Engage the Experts

Understanding diesel cylinder deactivation

October 21, 2020

Powering Business Worldwide

Tony Truelove

Global Marketing Communications Manager, Eaton

- Welcome!
- Fourth in a series of webinars on diesel cylinder deactivation
- Feel free to send us questions

Powering Business Worldwide

Engage the Experts: free webinars on commercial vehicle engine strategies

September 9 — **The truth about diesel CDA and NVH**
Tom Reinhart, Southwest Research Institute (SwRI)

September 30 — **Achieving 2027 emissions regulations**
Chris Sharp, Southwest Research Institute (SwRI)

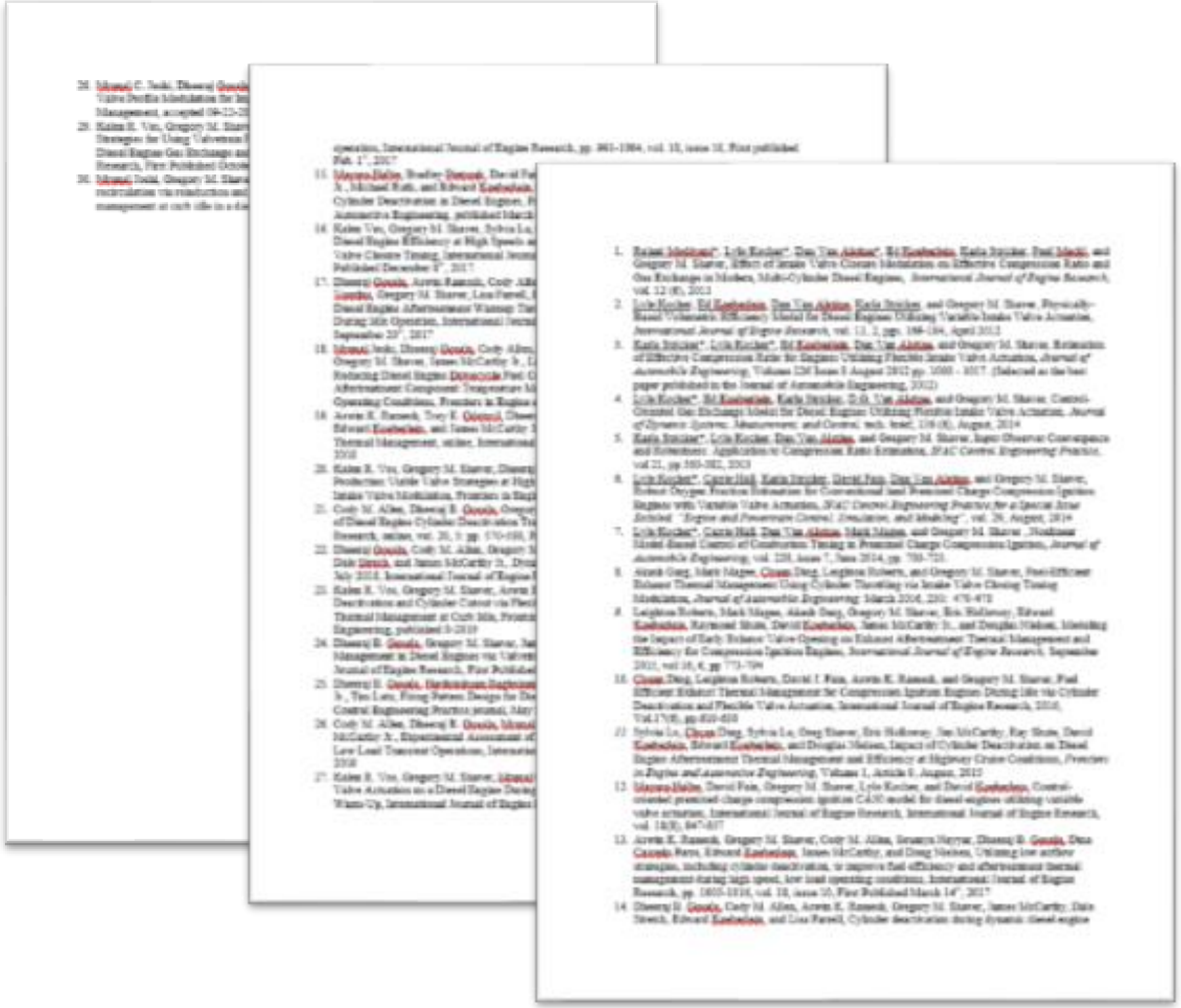
October 14 — **The advantages of CDA over real-world drive cycles**
Dr. Mrunal Joshi, Cummins

October 21 — **Understanding diesel cylinder deactivation**
Dr. Greg Shaver, Purdue University

October 28 — **CDA versus cylinder cutout: a technology overview**
Dr. Cody Allen, University of Illinois

EATON
Powering Business Worldwide

Today’s discussion



- Based on extensive research from 30 published papers
- List can be downloaded from the Resources area

Powering Business Worldwide

Dr. Dheeraj Gosala

Research engineer, Cummins

- Dheeraj Gosala is a research engineer in the Advanced Systems Performance group in Cummins Research & Technology. He works on advanced controls development for next-generation spark-ignited and diesel engine systems within electrified commercial vehicle powertrains.
- Dheeraj graduated with a PhD from Purdue University in 2018. His doctoral dissertation investigated the potential of diesel engine variable valve actuation, including cylinder deactivation, in achieving fuel-efficient emissions reduction.

EATON
Powering Business Worldwide

Dr. Cody Allen

Assistant Professor, University of Illinois

- Cody Allen is an Assistant Professor at the University of Illinois at Urbana-Champaign in the Department of Agricultural and Biological Engineering.
- His research focuses on creating cleaner, more efficient heavy-duty vehicles by exploring advanced powertrain technologies and architectures, including works resulting in over a half-dozen peer-reviewed publications related to diesel engine variable valve actuation and cylinder deactivation. He also develops model-based control algorithms and validation tools for machine automation leading to improved productivity, efficiency, and safety.
- Prior to joining the faculty at the University of Illinois, Cody worked as a Guidance, Navigation, and Control Engineer for Boeing Defense, Space & Security.
- He received a PhD in Mechanical Engineering from Purdue University in 2019, MSME from Purdue in 2016, and BSME with high honors from the University of Illinois in 2014

EATON
Powering Business Worldwide

Dr. James McCarthy, Jr.

Chief Engineer for Vehicle Technologies and Innovation, Eaton

- Prior to joining Eaton, Jim worked on diesel engine technologies at Detroit Diesel
- Focused on product innovation and growth to develop solutions for engine technologies to conserve fossil fuels and reduce emissions
- Holds a Ph.D., Masters of Science and Bachelors of Science in Mechanical Engineering from Purdue University

EATON
Powering Business Worldwide

Dr. Eckhard Groll

Head of the School of Mechanical Engineering, Purdue University

- Dr. Eckhard A. Groll is the Reilly Professor of Mechanical Engineering and also serves as the Head of Mechanical Engineering.
- He received his Diploma in Mechanical Engineering from the University of the Ruhr in Bochum, Germany, in 1989 and a Doctorate in Mechanical Engineering from the University of Hannover, Germany, in 1994.
- Prof. Groll teaches thermodynamics and his research focuses on the fundamental thermal sciences as applied to advanced energy conversion systems, components, and their working fluids. He is a world-renown expert in positive displacement compressors and expanders.
- He has been the principal investigator or co-principal investigator on more than 120 research grants and more than 40 educational grants from various governmental agencies, professional societies, and more than 30 different industrial sponsors.
- He has authored or co-authored more than 370 archival journal articles and conference papers. He has been the co-author of 4 book chapters and the editor or co-editor of 7 conference proceedings.
- He serves as the Regional Editor for the Americas for the International Journal of Refrigeration and is a fellow of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE).

Powering Business Worldwide

PURDUE UNIVERSITY | Mechanical Engineering

combines the
BEST OF INDUSTRY

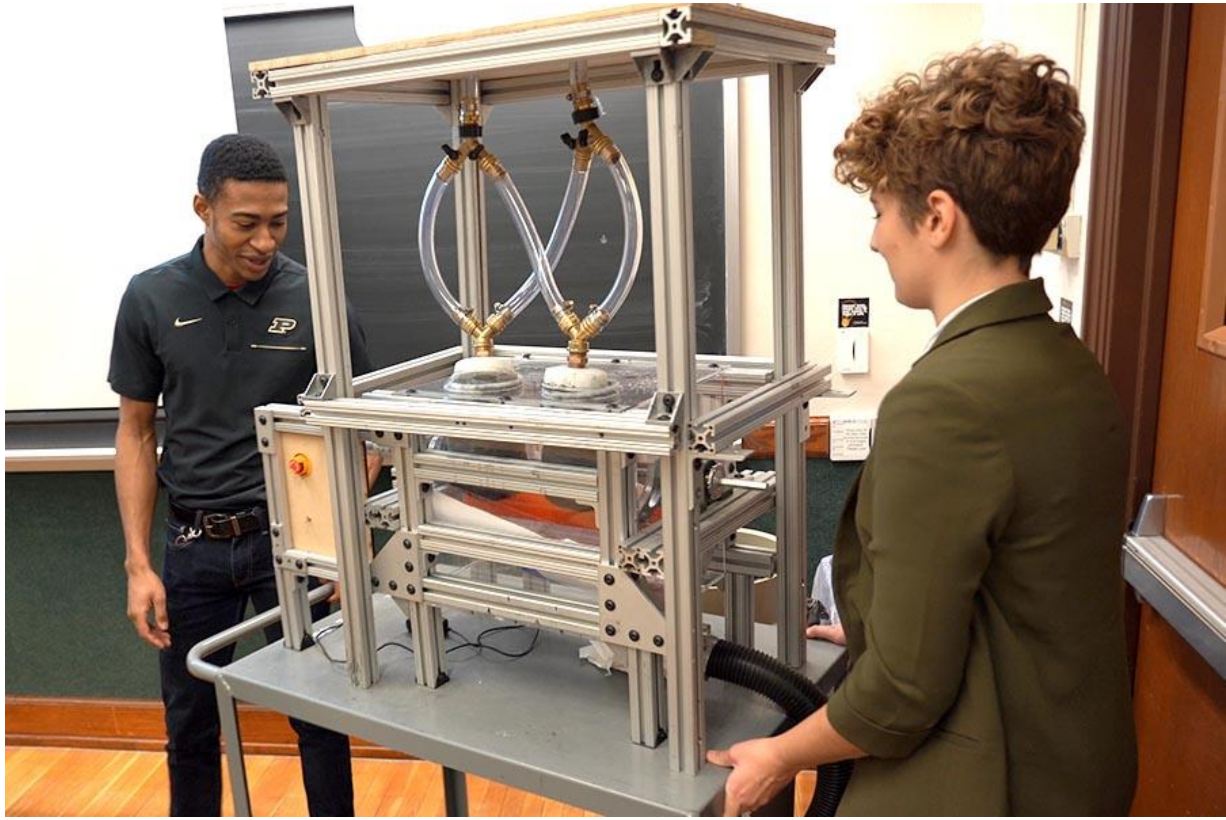
with the
BEST OF ACADEMIA

Undergraduates

- **More than 97% of Purdue ME students graduate with industry experience** *(internships, co-ops, and research)*
- **75% of graduates go to work in industry** *(automotive, aerospace, defense, energy, biomedicine, manufacturing, management, and much more!)*

Company-Sponsored Student Design Projects

- 14 senior design projects (approx. 28% of all teams) were direct collaborations with industry partners
  - Teams of 4-6 seniors spend their final semester tackling a company's engineering issue
  - Could be a manufacturing problem, a new feature for an existing product, or any other issue large or small
  - Many companies implement their designs, and hire the students right after graduation!
- Corporate Partners Program has grown to include 13 partners
  (Phillips 66, EBI, Modineer, ArcelorMittal, Eaton, Lilly, Sandia, Norfolk Southern, Exxon, Altair, Lawrence Livermore, Air Products, Whirlpool)



Rolls-Royce | BorgWarner | iRobot | Boeing
Allison Transmission | Northrop Grumman | FCA Fiat Chrysler Automobiles | oerlikon

A Master's Degree for Working Professionals

- 26% of Purdue ME graduate students are fully online
- Purdue ME's Online Masters program ranked **#1 in the country** by US News & World Report
- Flexibility for working professionals, anywhere in the world
- **purdue.edu/ME/online**

BEST ONLINE PROGRAMS
US News & WORLD REPORT
GRAD ENGINEERING
MECHANICAL
2020

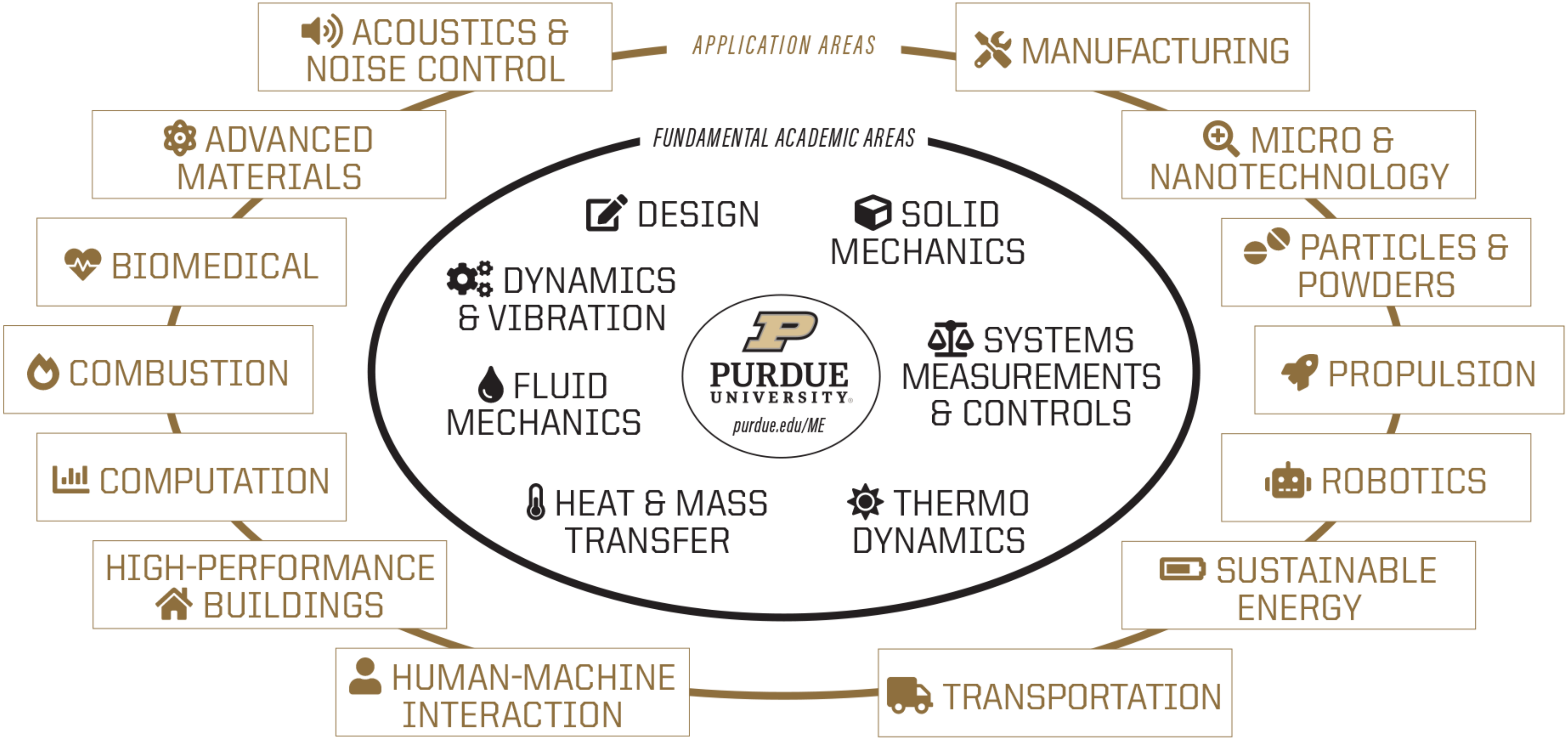
"This degree has opened doors for me into a new position on the research side here at 3M. Corporate R&D is something I had always wanted to get into from the beginning and this Purdue program has really enabled that to happen."

PURDUE UNIVERSITY | Mechanical Engineering

Purdue is a Research Powerhouse

- Purdue generates **half a billion dollars** in research funding every year
- World-class facilities and labs found nowhere else
- **90 mechanical engineering faculty** in 21 different research areas
- **$38.1 million** in research expenditures in 2019-20
- More than a 50% increase in just 4 years!
- Just recently:
  - $8M from US Army for Energetic Materials research
  - $5M from NSF to use augmented reality in manufacturing worker education
  - $5M from NSF for precision agriculture with Internet-of-Things

MECHANICAL ENGINEERING RESEARCH AREAS



Many ways to get involved!

- **There's a place for your research at Purdue!**
- Sponsor a project with one faculty, or participate in a research center
- Share costs with government-funded projects from DOE, DOD, NASA, etc.
- Small-business grants available for startup companies
- Purdue has decades of experience with hundreds of corporate partners!

Dr. Greg Shaver

Professor of Engineering, Purdue University

- Dr. Shaver is a Full Professor, University Faculty Scholar, and College of Engineering Early Career Research Award recipient. He joined the Purdue Faculty in 2006.
- He is focused on creating challenging, interesting, relevant, career-launching research and learning opportunities for Purdue students. His research program is dedicated to clean, safe, and efficient commercial vehicles – via advanced diesel & natural gas engine systems/controls, powertrain electrification, and vehicle automation/connectivity.
- His efforts are well known in the industry and regulatory agencies, including the U.S. EPA and California Air Resources Board. This is a result of Greg's students and industry collaborators demonstrating that future diesel engines can simultaneously reduce emissions (NOx and soot), fuel consumption, and CO_2 emissions through the use of variable valve actuation (VVA) and cylinder deactivation.
- Greg earned graduate (PhD 2005, MSME 2004) and undergraduate (BSME 2000 w/ highest distinction) degrees from Stanford and Purdue, respectively.

Powering Business Worldwide

Understanding Diesel Engine Cylinder Deactivation

(and some context relative to other approaches)

October 21st, 2020

PI: Dr. Gregory Shaver

Project management: Eric Holloway

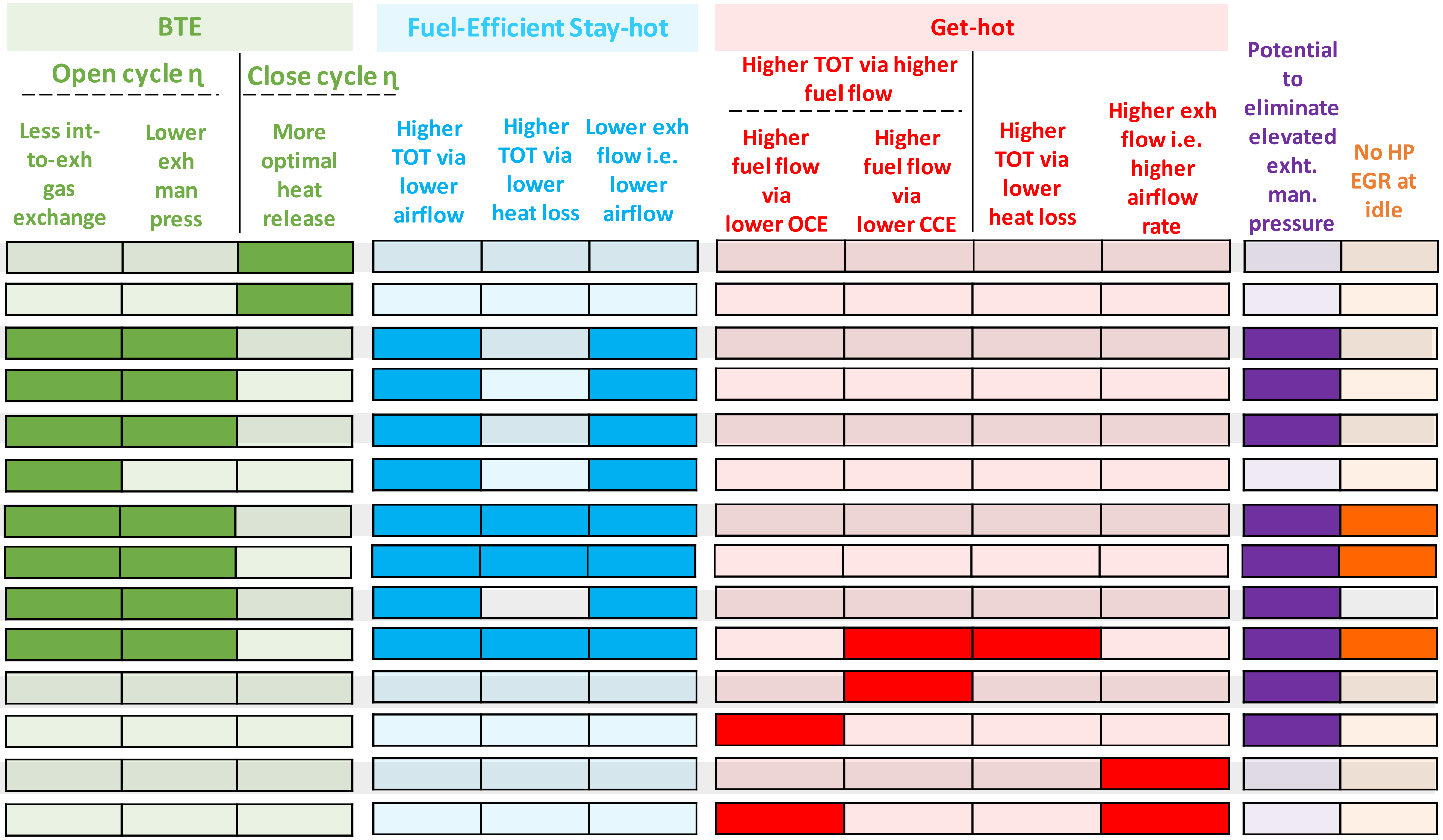
With funding from, and in collaboration with:

PURDUE UNIVERSITY

Cummins

EATON Powering Business Worldwide

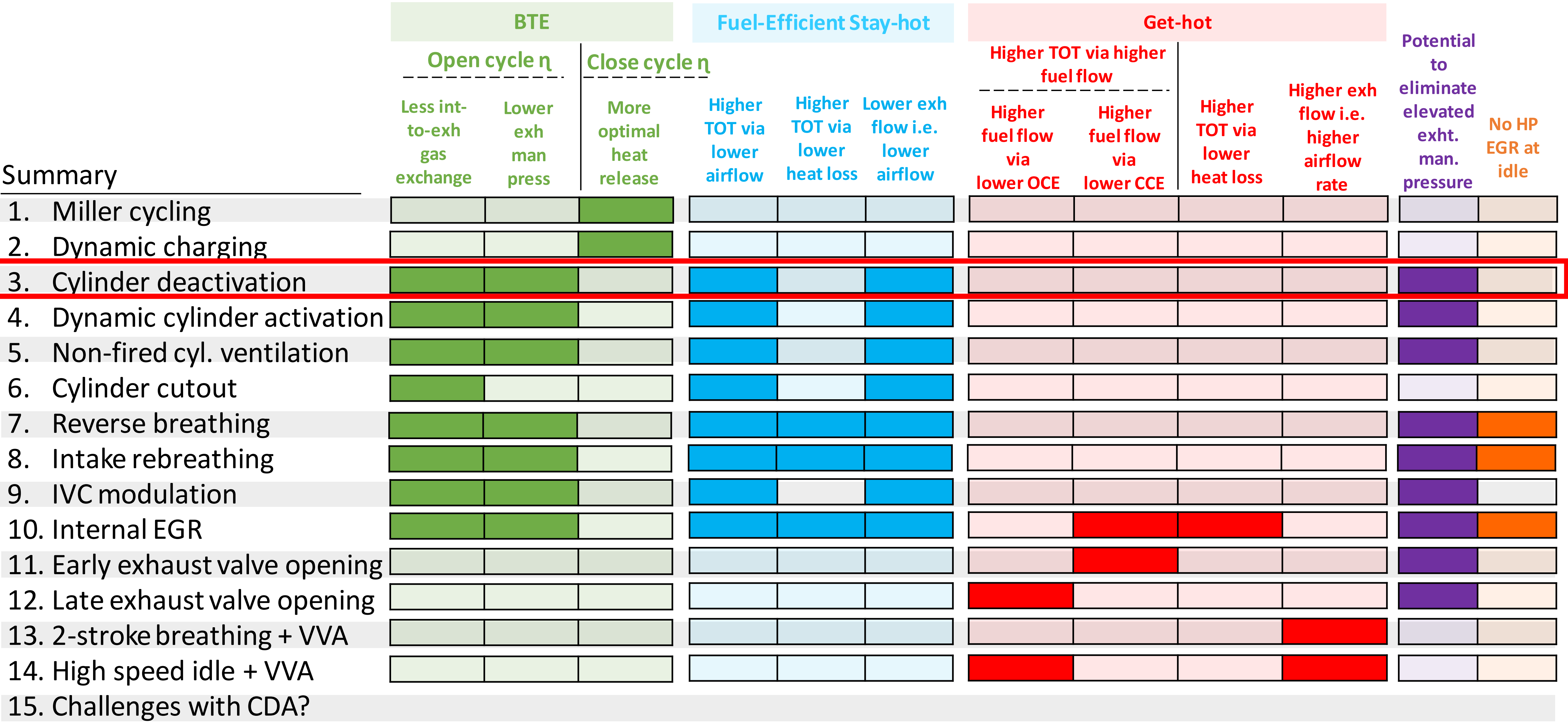
VVA improves diesel engine fuel efficiency and aftertreatment thermal management.



