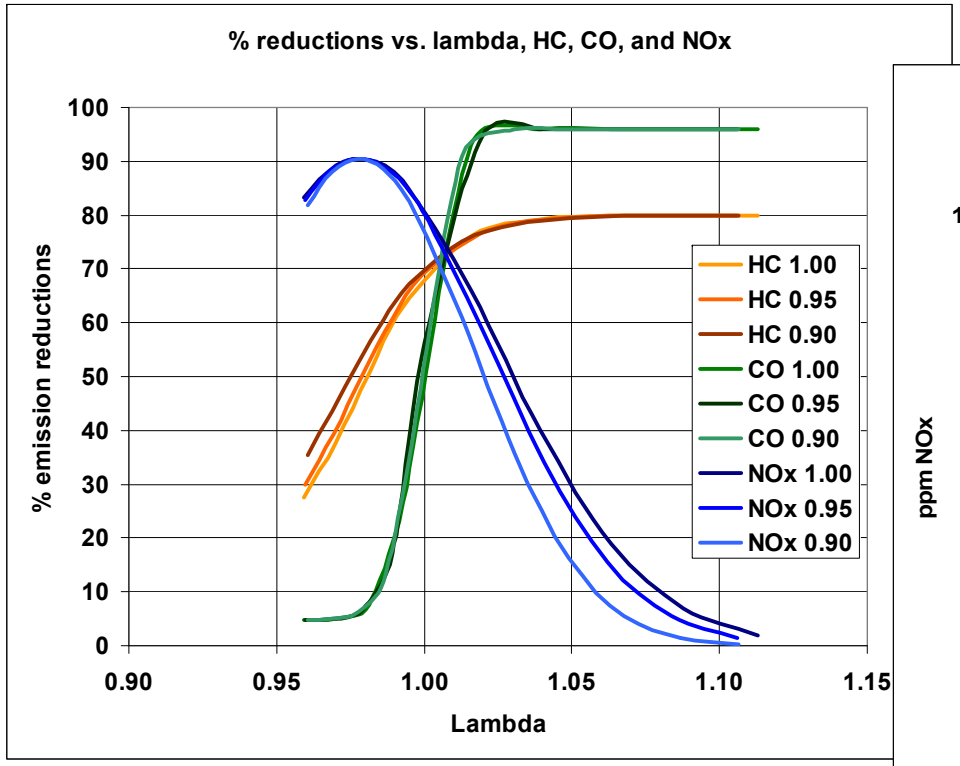
Experimental vs. modeled NOx reductions for un-aged catalyst