Summary

1. Miller cycling
2. Dynamic charging
3. Cylinder deactivation
4. Dynamic cylinder activation
5. Non-fired cyl. ventilation
6. Cylinder cutout
7. Reverse breathing
8. Intake rebreathing
9. IVC modulation
10. Internal EGR
11. Early exhaust valve opening
12. Late exhaust valve opening
13. 2-stroke breathing + VVA
14. High speed idle + VVA
15. Challenges with CDA?

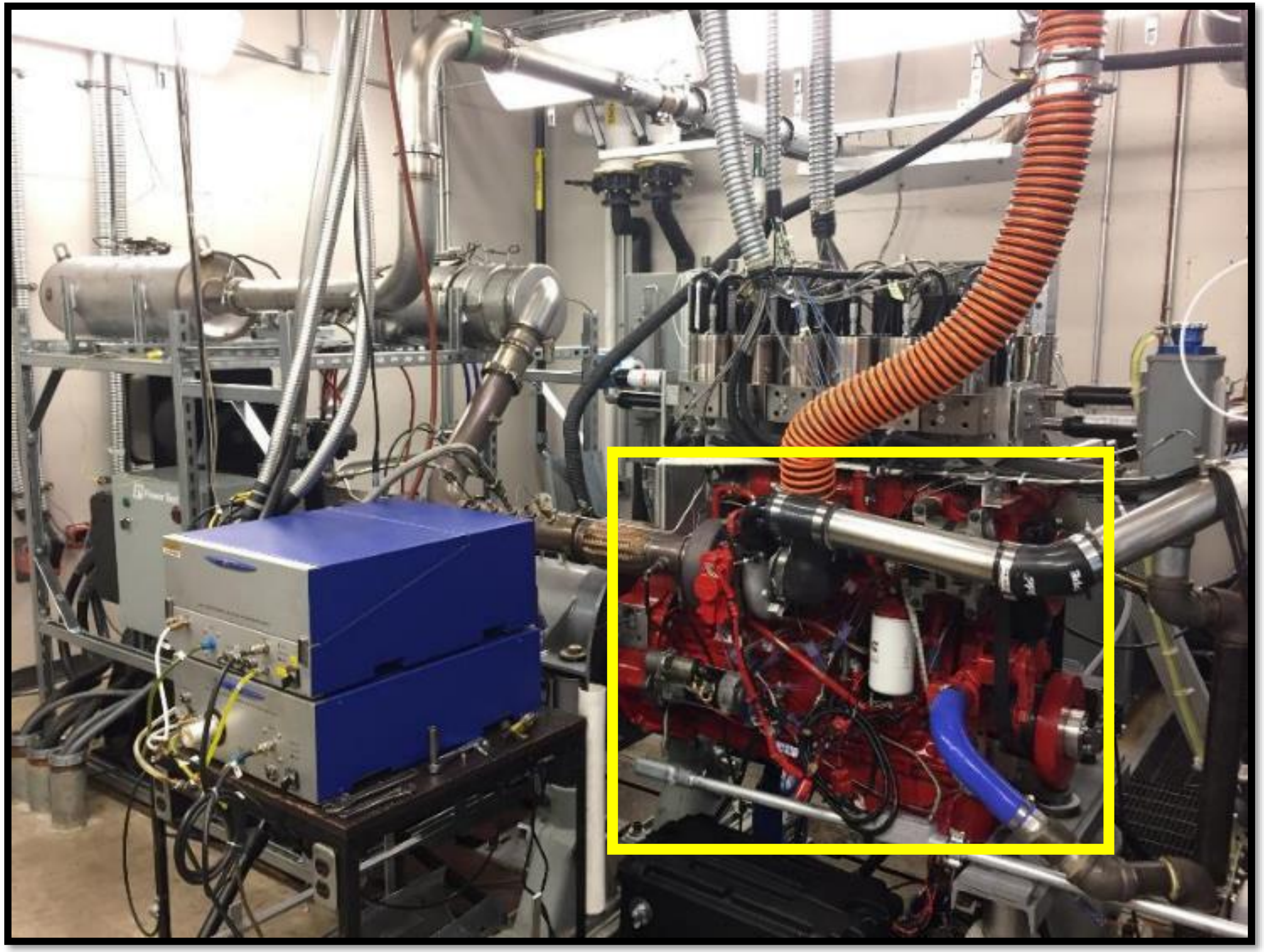
VVA improves diesel engine fuel efficiency and aftertreatment thermal management.



Presentation focus is cylinder deactivation (CDA), but I will draw comparisons to several other methods.

Experimental Setup at Purdue University

Cummins Power Lab – Test Cell 1



Cummins 6-cylinder camless diesel engine

Fully flexible VVA system

Cylinder-to-cylinder, cycle-by-cycle control

Aftertreatment system

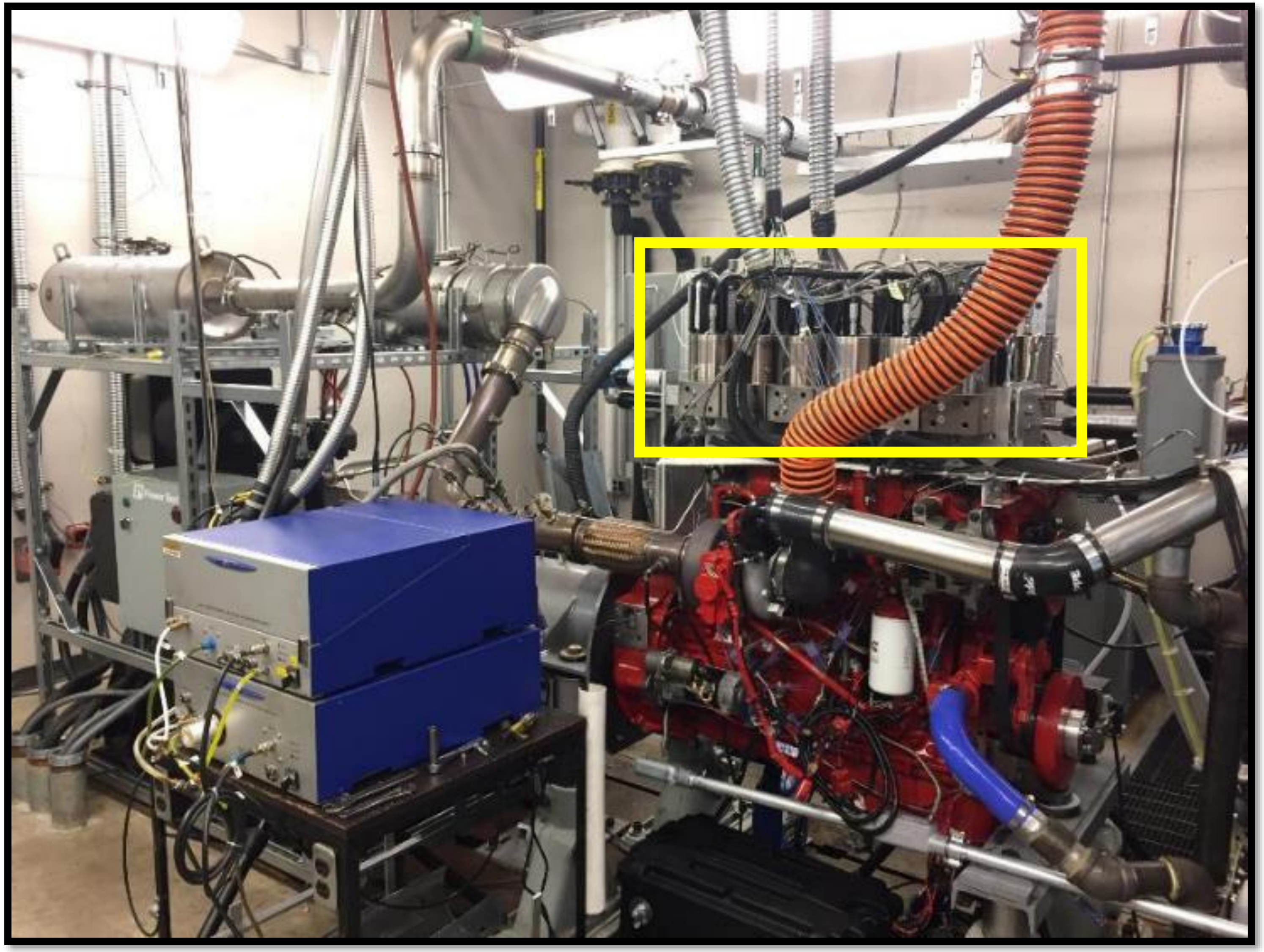
DOC-DPF-SCR

Measurements

Emissions, temperatures, pressures, flow rates etc.

Experimental Setup at Purdue University

Cummins Power Lab – Test Cell 1



Cummins 6-cylinder camless diesel engine

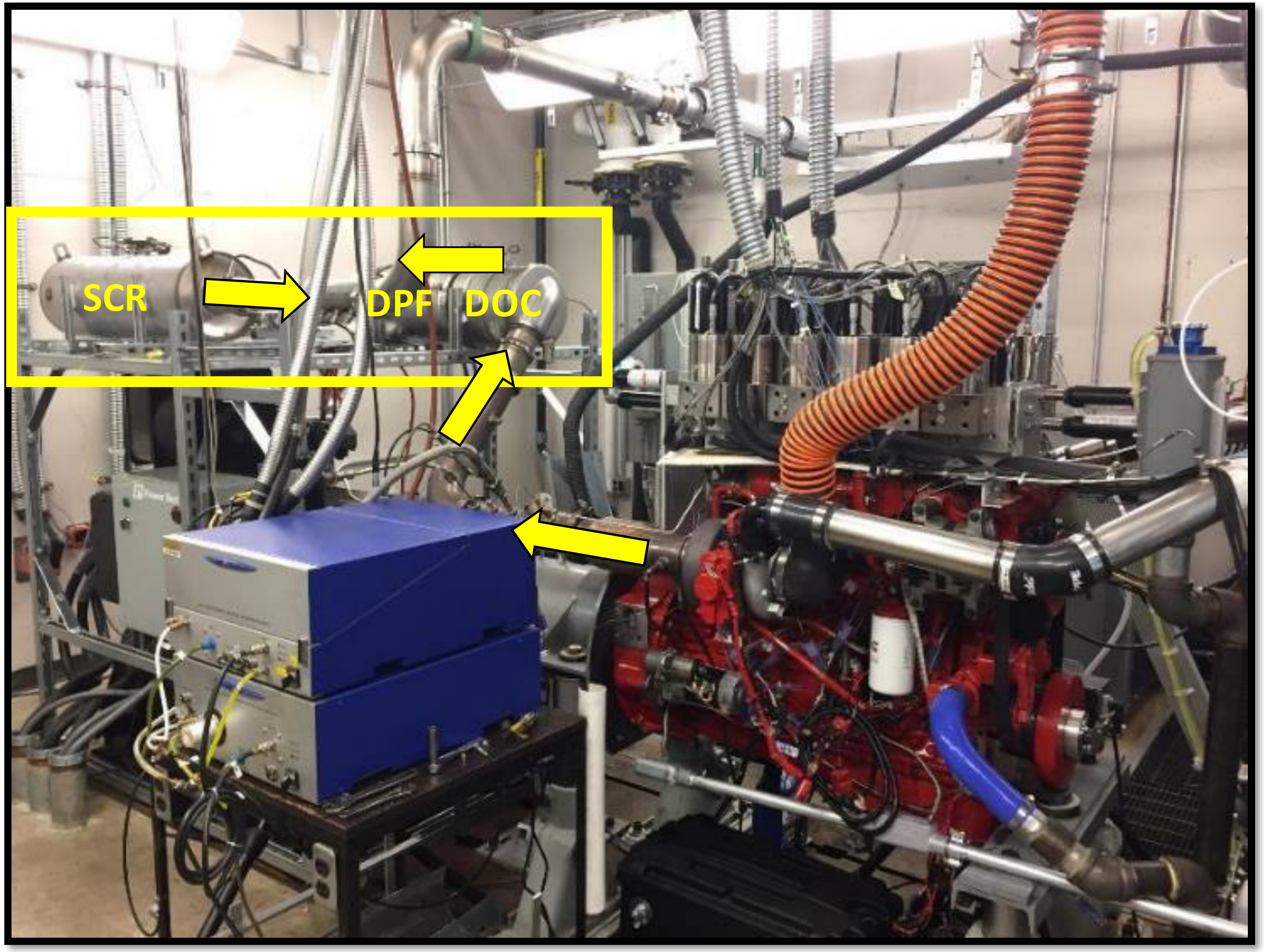
Fully flexible VVA system
Cylinder-to-cylinder, cycle-by-cycle control

Aftertreatment system
DOC-DPF-SCR

Measurements
Emissions, temperatures, pressures, flow rates etc.

Experimental Setup at Purdue University

Cummins Power Lab – Test Cell 1



Cummins 6-cylinder camless diesel engine

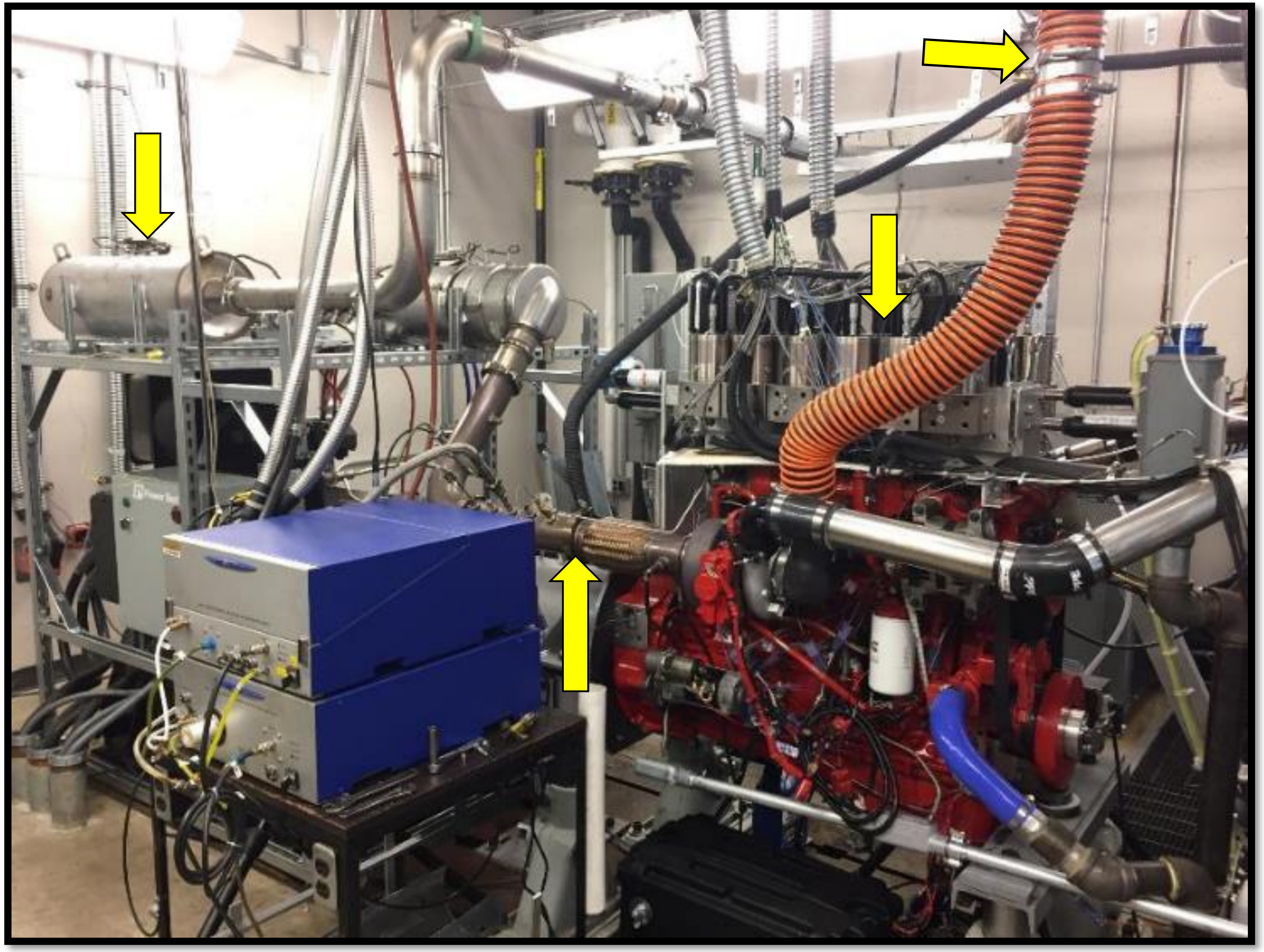
Fully flexible VVA system
Cylinder-to-cylinder, cycle-by-cycle control

Aftertreatment system
DOC-DPF-SCR

Measurements
Emissions, temperatures, pressures, flow rates etc.

Experimental Setup at Purdue University

Cummins Power Lab – Test Cell 1



Cummins 6-cylinder camless diesel engine

Fully flexible VVA system

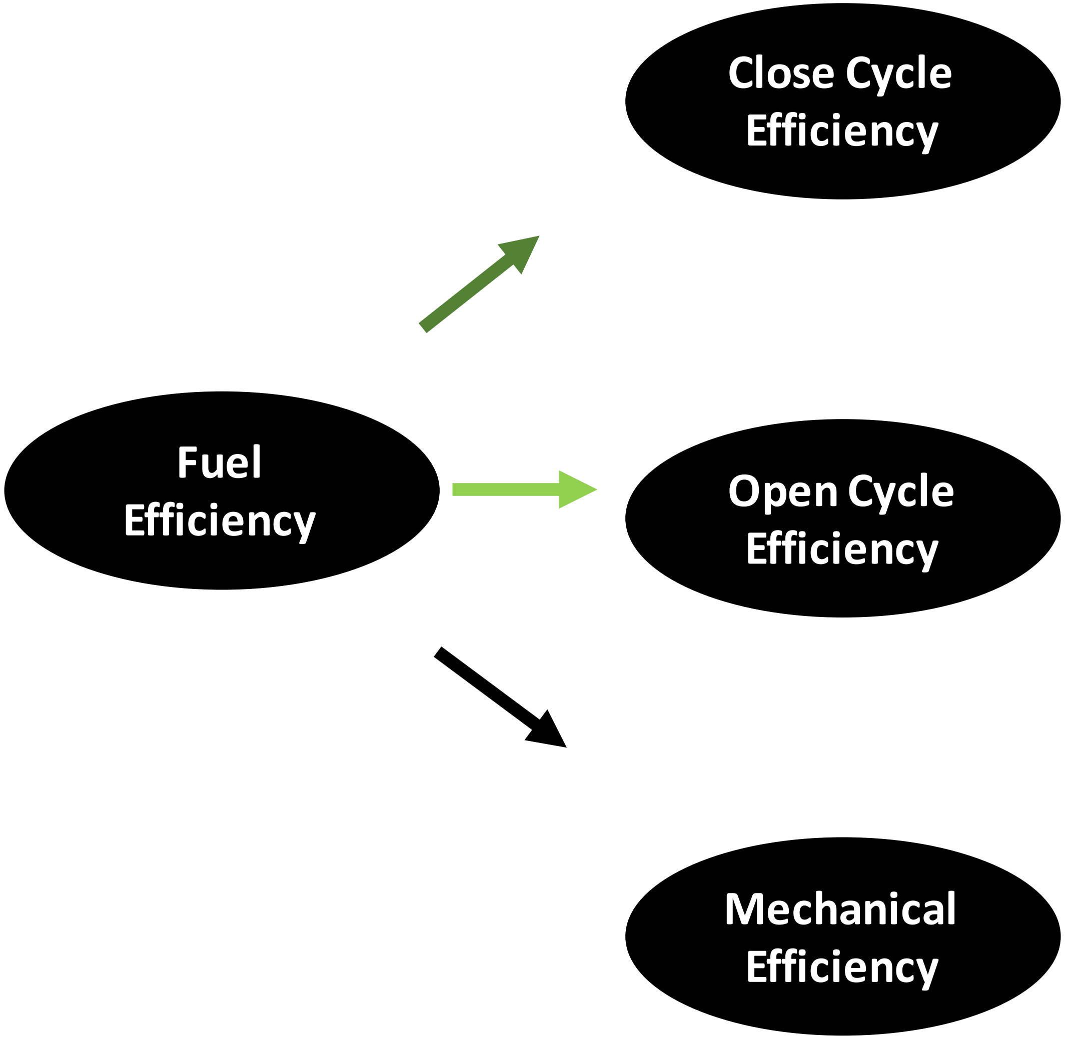
Cylinder-to-cylinder, cycle-by-cycle control

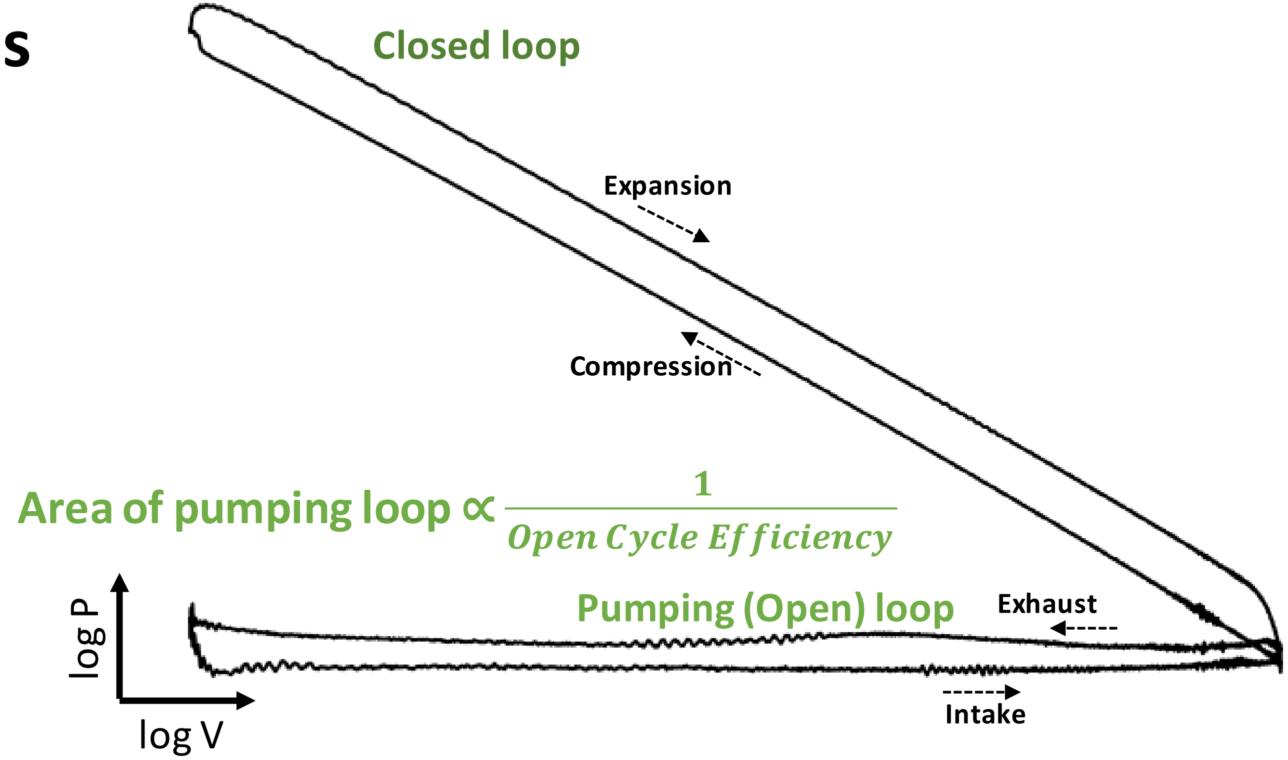
Aftertreatment system

DOC-DPF-SCR

Measurements
Emissions, temperatures, pressures, flow rates etc.

Potential for fuel efficiency improvements with VVA

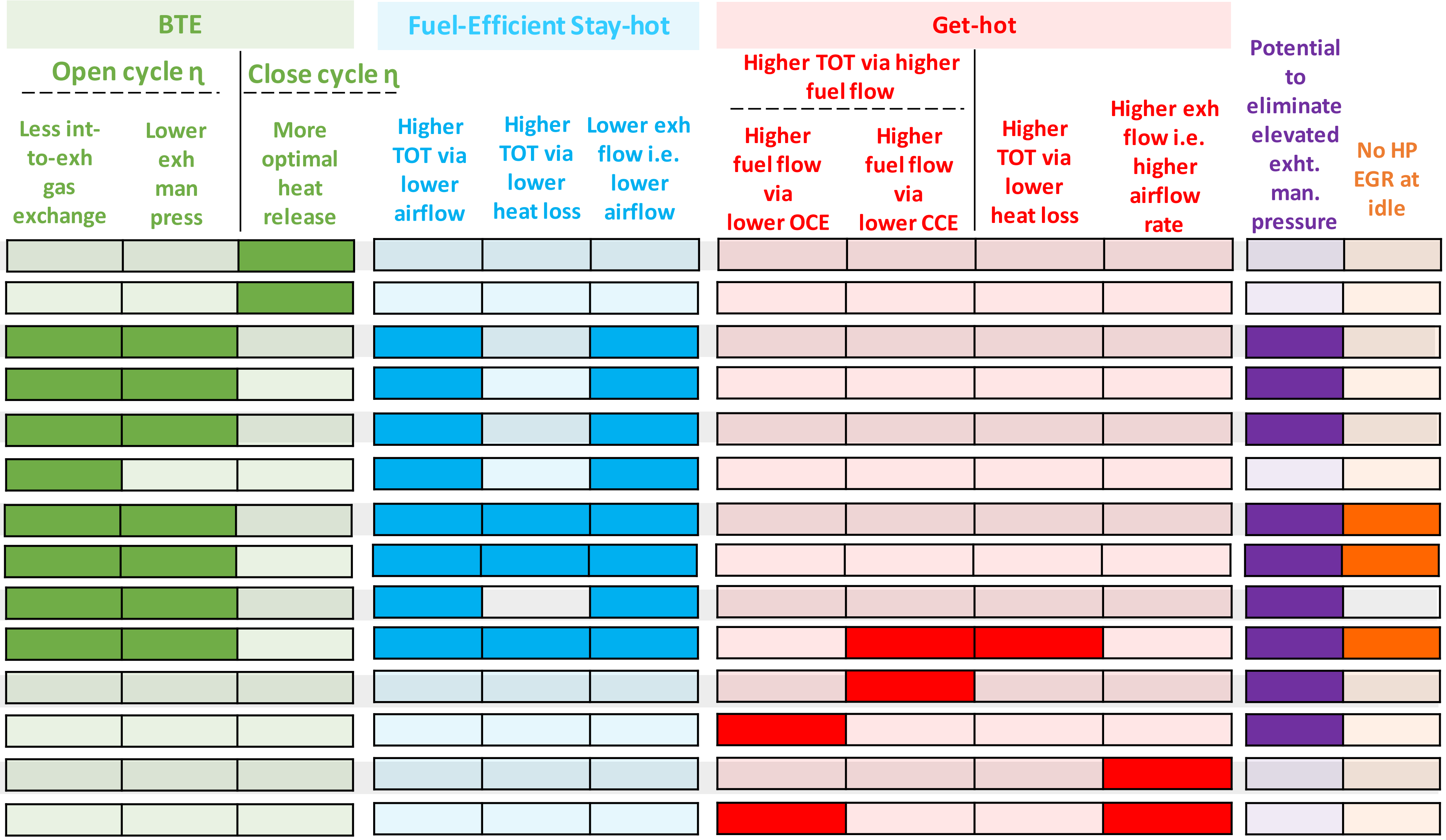




Ways to increase open cycle efficiency

- Reduce intake-to-exhaust manifold gas exchange
    - Use VVA to lower per cylinder int.-to-exht. man. gas exchange (iEGR, IVC)
    - Use VVA to decrease # of cylinders exchanging gas from int-to-exht. man. (CDA, DCA, NFCV, rev. breathing, cyl. cut, etc.)
- Lower exhaust manifold pressure
    - Use VVA to reduce back pressure req'd for thermal management or to drive HP EGR (CDA, DCA, NFCV, rev. breathing, iEGR, IVC)

VVA improves diesel engine fuel efficiency and aftertreatment thermal management.



Summary

1. Miller cycling
2. Dynamic charging
3. **Cylinder deactivation**
4. Dynamic cylinder activation
5. Non-fired cyl. ventilation
6. Cylinder cutout
7. Reverse breathing
8. Intake rebreathing
9. IVC modulation
10. Internal EGR
11. Early exhaust valve opening
12. Late exhaust valve opening
13. 2-stroke breathing + VVA
14. High speed idle + VVA
15. Challenges with CDA?

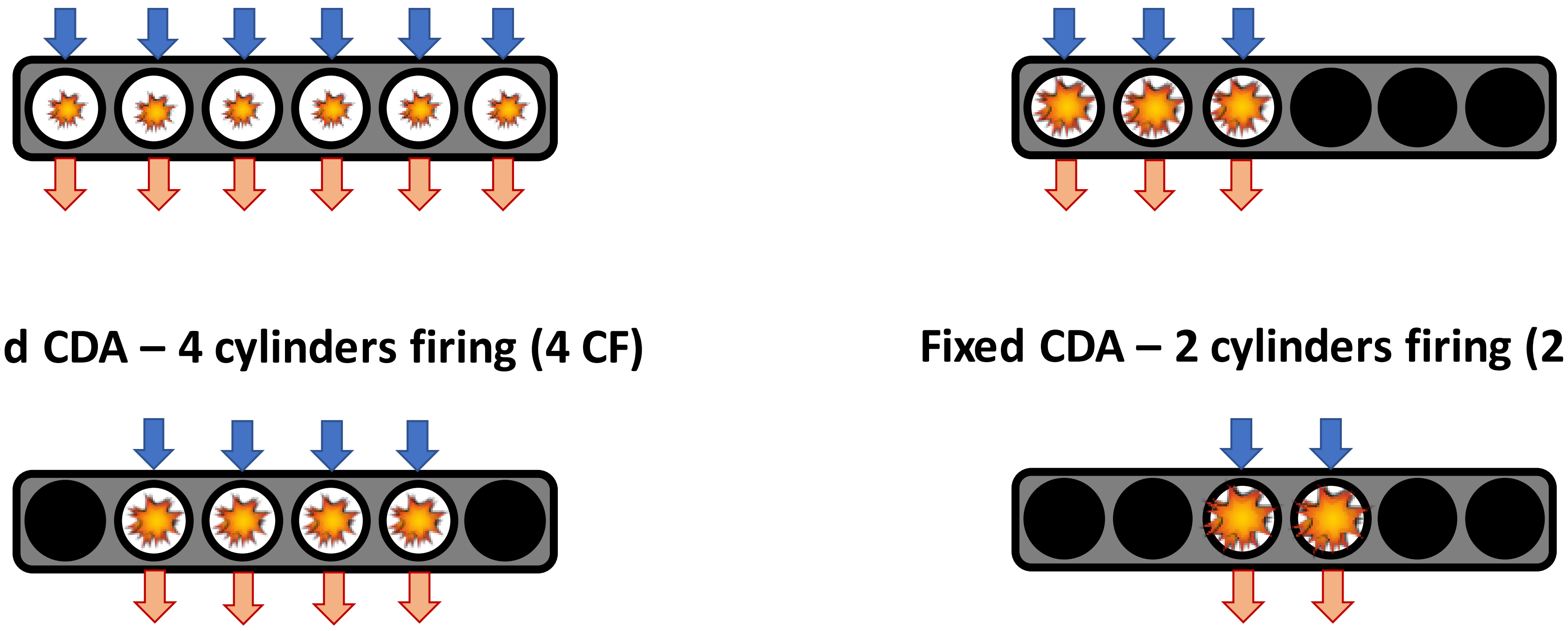
Cylinder Deactivation

Conventional six-cylinder operation

Fixed CDA – 3 cylinders firing (3 CF)

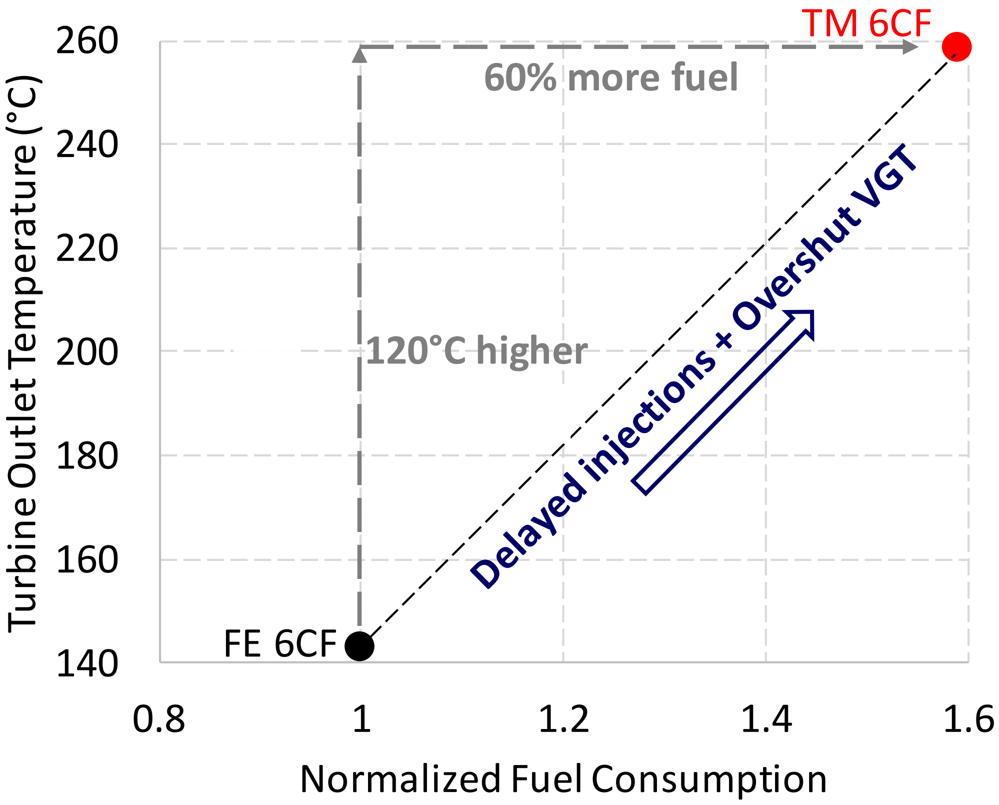
Fixed CDA – 4 cylinders firing (4 CF)

Fixed CDA – 2 cylinders firing (2 CF)

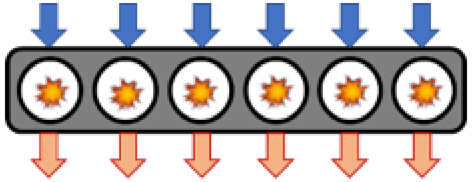


- Both valve actuation and fuel injection are disabled
- Fuel injected in the active cylinders is increased to meet torque/power
- Fixed set of cylinders are deactivated every engine cycle

Cylinder Deactivation – 800 rpm, 1.3 bar (curb idle)



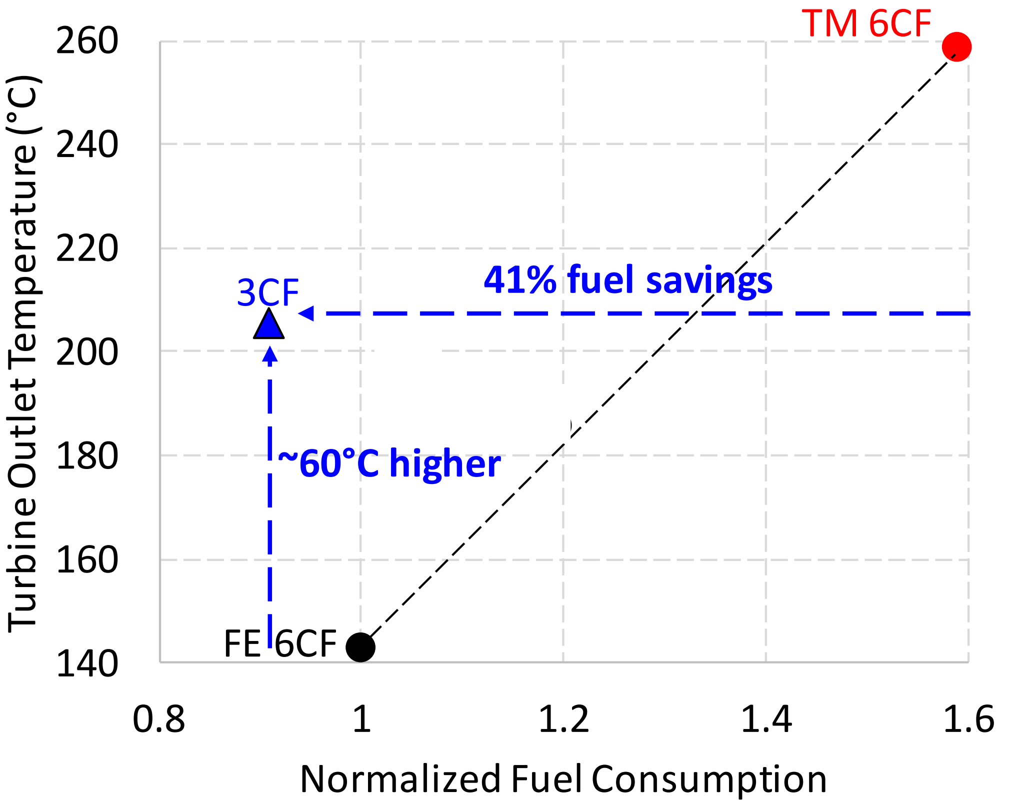
6 cylinder operation (6CF)



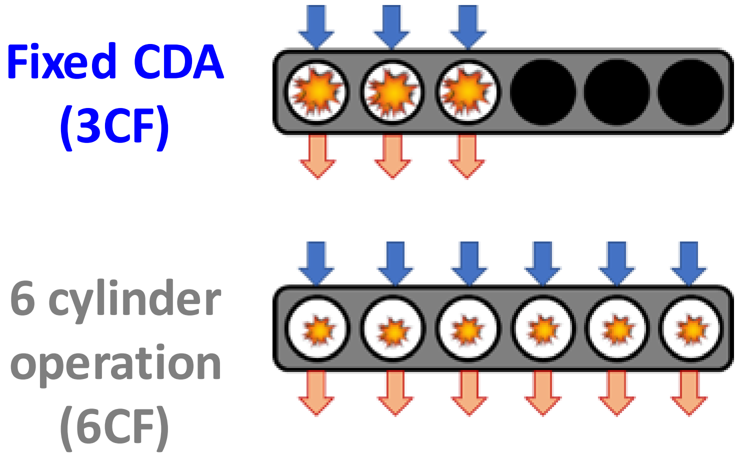
TM – conventional thermal management mode

FE – conventional fuel efficient mode

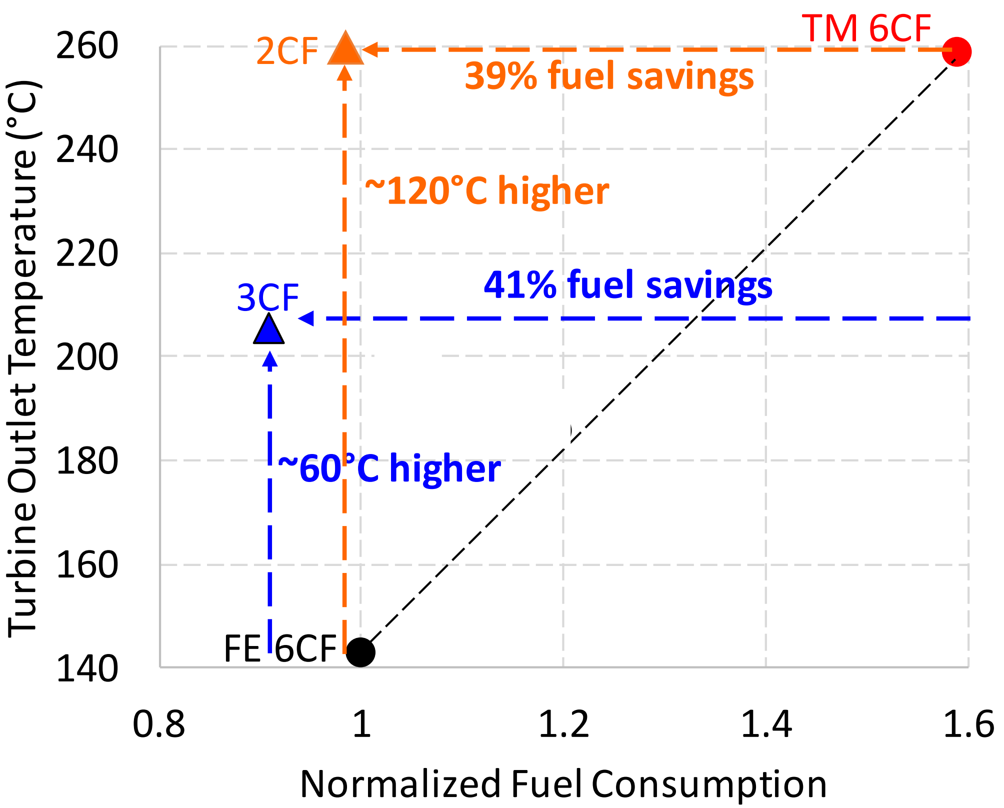
Cylinder Deactivation – 800 rpm, 1.3 bar (curb idle)



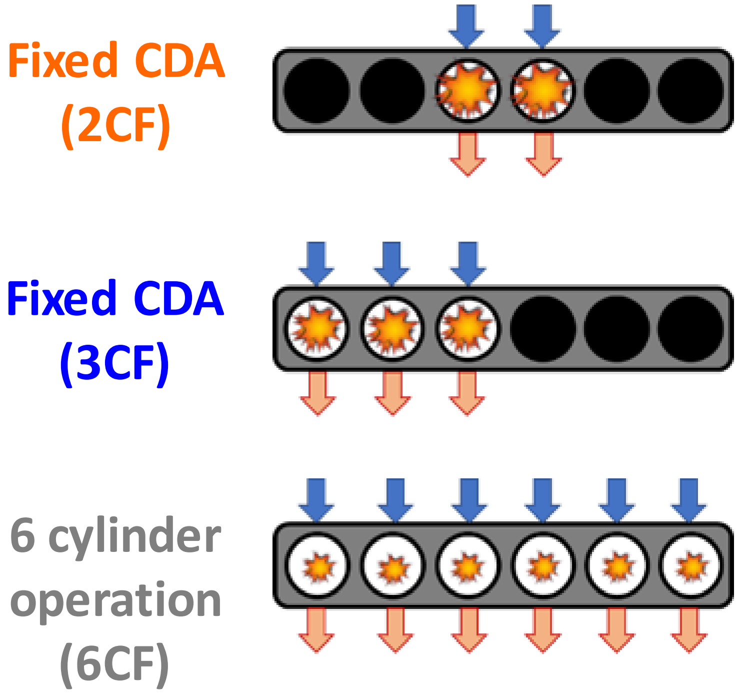
CDA achieves elevated engine-out temperatures at lower fuel consumption