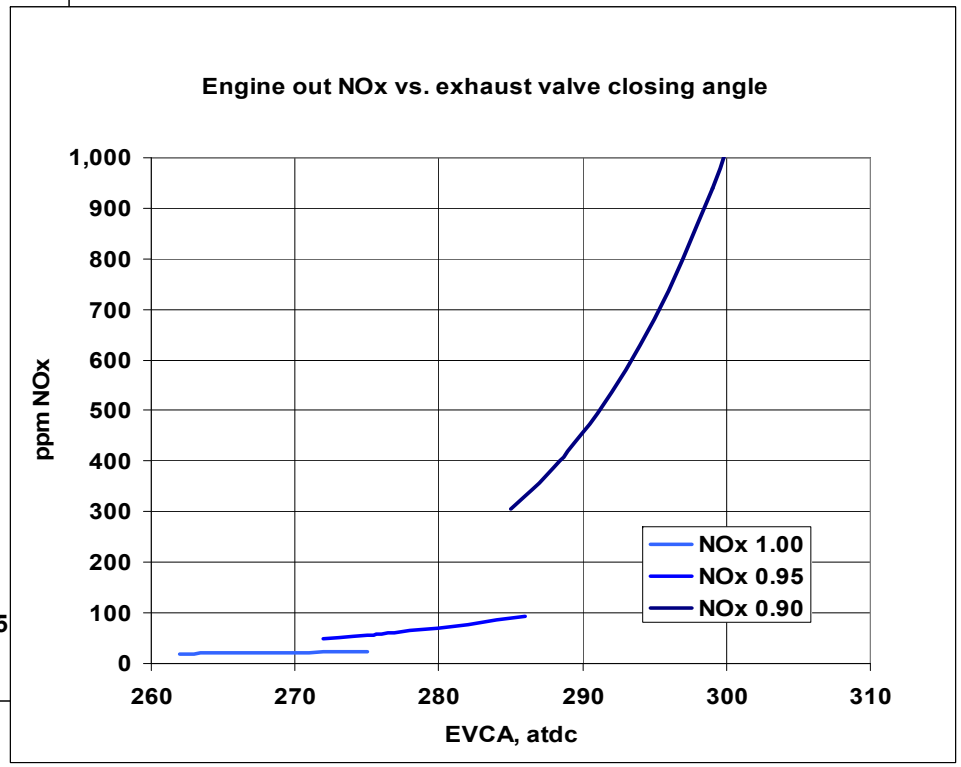


One source of variation is sequential measurements for cat in and cat out emissions combined with slow engine drift



Performance of un-aged catalyst

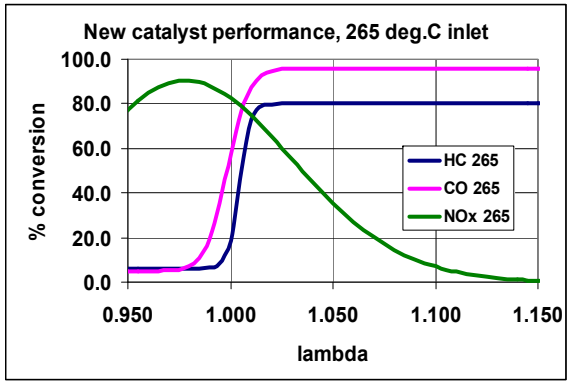


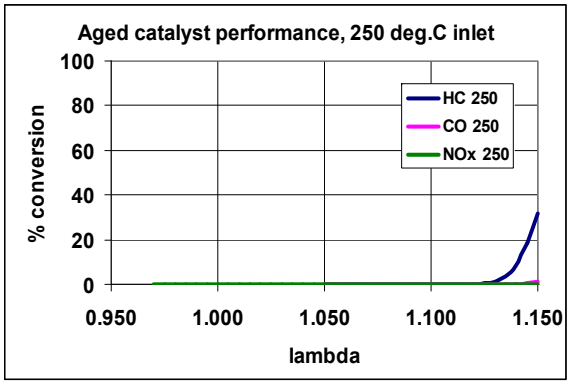


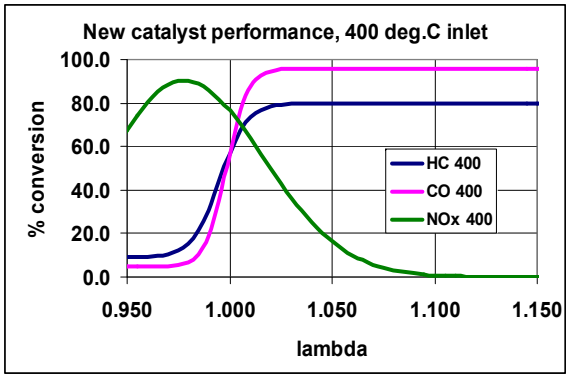
Un-aged catalyst not as good as expected,
Maximum reductions ≈ 90% NOx, 96% CO, and 80% HC,
Crossover conversion is low (70%), 95% expected

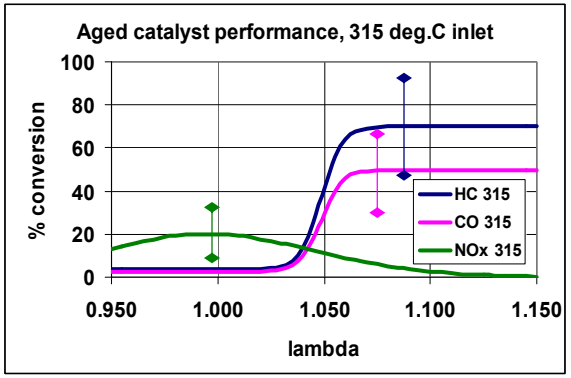
Could this be due to high or different HC from HCCI operation?
Also, don't forget over-temperature events and
effects of experimental variations on on the statistical model

Significant loss in performance from aging
(however, aging cycle used may have been too severe or incomplete)









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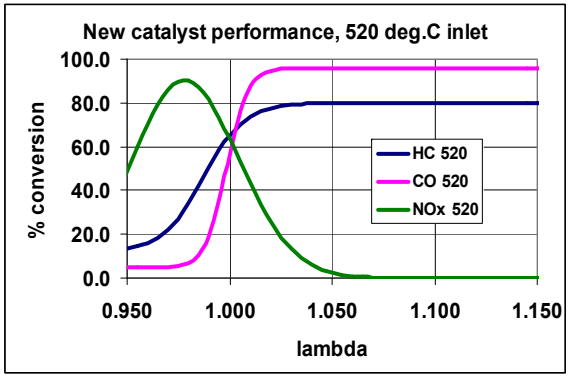
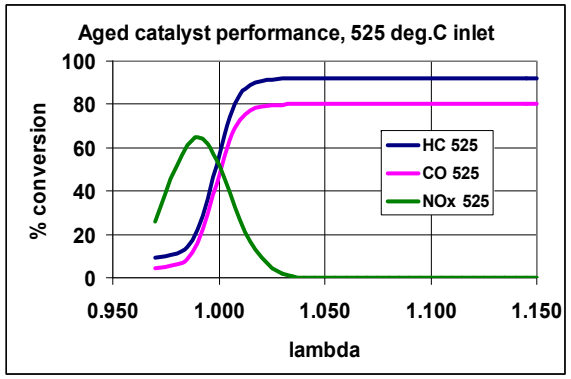
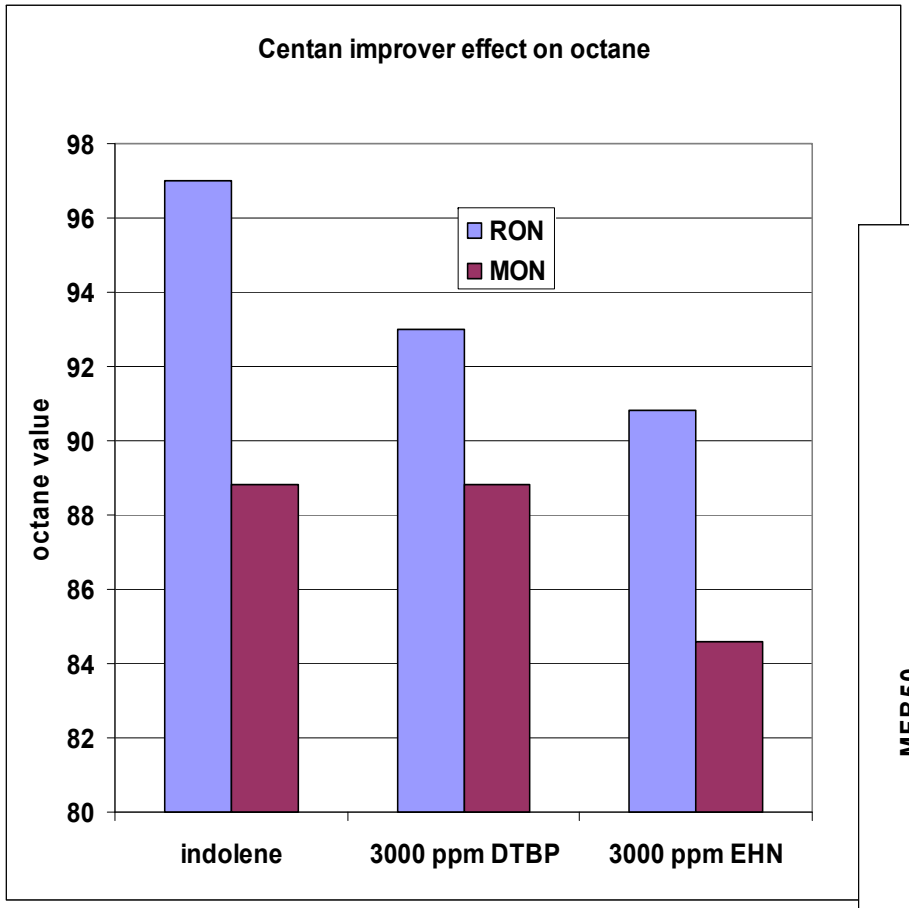
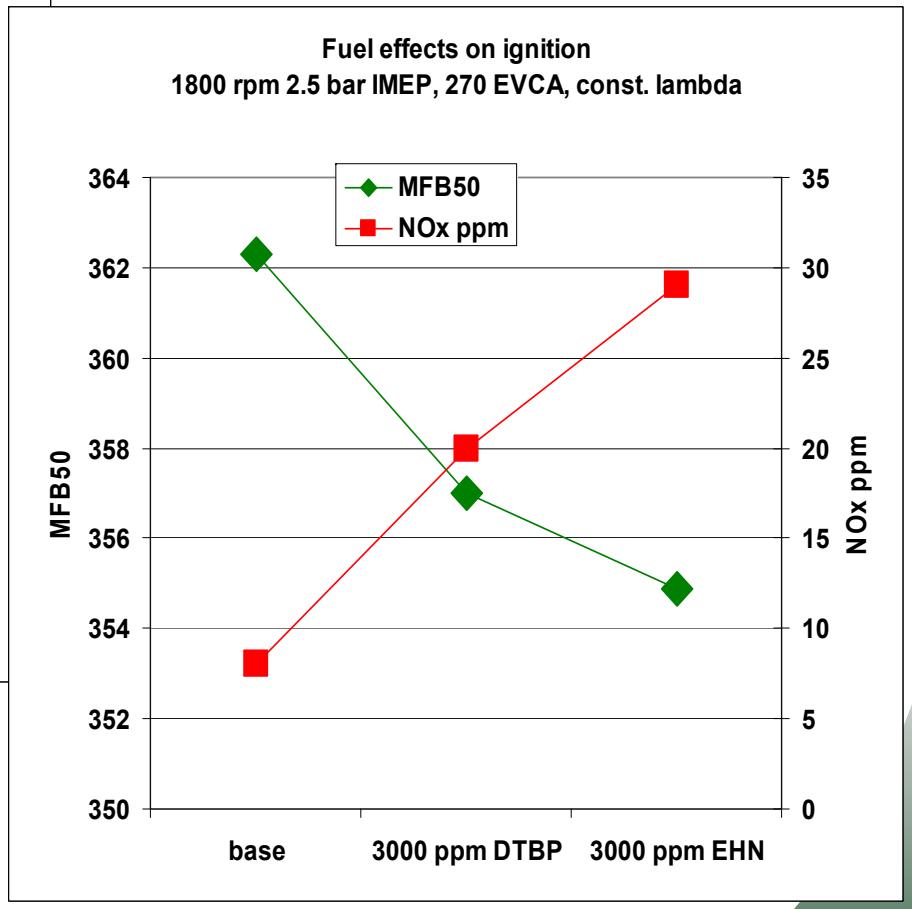