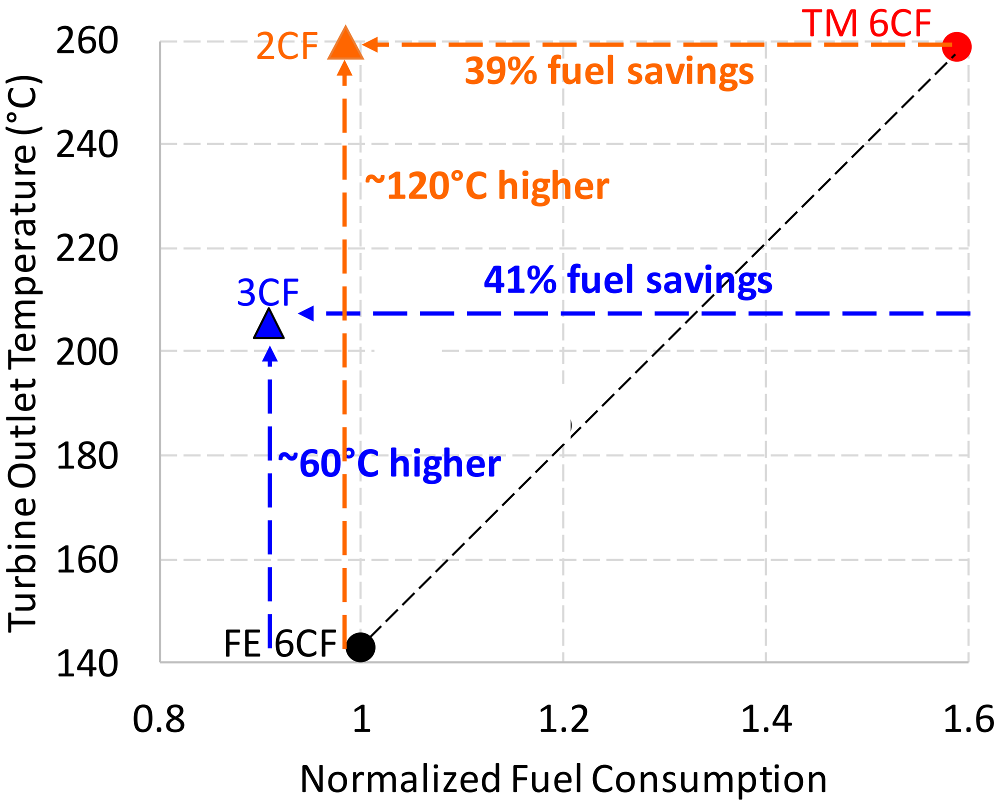
Cylinder Deactivation – 800 rpm, 1.3 bar (curb idle)



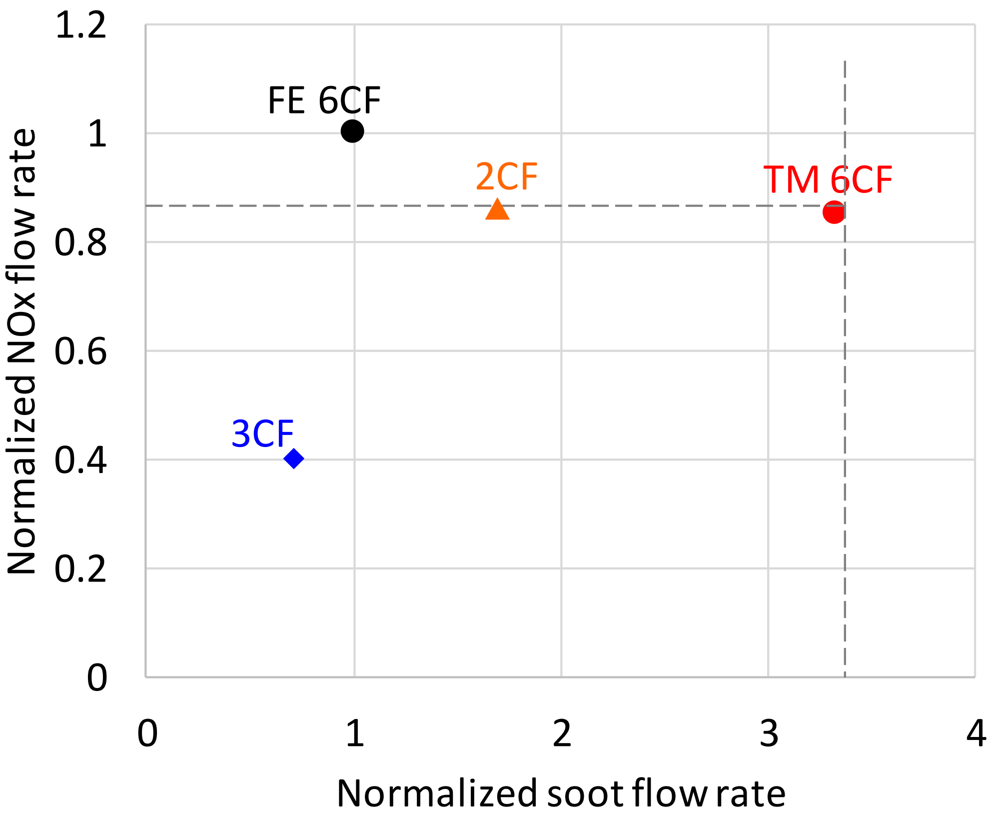
CDA achieves elevated engine-out temperatures at lower fuel consumption



Cylinder Deactivation – 800 rpm, 1.3 bar (curb idle)

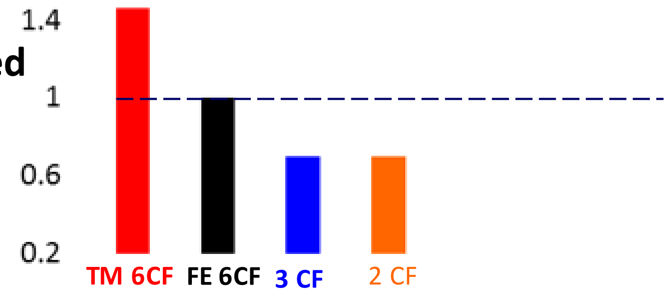


CDA achieves elevated engine-out temperatures at lower fuel consumption

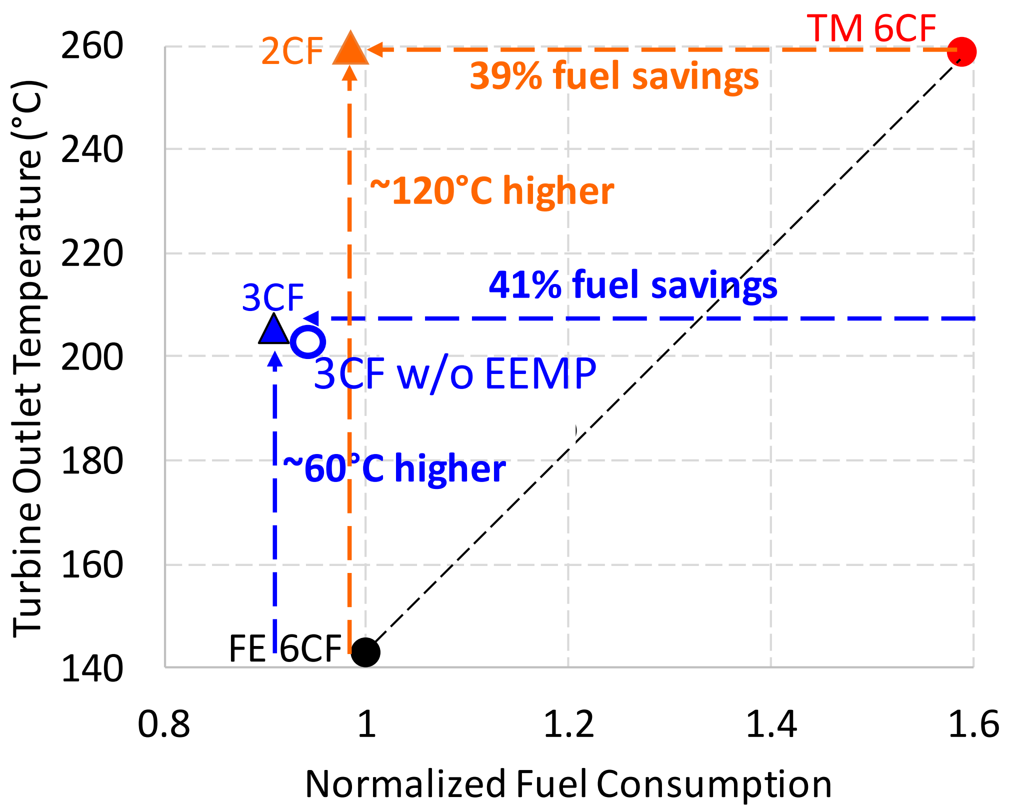


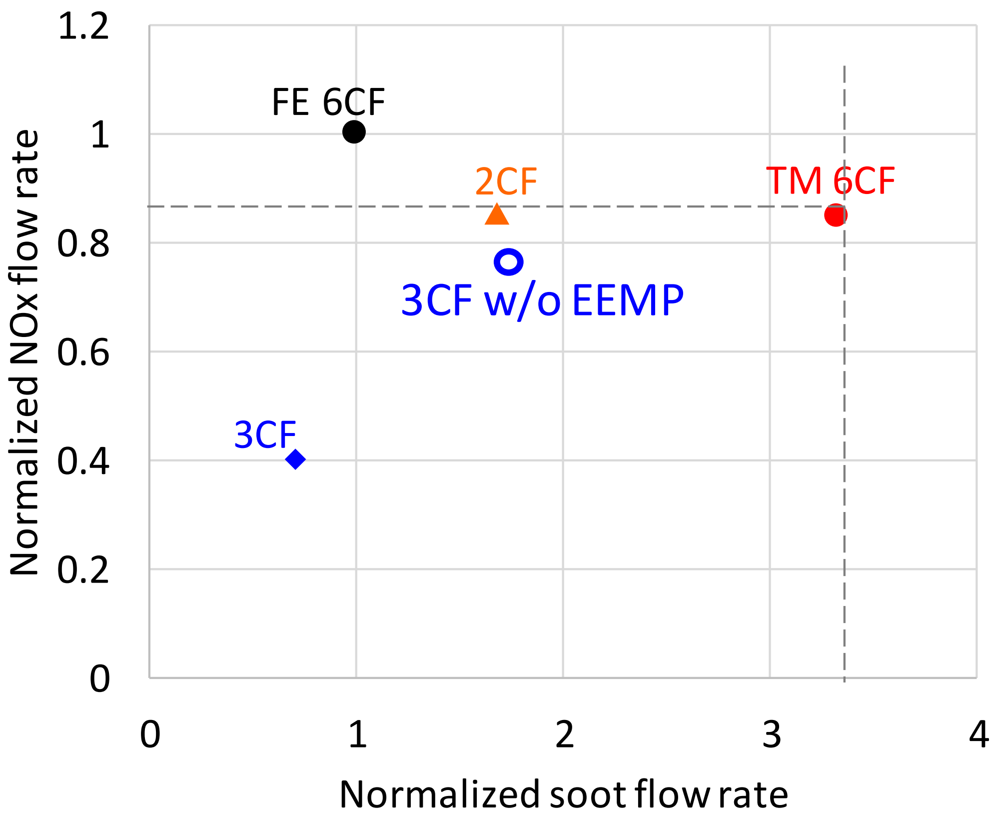
CDA shows lower engine-out NOx and soot emissions than conventional 6-cylinder thermal management operation

Normalized exhaust flow rates



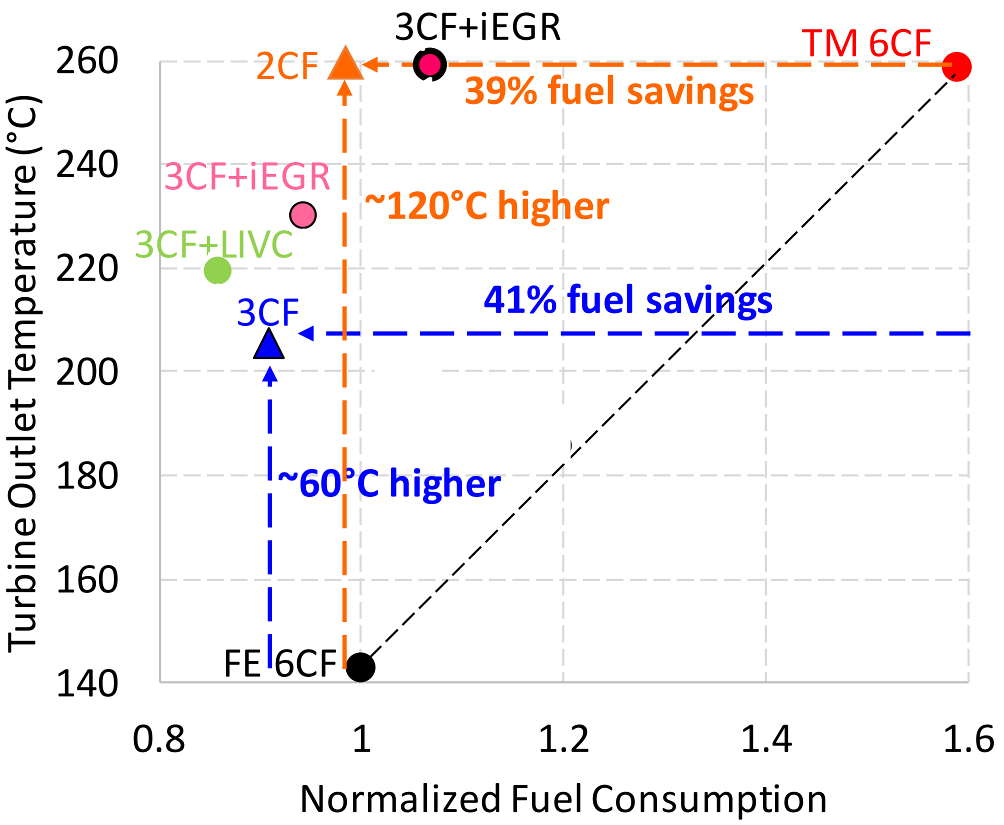
Cylinder Deactivation – Elev. Ext. Man. Pressure, at 800 rpm, 1.3 bar (curb idle)

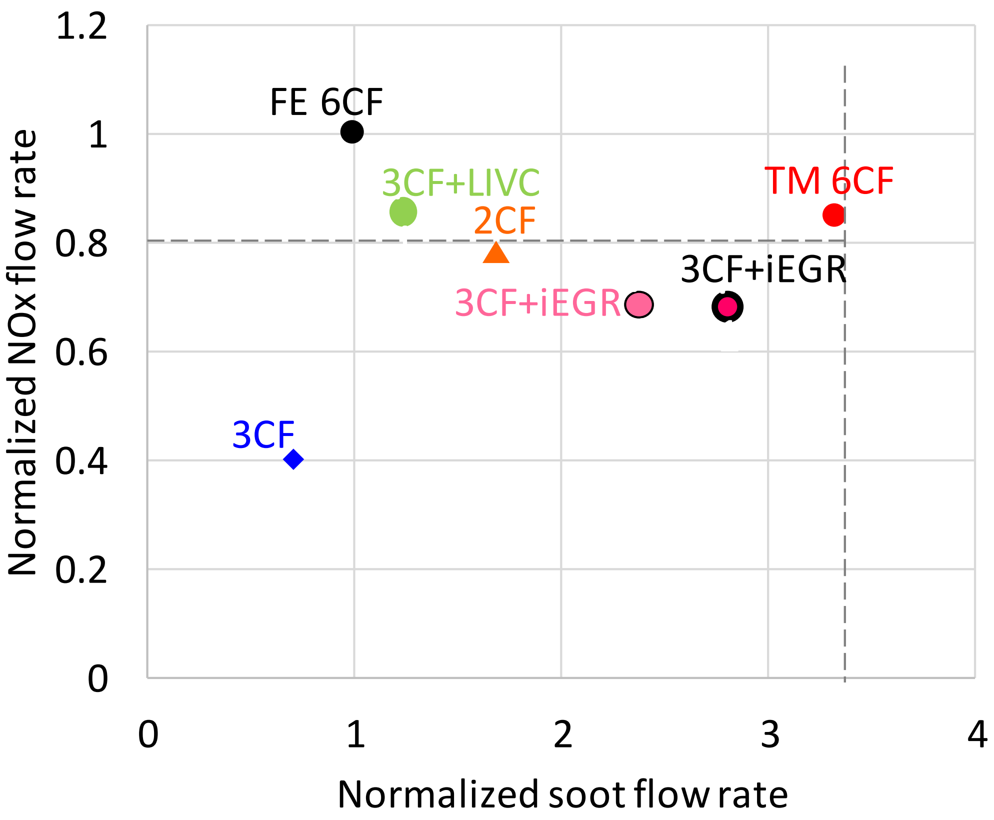




CDA can achieve elevated engine-out temperatures at lower fuel consumption
without requiring elevated exhaust manifold pressure (EEMP)

Cylinder Deactivation – CDA+LIVC and CDA+iEGR at 800 rpm, 1.3 bar (curb idle)





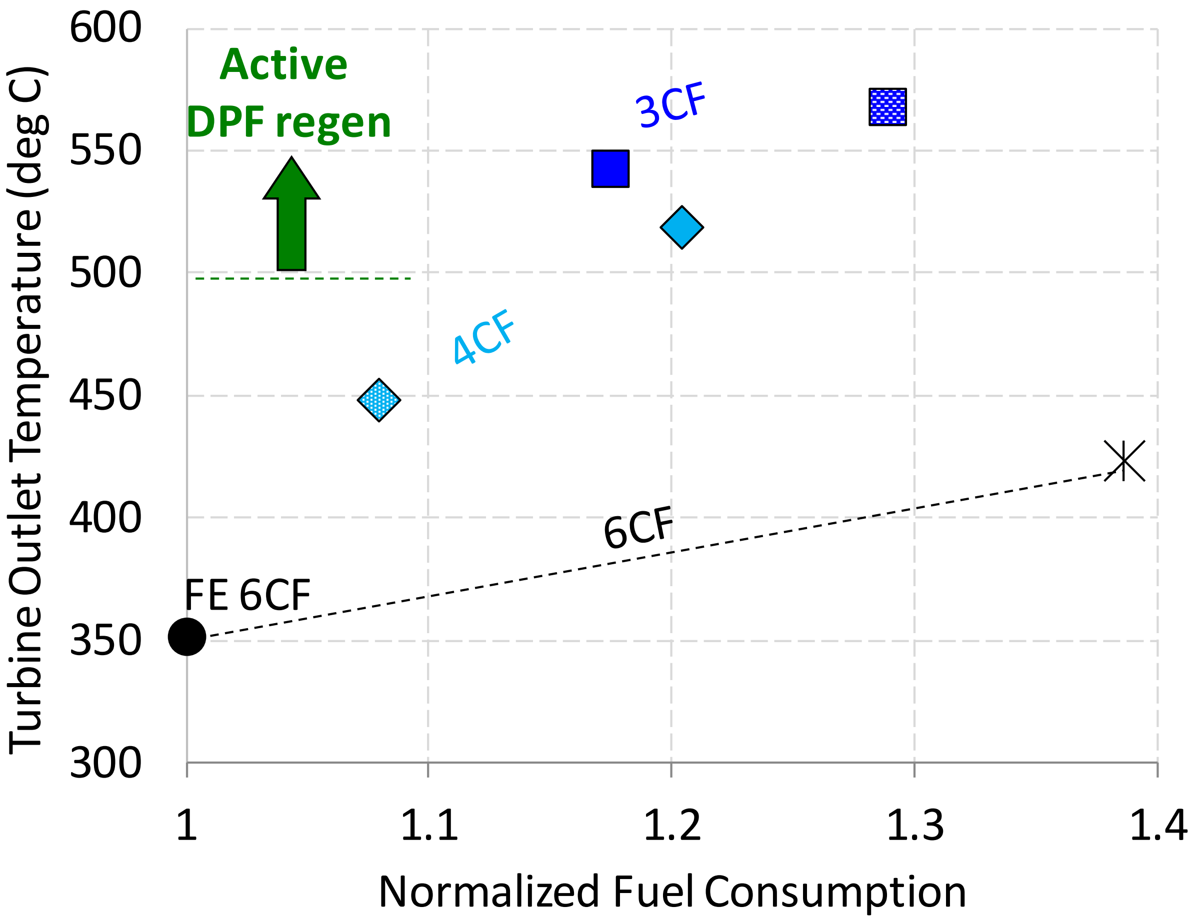
- CDA+LIVC : Higher TOT, lower fuel consumption than 3CF
- CDA+iEGR : Enables improved TOT vs FC tradeoff

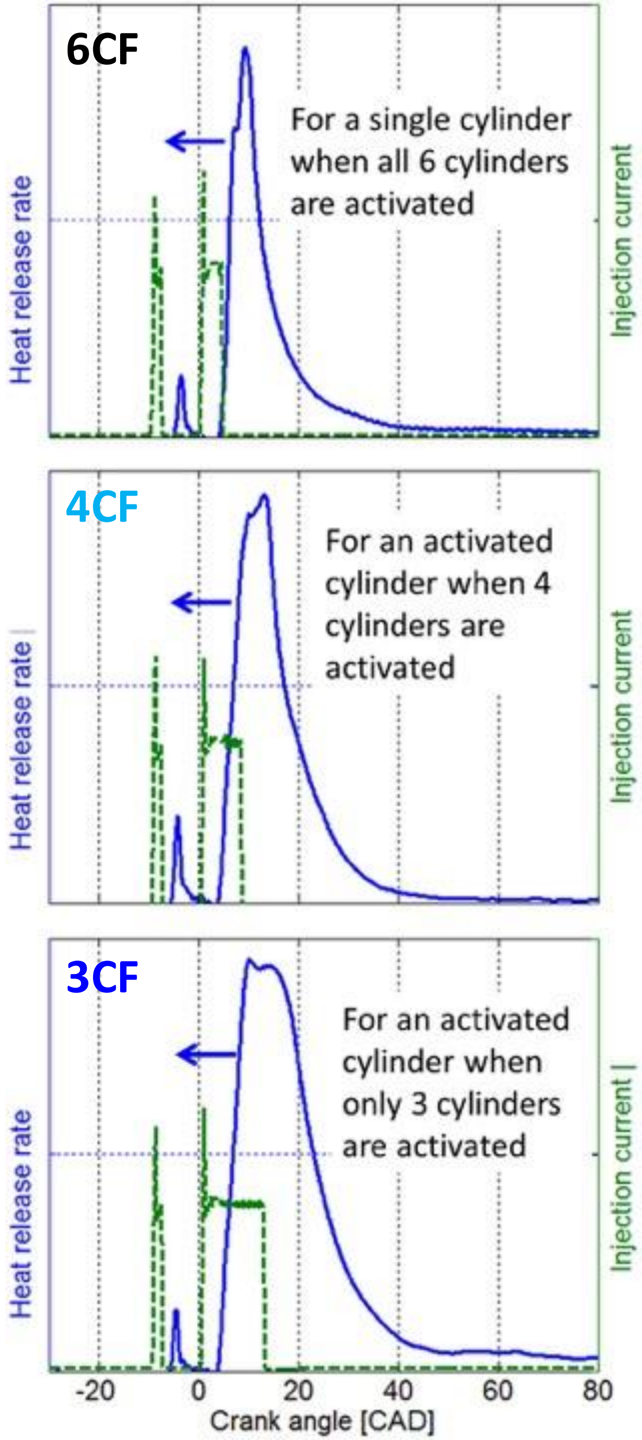
- CDA+LIVC
- CDA+iEGR

} Within desired emission constraints

Cylinder Deactivation – Highway cruise 1200 rpm, 7.6 bar

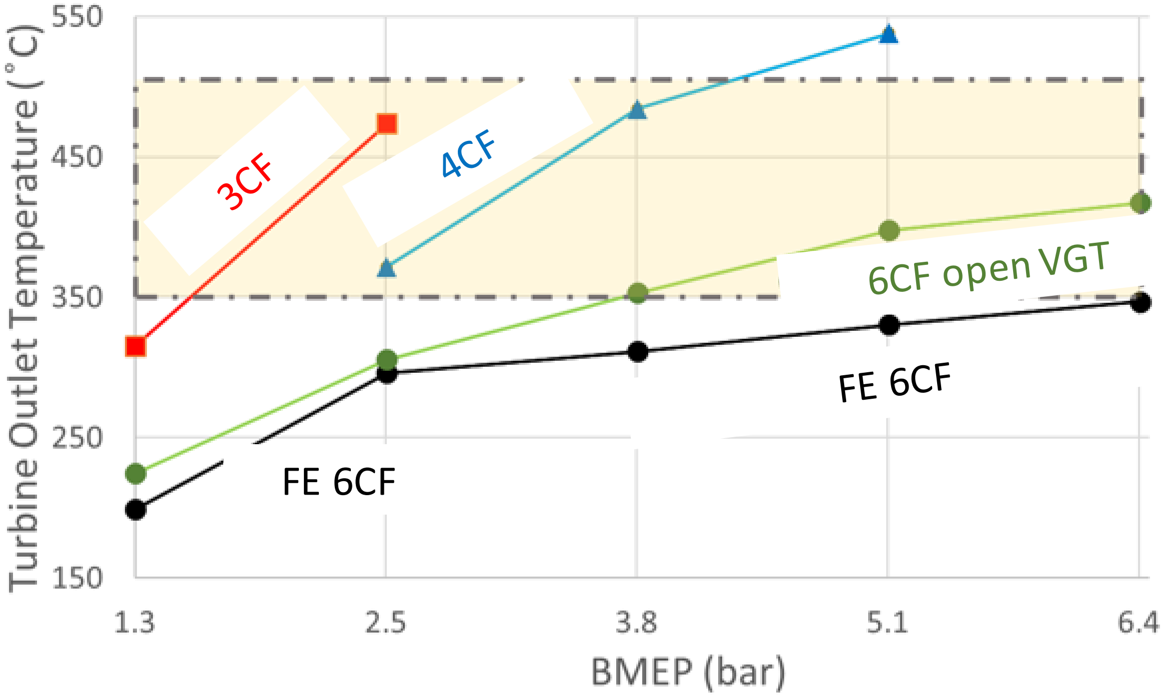
- CDA yields higher engine-outlet temperatures than 6-cylinder operation, making it possible to perform DPF regeneration during highway cruise
- Fuel penalty with respect to best BSFC 6-cyl operation