Cetane improver effects



Cetane improvers lower octanes, advances combustion phasing, and increases NOx



Could not separate out NOx effects With EHN, too tied-in with octane values for this limited set of fuels

Conclusions

- An NVO engine can be operated at stoichiometric conditions
  - We used EVCA and throttling to achieve some independence of MFB50 and lambda
  - This engine was not particularly happy at stoichiometric operation
    - High CO, HC, COV
  - If stoichiometric operation is achieved with throttling, a fuel penalty is incurred
  - Are these characteristics universal or related to engine used?
- TWC can provide NOx, HC, and CO reduction on stoichiometric HCCI engine
  - This is a challenging application
    - High HC and CO emissions
    - Low exhaust temperatures
      - Or is this just an artifact of single cylinder engine?
- Cetane improvers can be used to improve ignition of high octane gasoline and do reduce octane numbers
  - Dosage rate is high for a significant change
  - EHN and DTBP behave slightly differently
  - We were unable to separate out EHN contribution to NOx from small number of fuels in this program

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Notes from our previous research on gasoline HCCI

- Low NOx is achieved by high dilution, either from lean operation or very high EGR
- There is nothing magical about HCCI except that it stabilizes combustion at very high dilution levels, thereby enabling ultra-low NOx operation
- A spark assist can help stabilize gasoline HCCI under certain conditions
- Improved efficiency for gasoline HCCI comes largely from un-throttled operation

Future work

- Continue to study stoichiometric HCCI in order to
  - Understand and expand operating range
  - Gain improved fuel economy along with low NOx
  - Develop better understanding of different operating modes and mode switching
    - Lean and stoichiometric HCCI
    - Lean and stoichiometric conventional with high EGR
    - PCCI (or 'partially stratified HCCI'?)
  - Better define catalyst requirements, operating conditions, catalyst performance, and aging effects
    - Both stoichiometric and lean operation
- Continue to use fuel variations in these experiments
  - Define fuel chemistry and property effects
  - Determine characteristics of an 'optimum' HCCI fuel
  - Determine control robustness across expected range of fuels

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