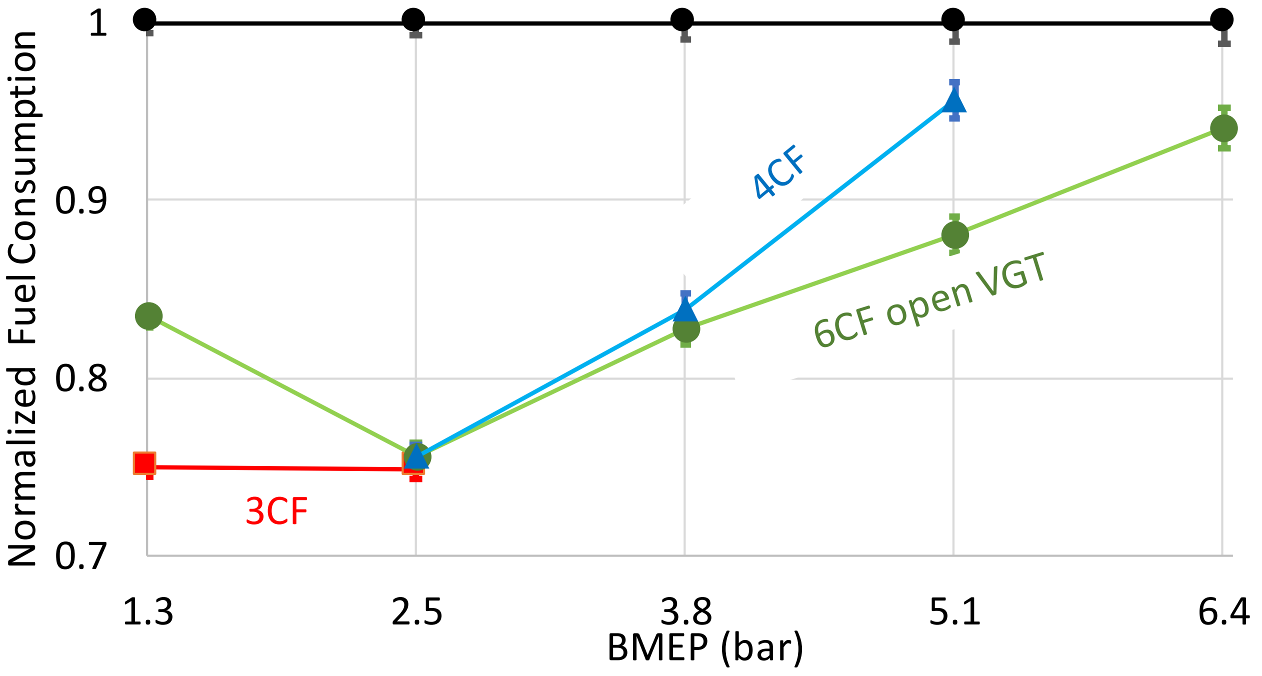




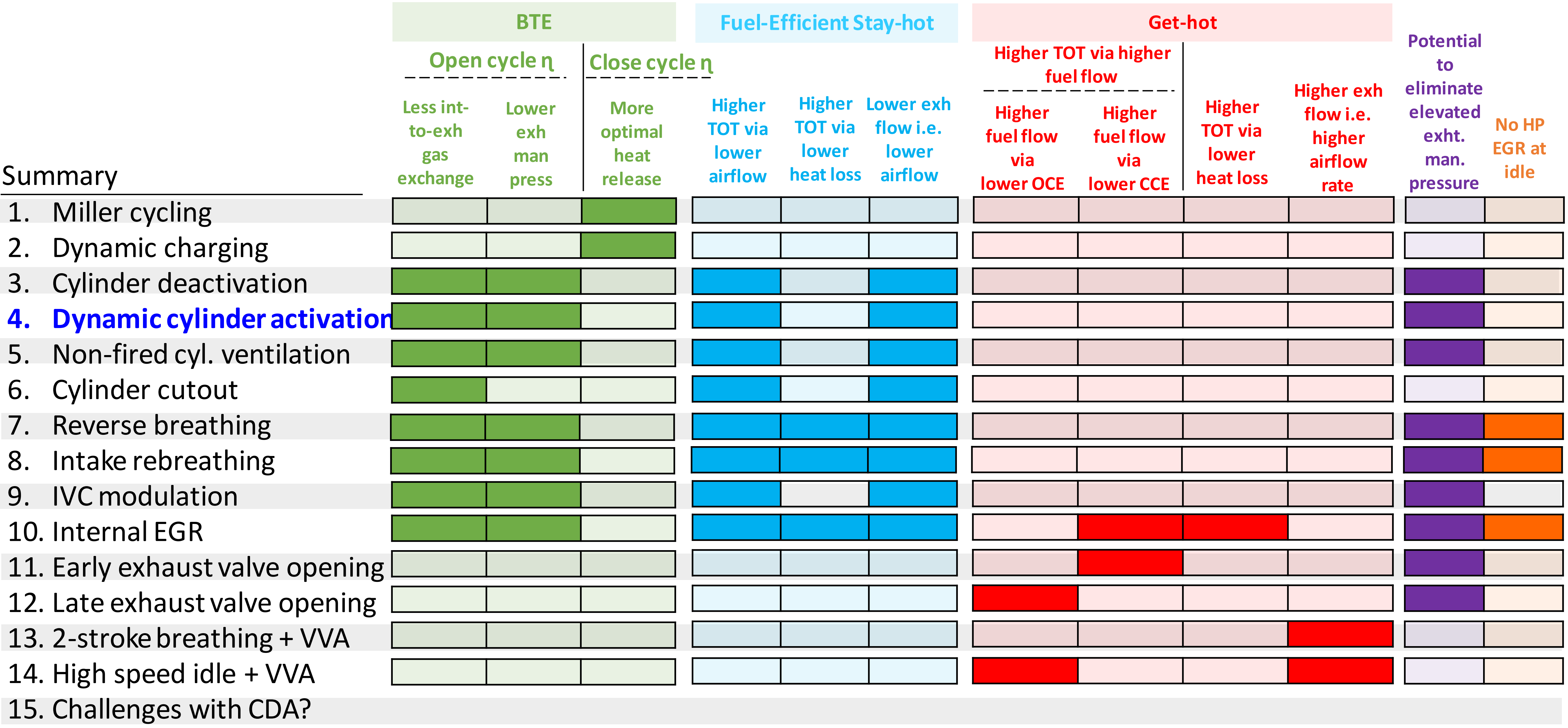
Cylinder Deactivation – 2200 rpm, 1.3-5.2 bar

CDA results in 4-25% fuel savings, depending on engine load, and yields up to 200 deg C higher engine-out temperatures





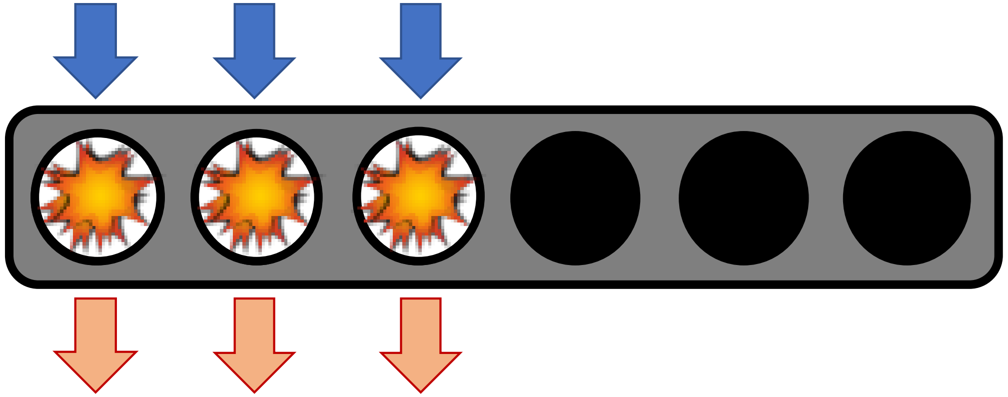
VVA improves diesel engine fuel efficiency and aftertreatment thermal management.



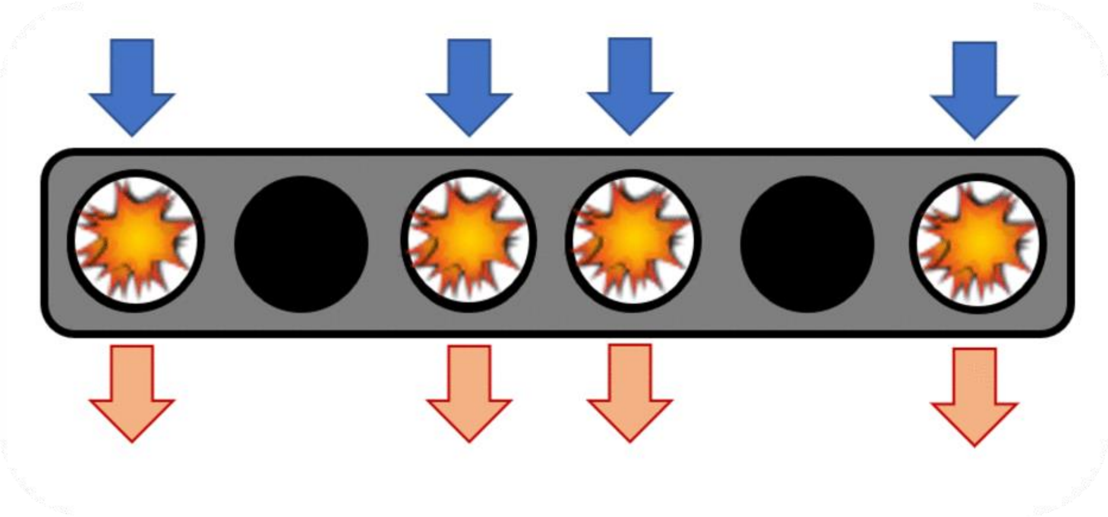
Dynamic Cylinder Activation (DCA)

Form of CDA with a different set of active cylinders each engine cycle

Fixed Cylinder Deactivation
Fixed CDA (3 CF)

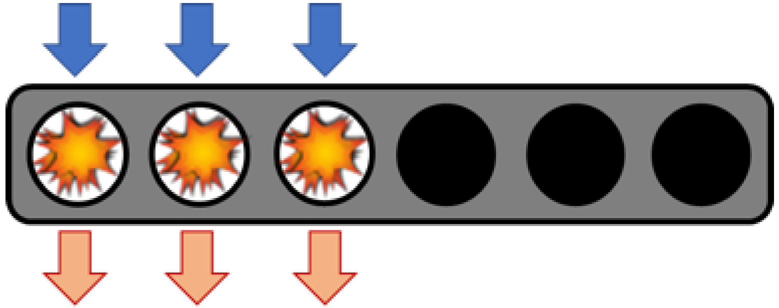


Dynamic Cylinder Activation
DCA (3 CF equivalent)

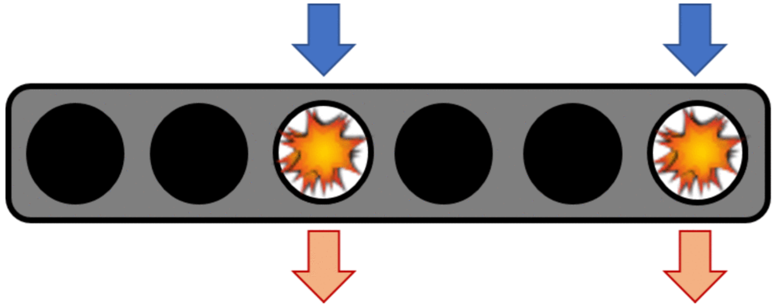


Dynamic Cylinder Activation is studied using two ‘recipes’

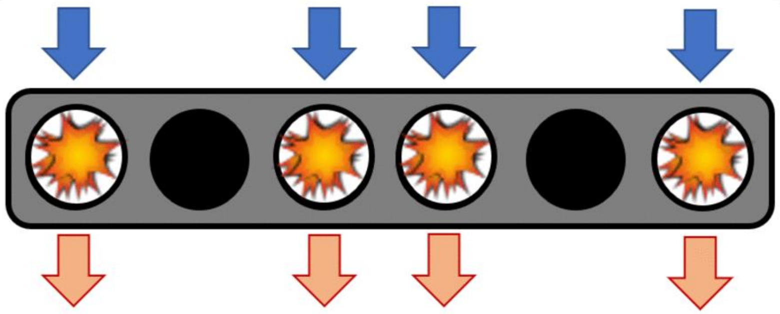
Fixed CDA



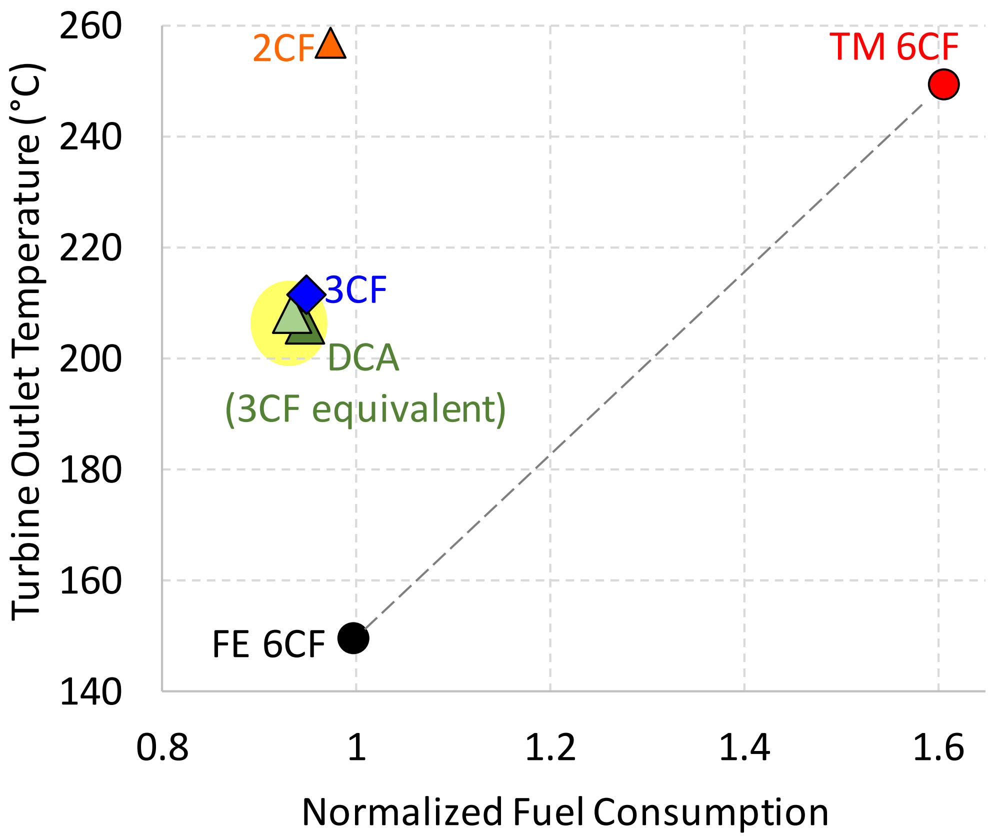
DCA
alternating pattern

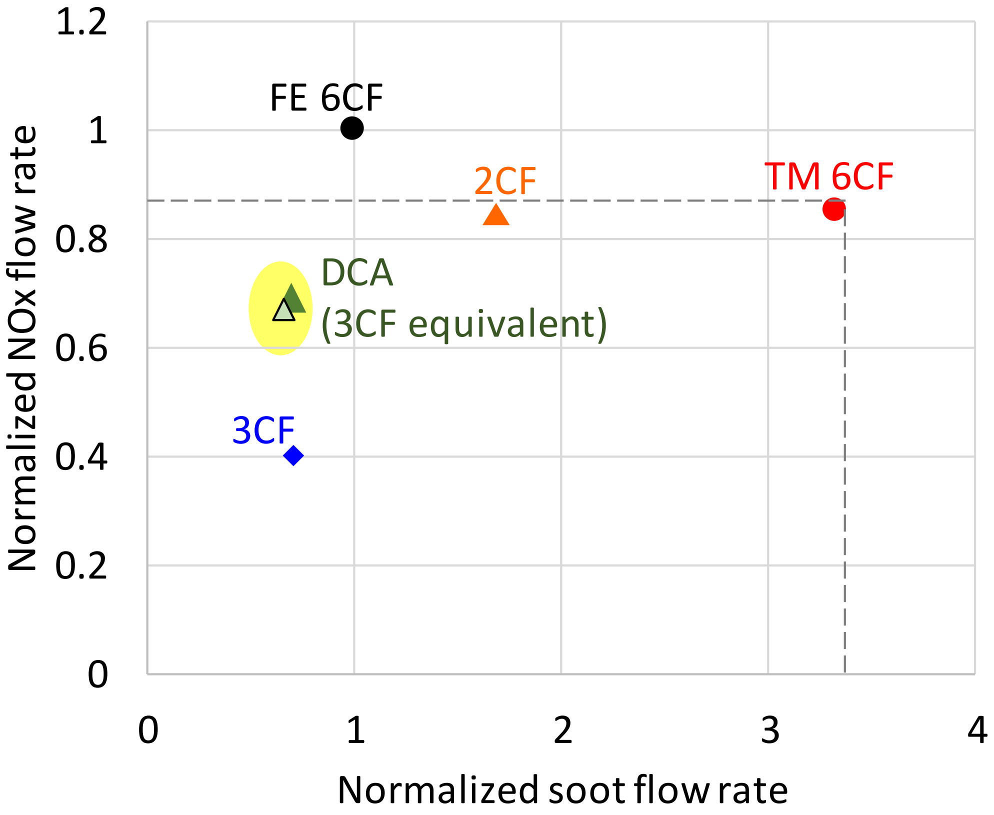


DCA
aperiodic pattern



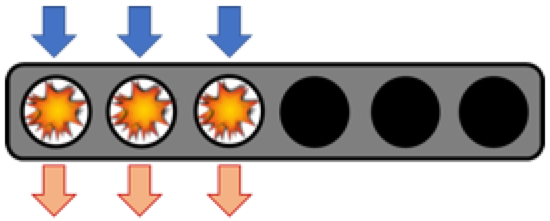
Dynamic Cylinder Activation at 800 rpm, 1.3 bar

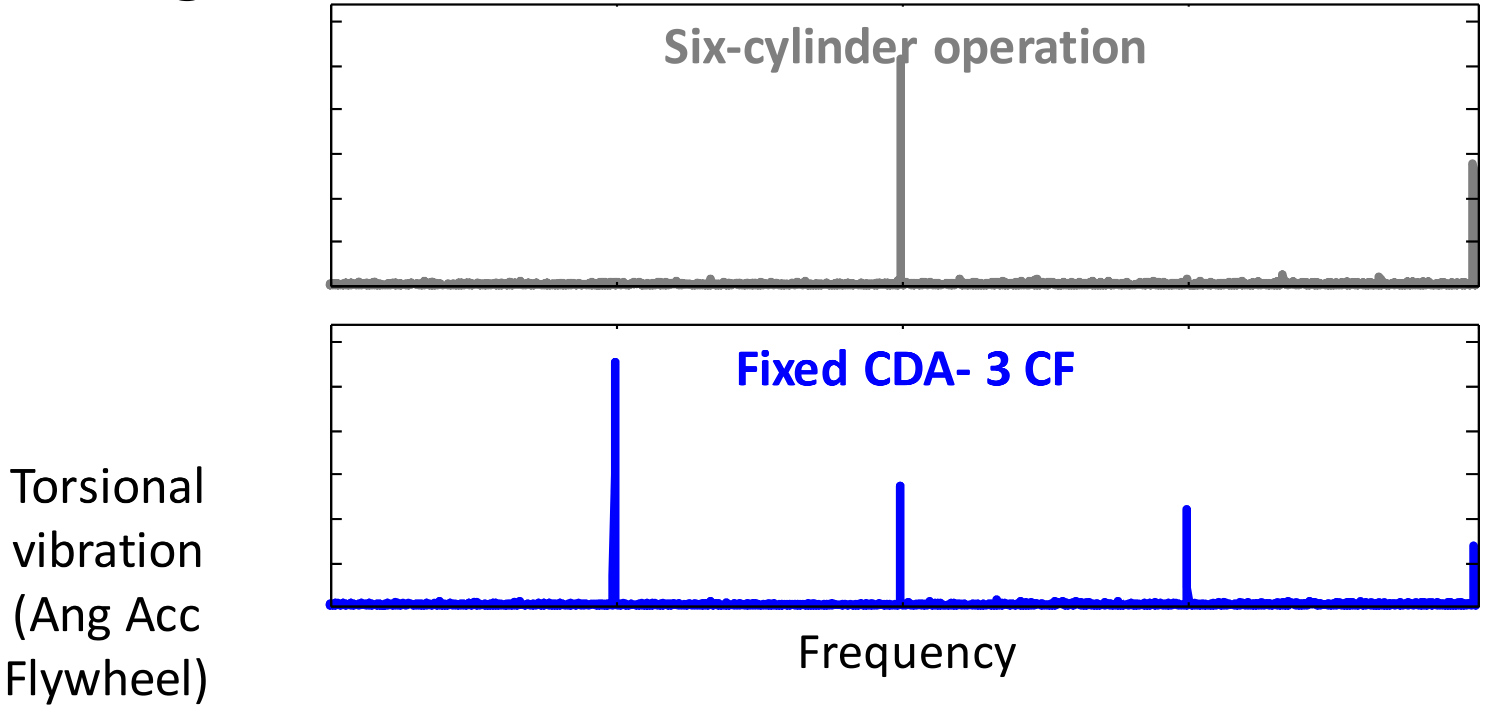




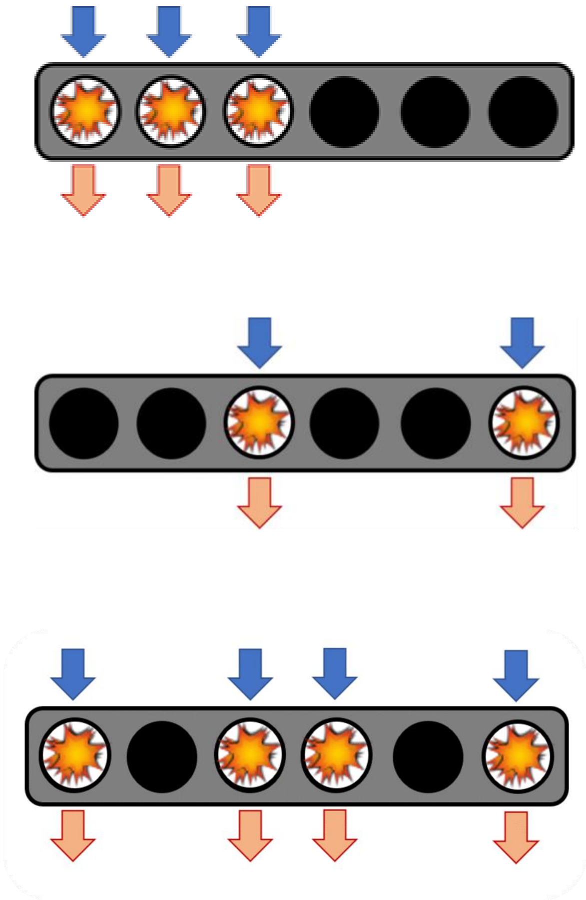
DCA shows similar fuel savings, exhaust temperatures and emissions as fixed CDA with equivalent number of cylinders firing

Torsional vibration in DCA- Additional degree of freedom

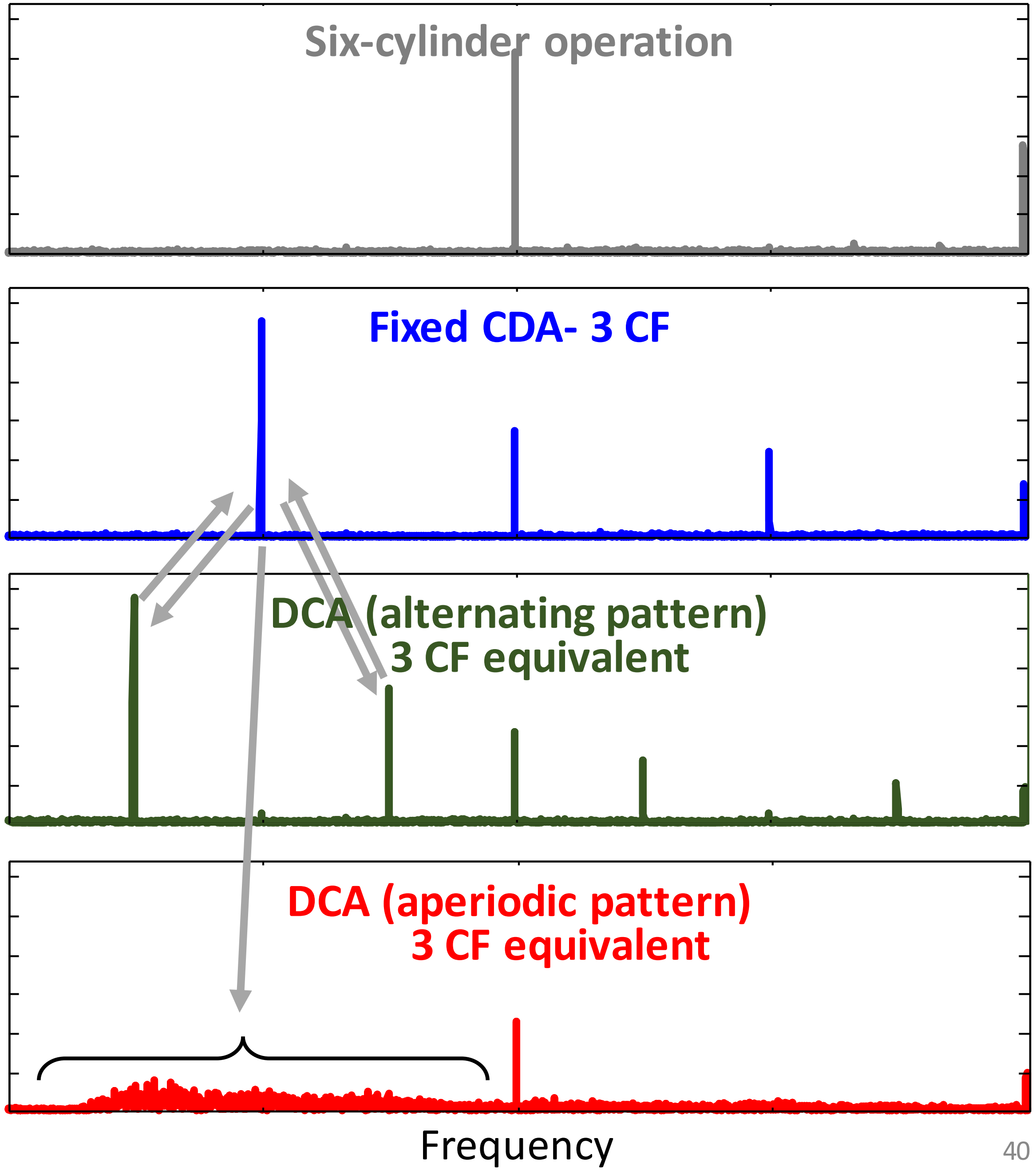




Torsional vibration in DCA- Additional degree of freedom

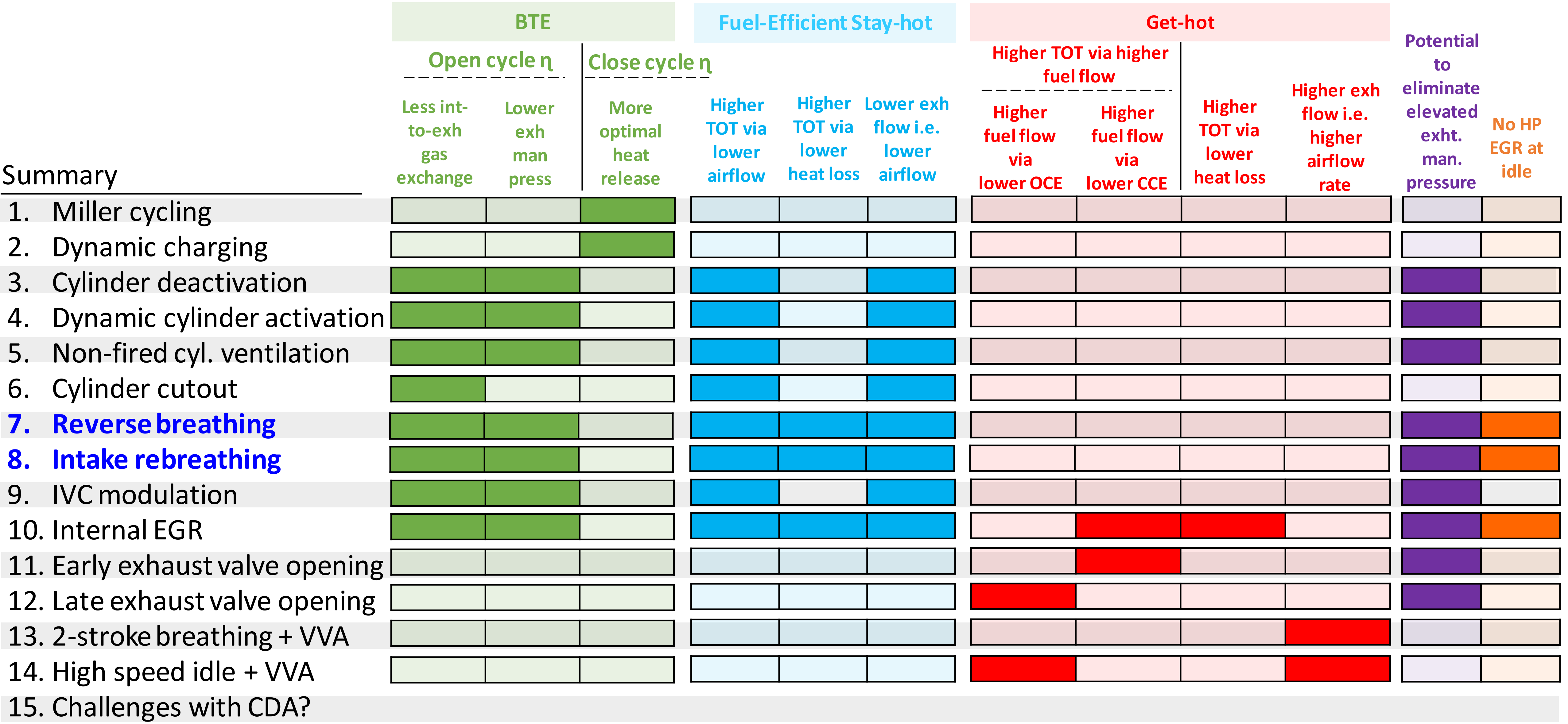


Torsional vibration (Ang Acc Flywheel)

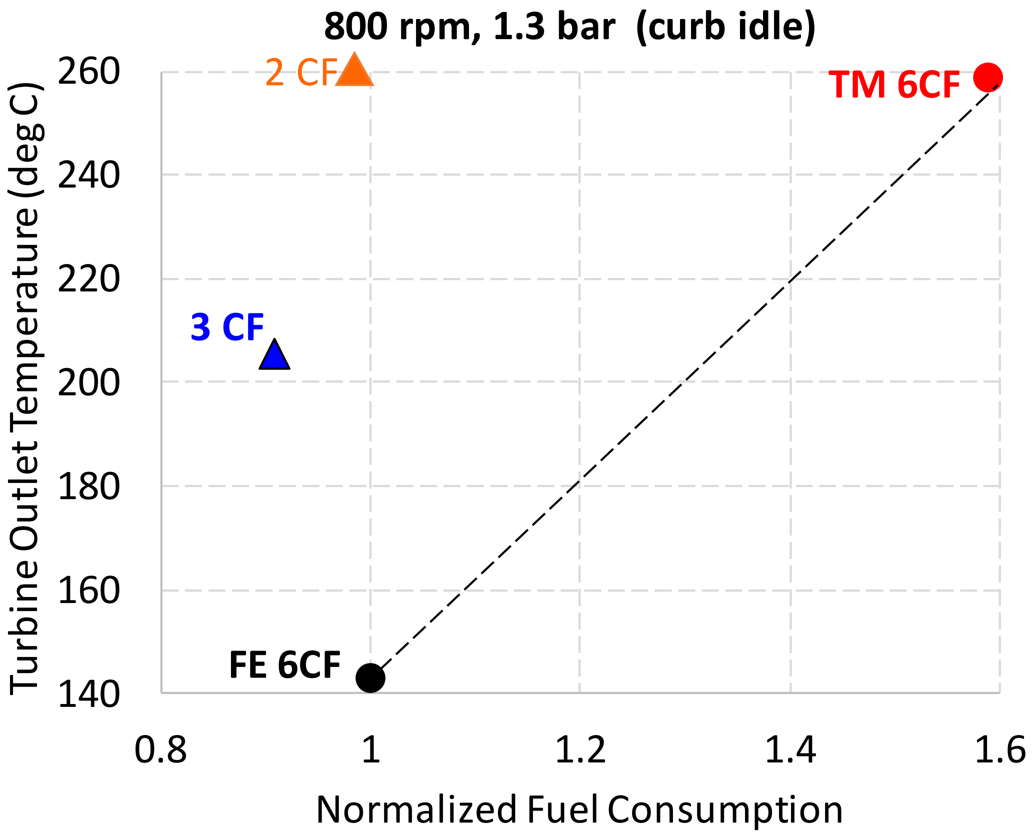


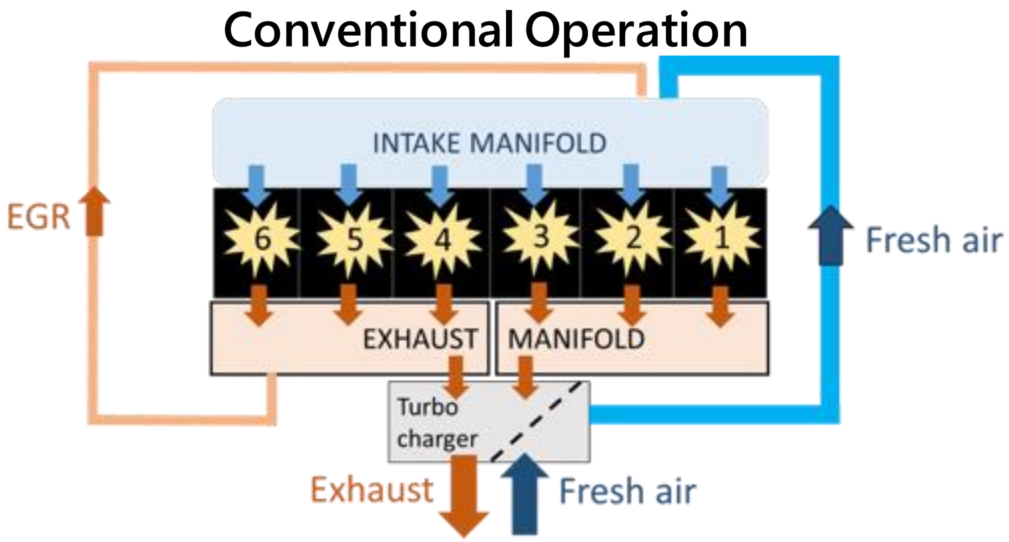
Acceptable torsional vibration –
Switch between fixed CDA and appropriate DCA strategy depending on engine speed

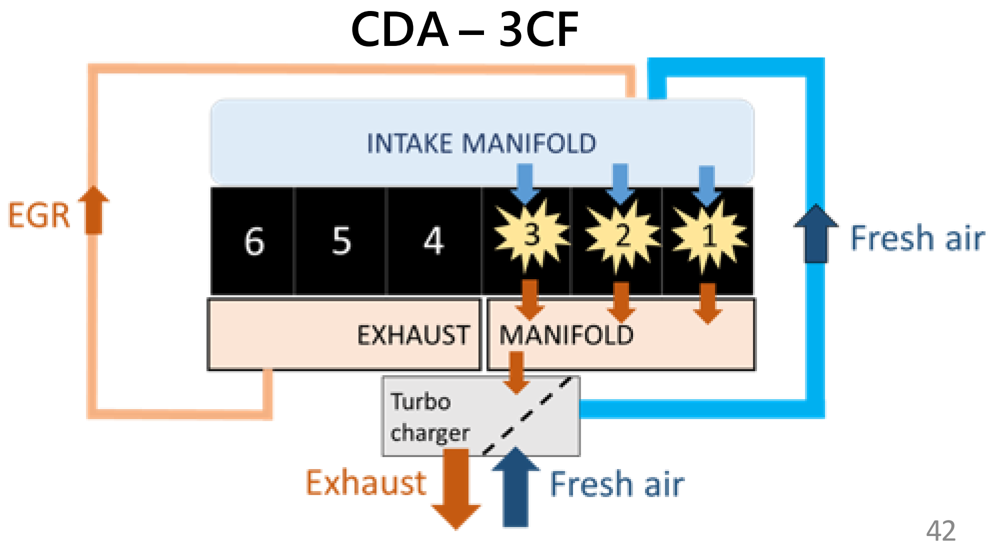
VVA improves diesel engine fuel efficiency and aftertreatment thermal management.



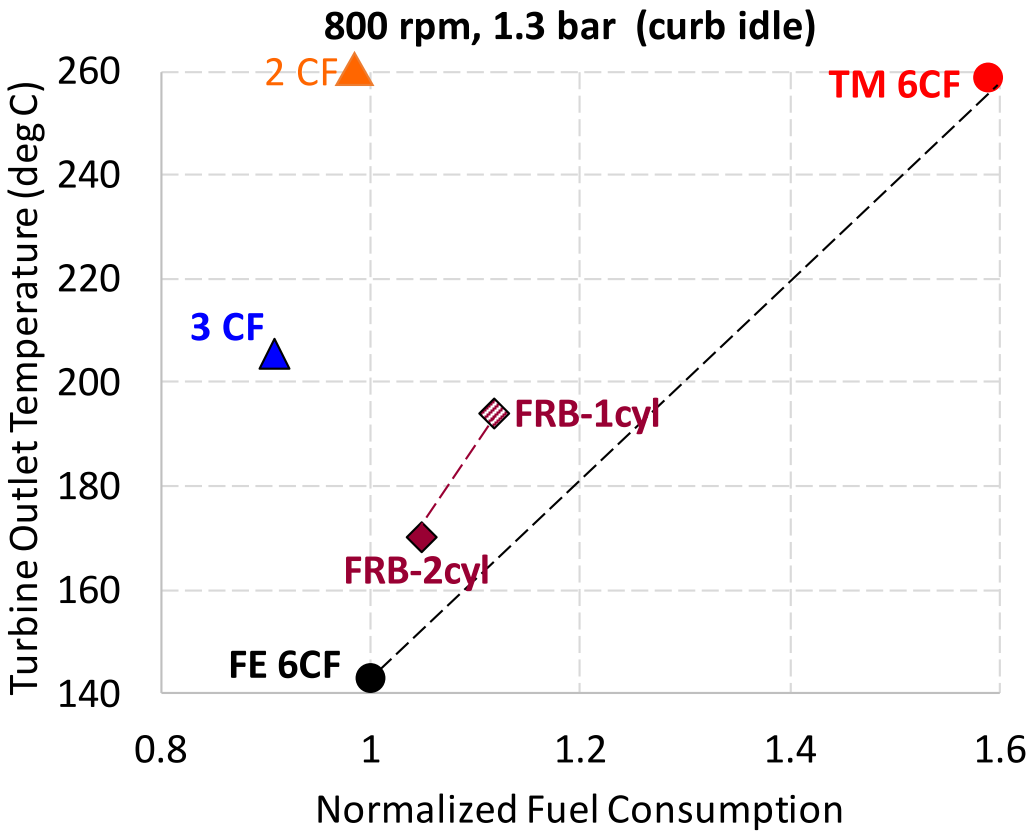
Reverse breathing and intake rebreathing for stay-hot



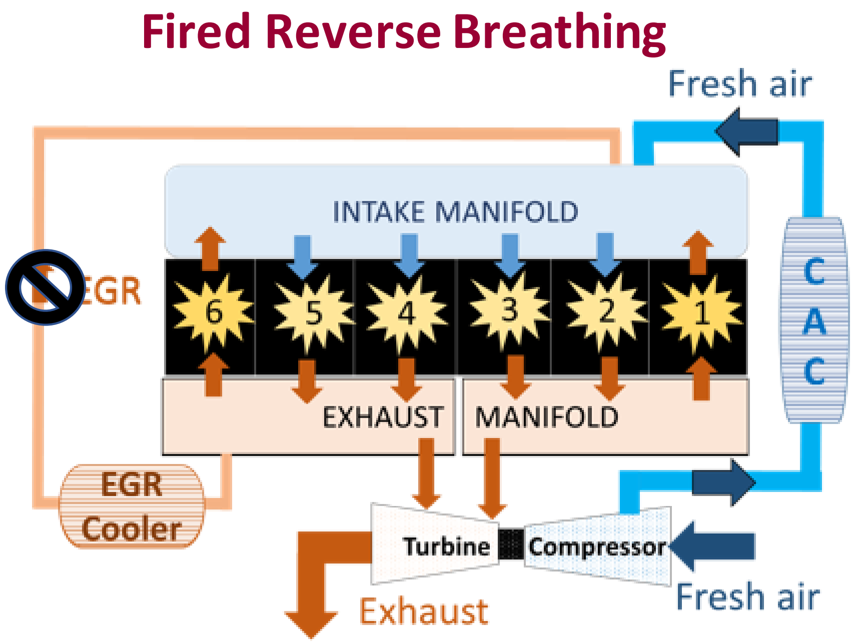




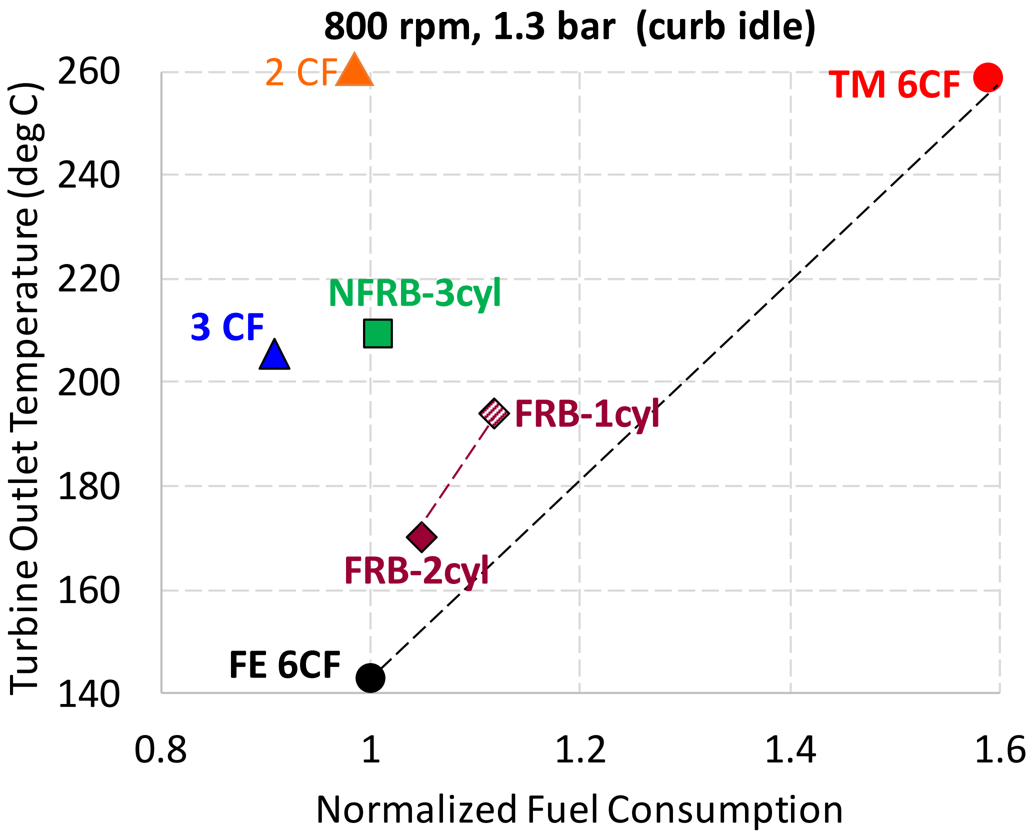
Reverse breathing and intake rebreathing for stay-hot



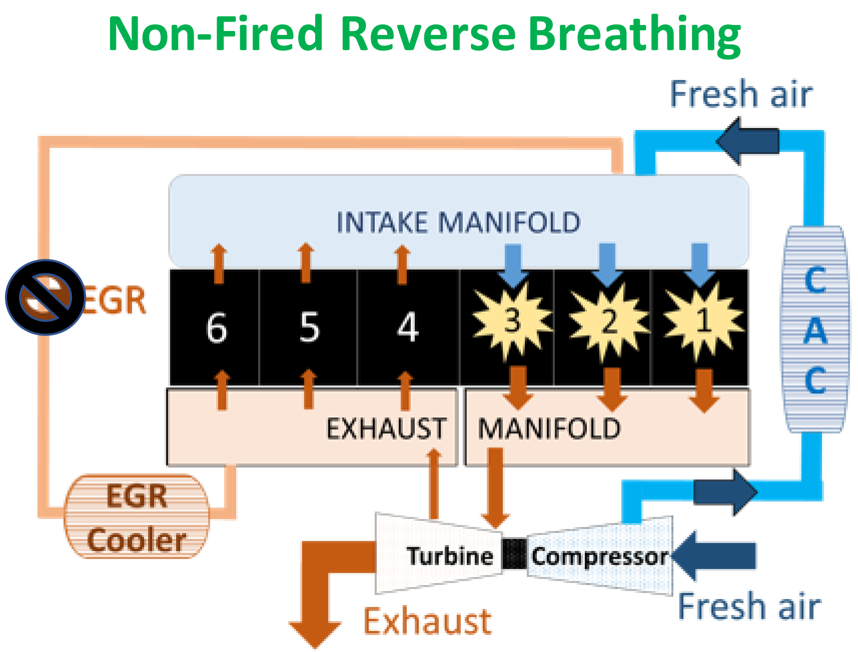
- Uses no external EGR
- Low airflow strategy



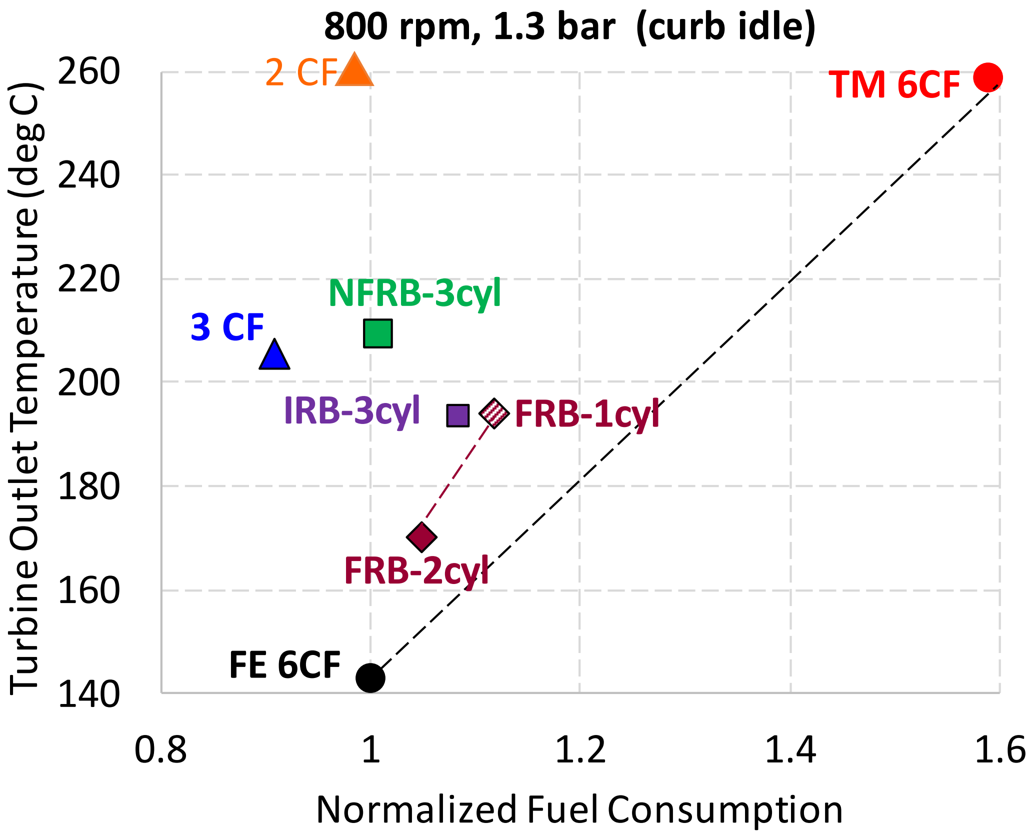
Reverse breathing and intake rebreathing for stay-hot



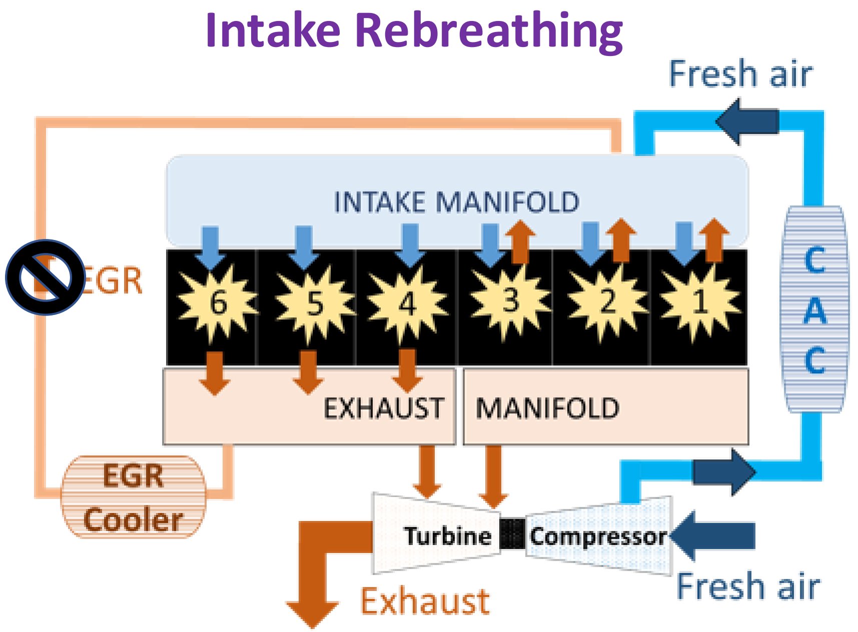
- Uses no external EGR
- Low airflow strategy



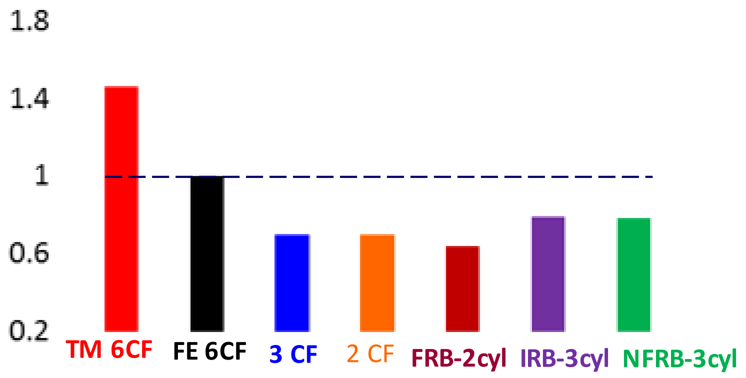
Reverse breathing and intake rebreathing for stay-hot



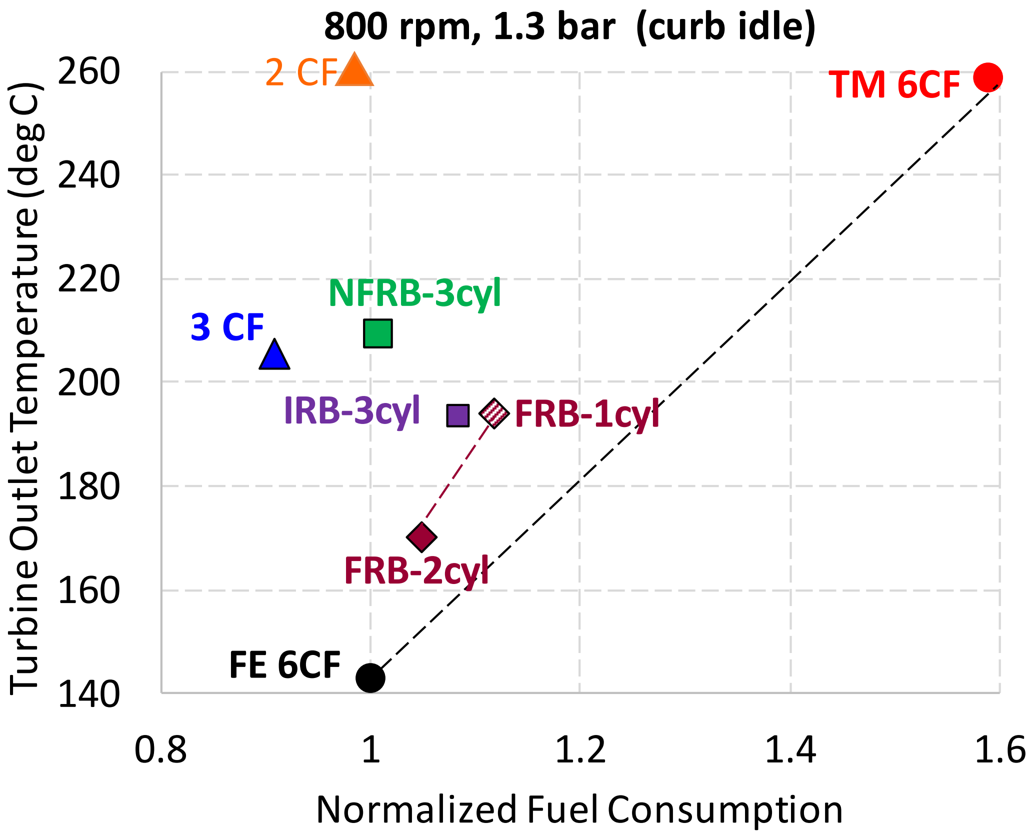
- Uses no external EGR
- Low airflow strategy

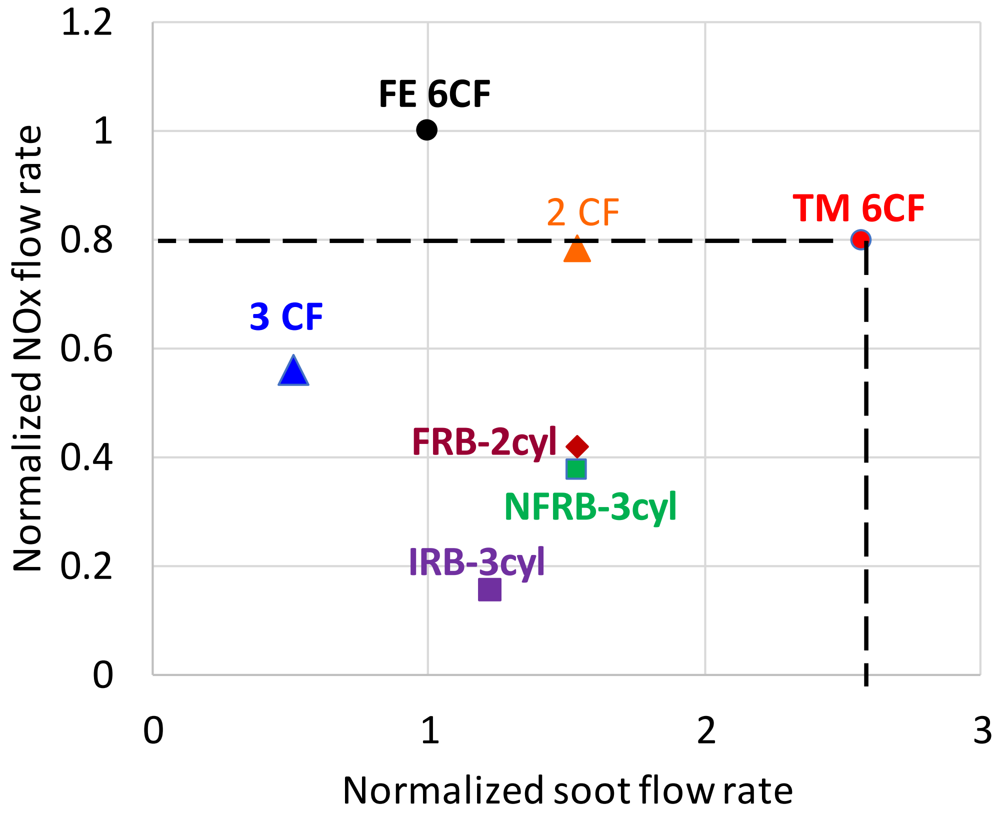


Normalized exhaust flow rates

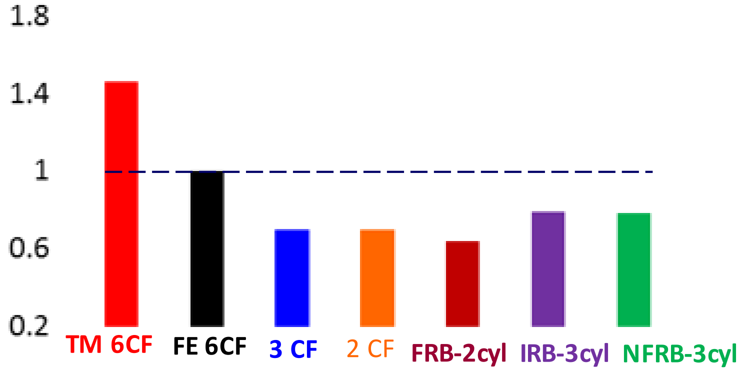


Reverse breathing and intake rebreathing for stay-hot

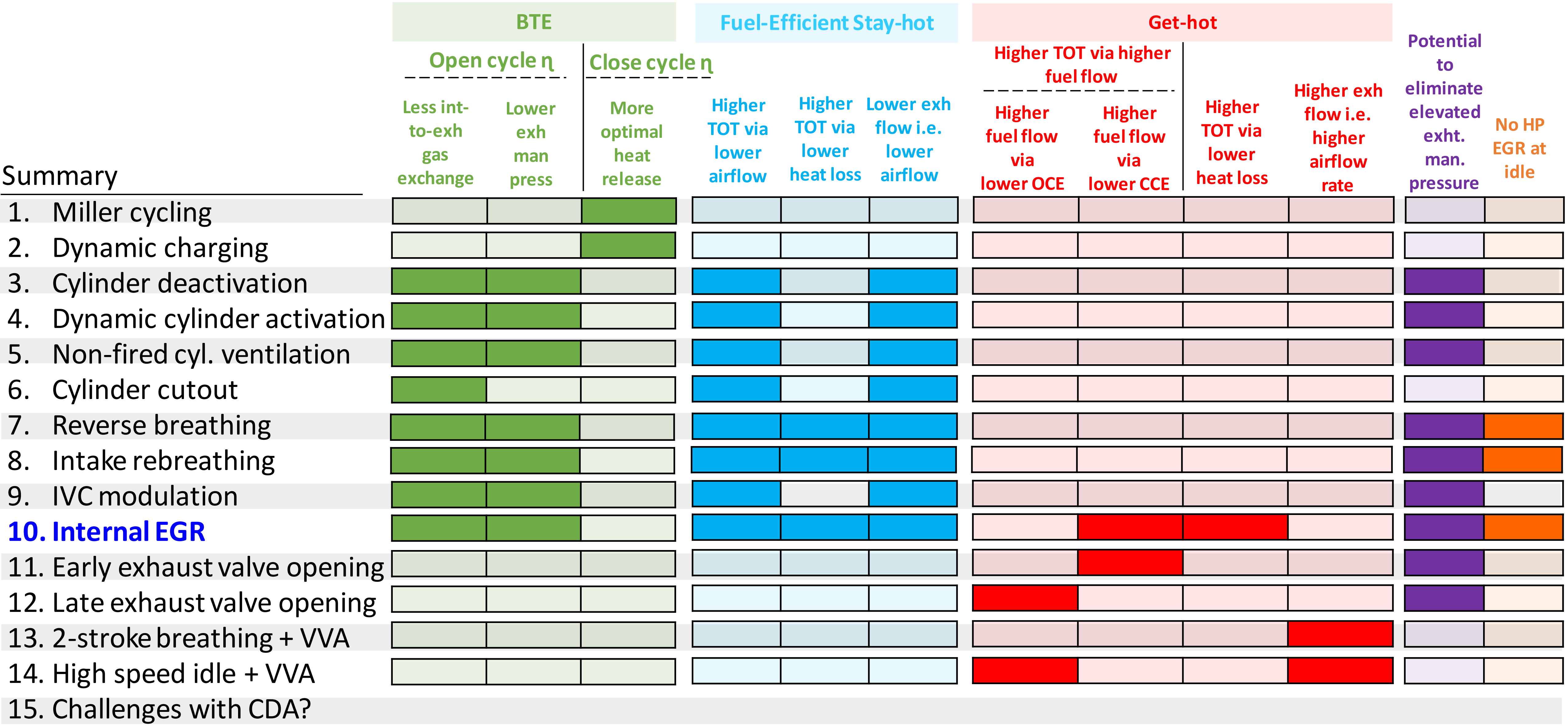




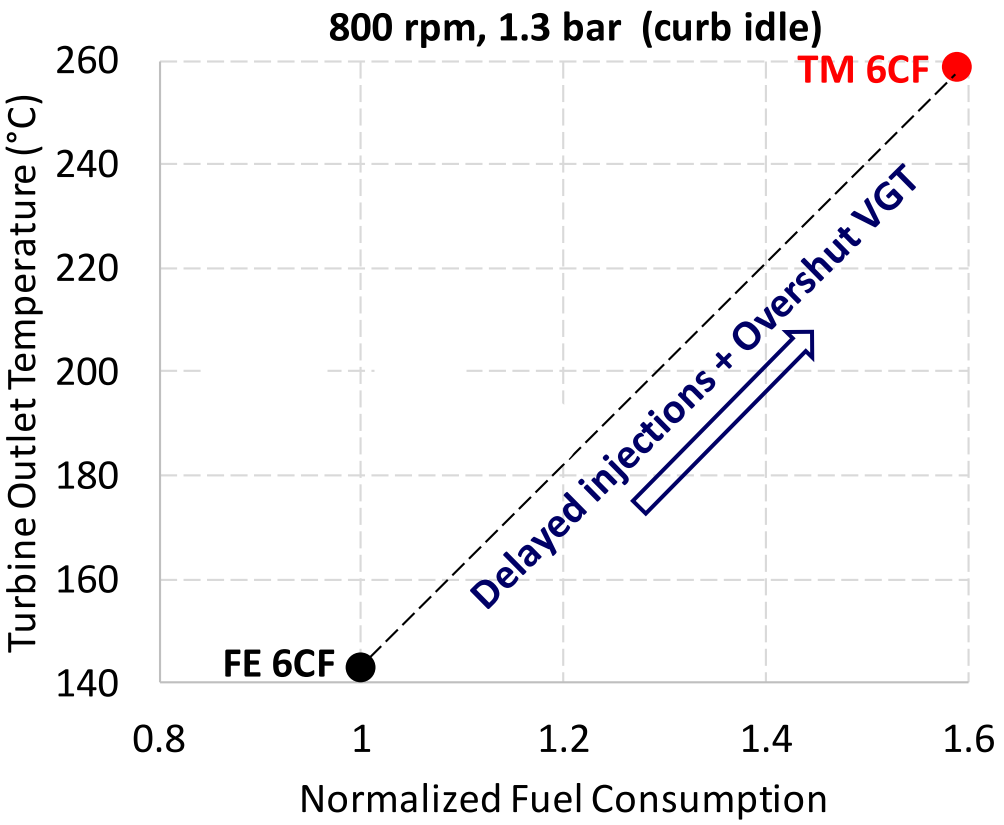
Normalized exhaust flow rates



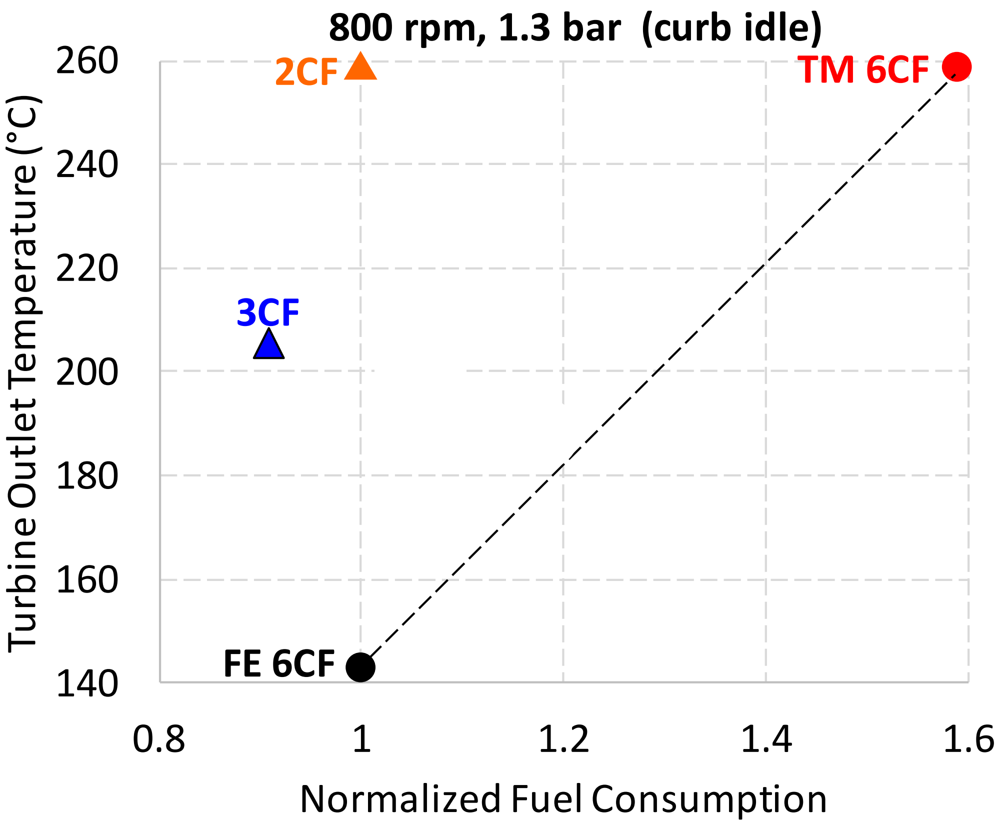
VVA improves diesel engine fuel efficiency and aftertreatment thermal management.



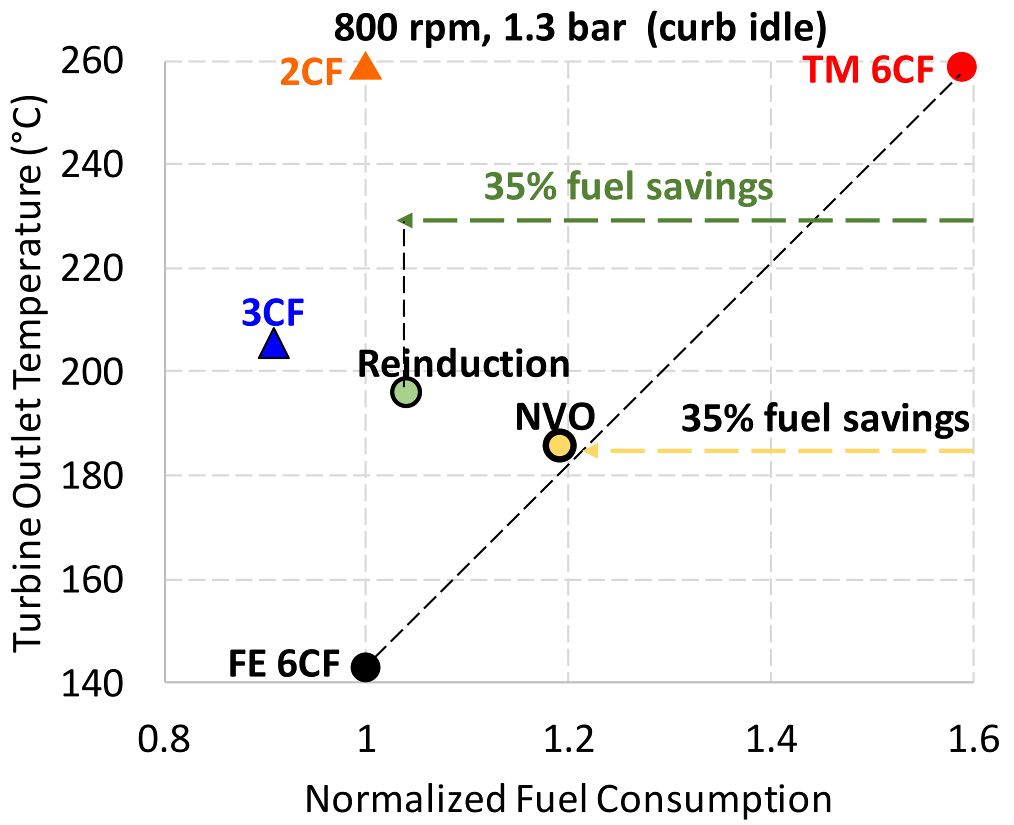
Stock operation for fuel efficiency and thermal management



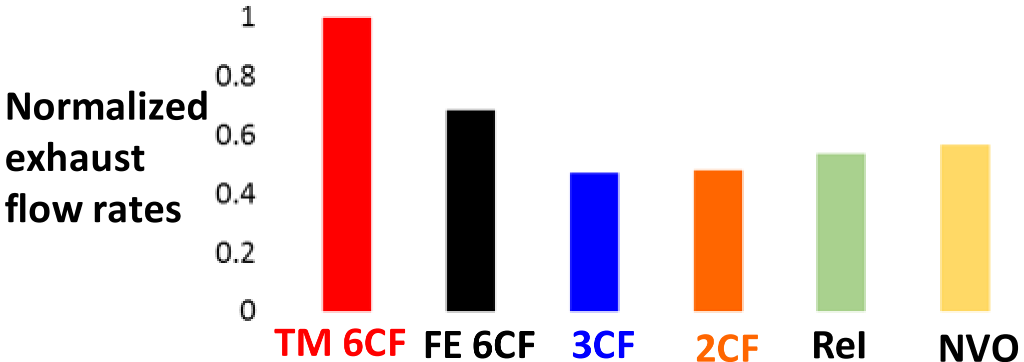
Internal EGR for fuel-efficient stay-hot while using zero external EGR

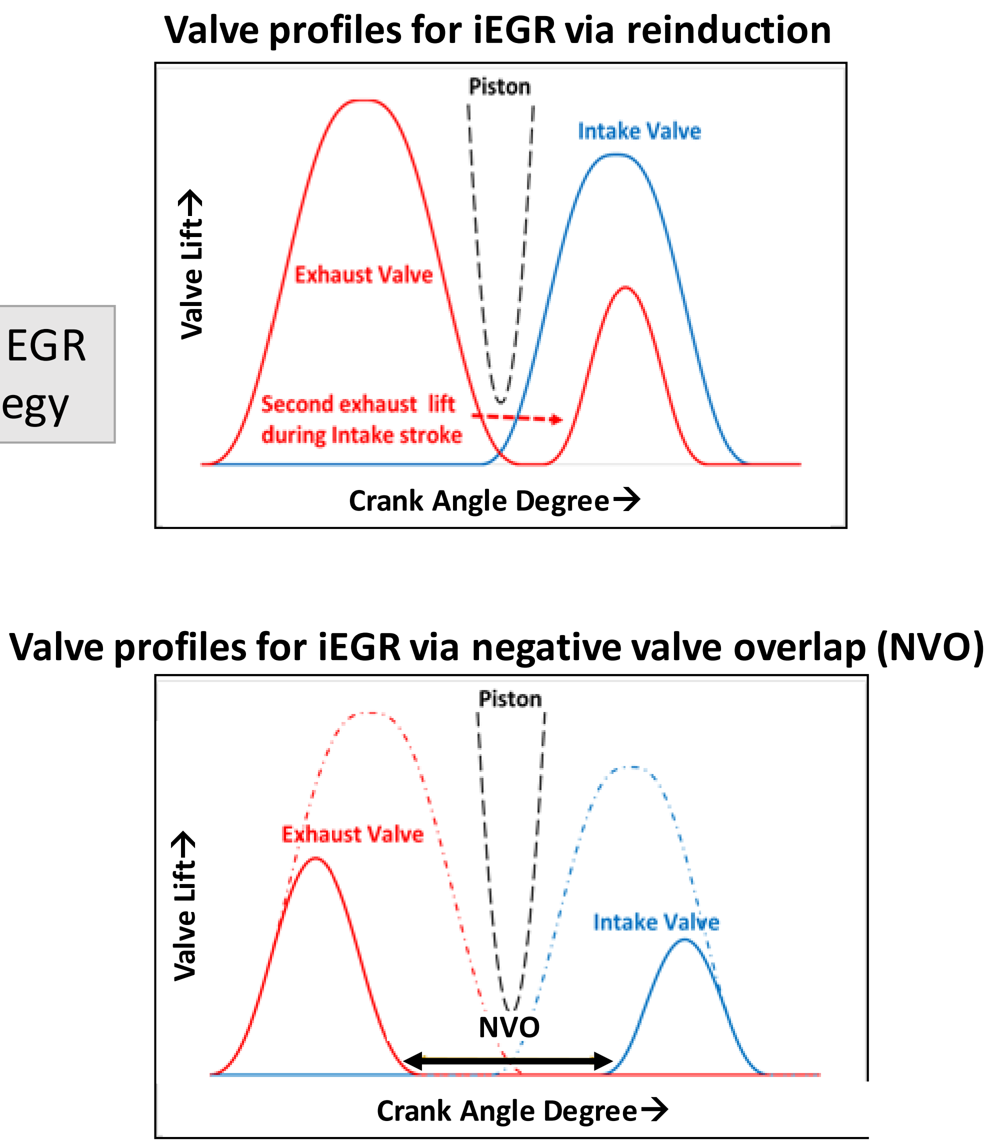


Internal EGR for fuel-efficient stay-hot while using zero external EGR

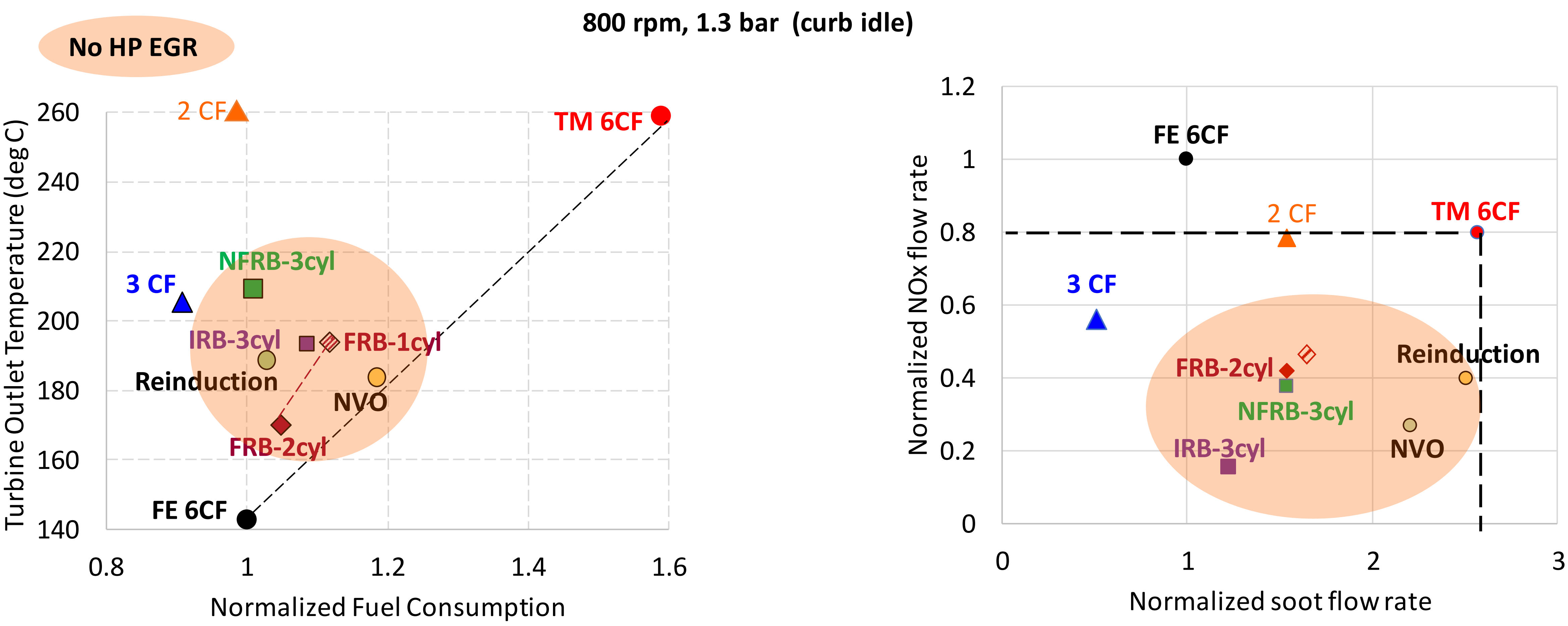


- Uses no external EGR
- Low airflow strategy



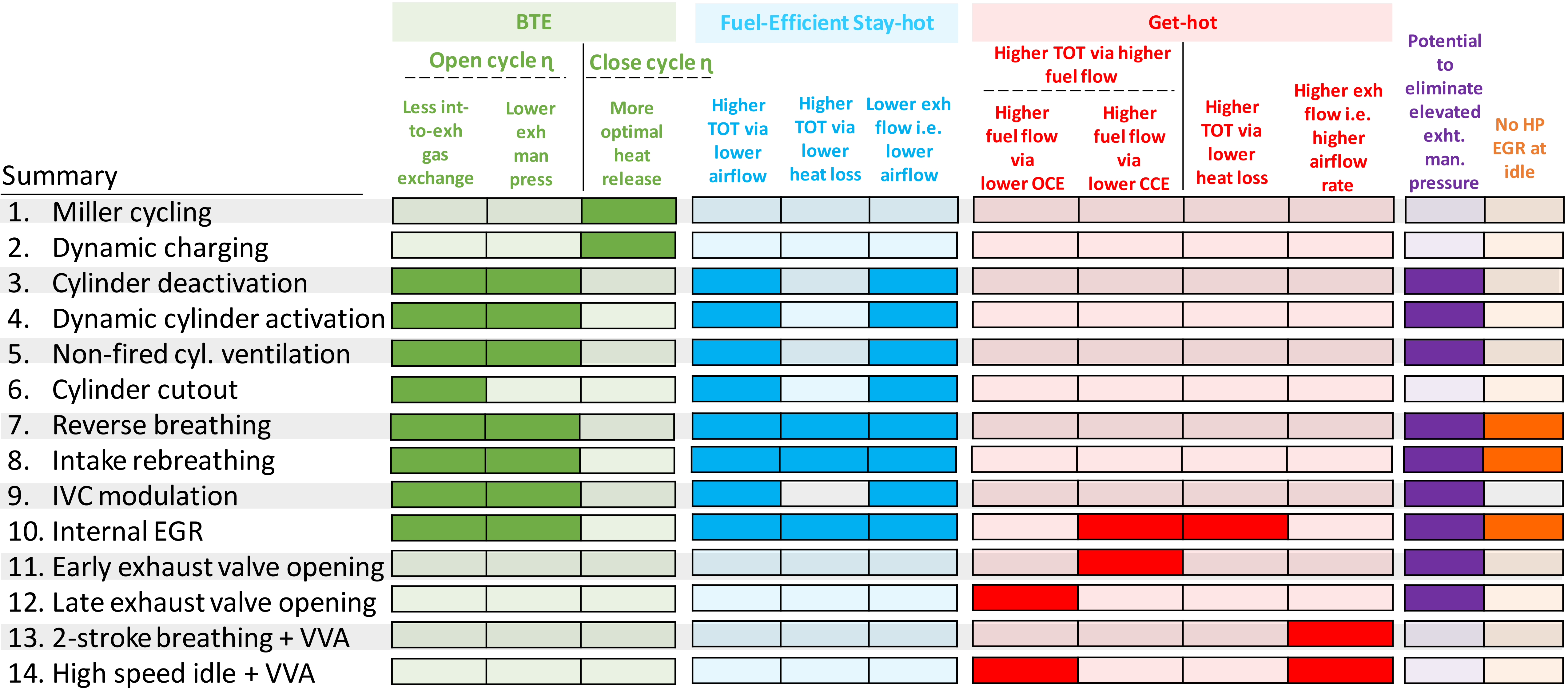


Internal EGR strategies for stay-hot – Zero HP external EGR



VVA can be used for fuel efficient stay-hot while maintaining all emissions within constraints without requiring any external HP EGR

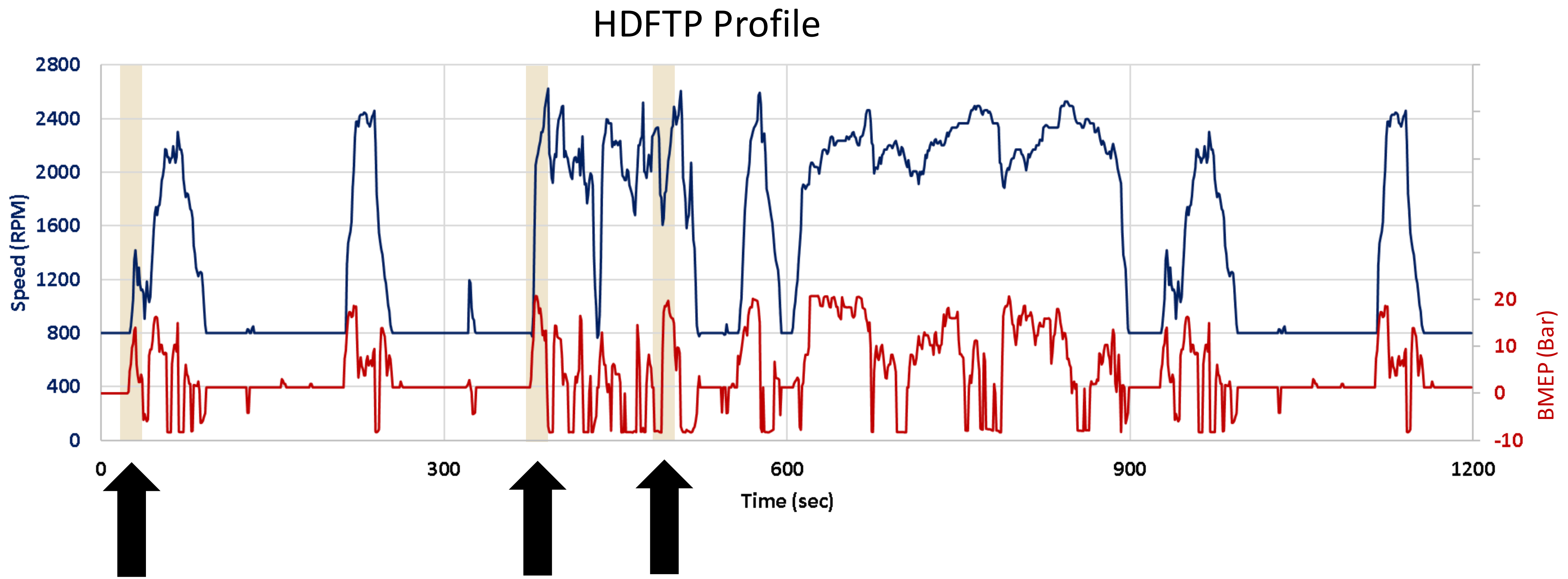
VVA improves diesel engine fuel efficiency and aftertreatment thermal management.



15. Challenges with CDA?

- **CDA during transient operation**

CDA during transient operation

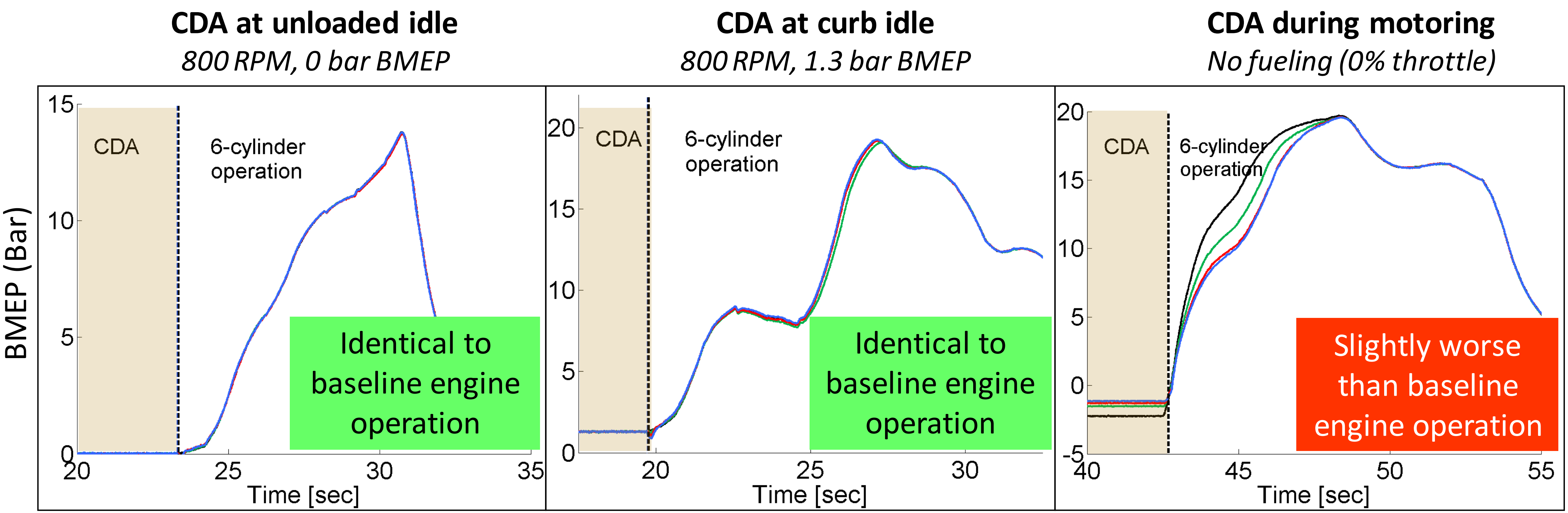


Unloaded idle initial condition

Curb idle initial condition

Motoring initial condition

CDA during transient operation



6 cyl mode throughout

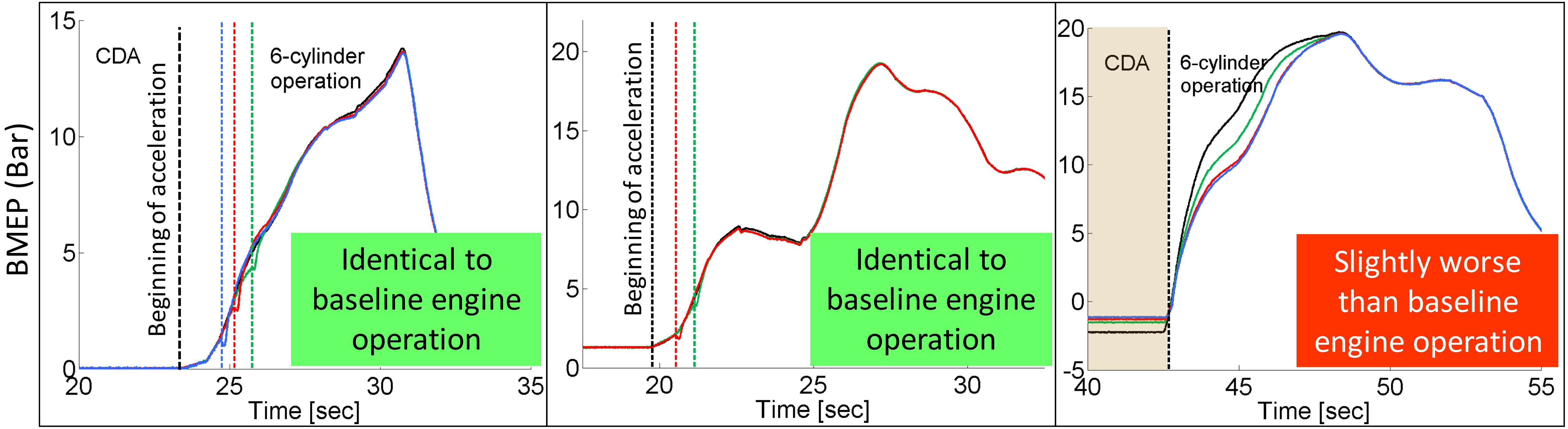
CDA (4 CF) → 6 cyl mode

CDA (3 CF) → 6 cyl mode

CDA (2 CF) → 6 cyl mode

CDA during transient operation

CDA at unloaded idle	**CDA at curb idle**	**CDA during motoring**
800 RPM, 0 bar BMEP	*800 RPM, 1.3 bar BMEP*	*No fueling (0% throttle)*

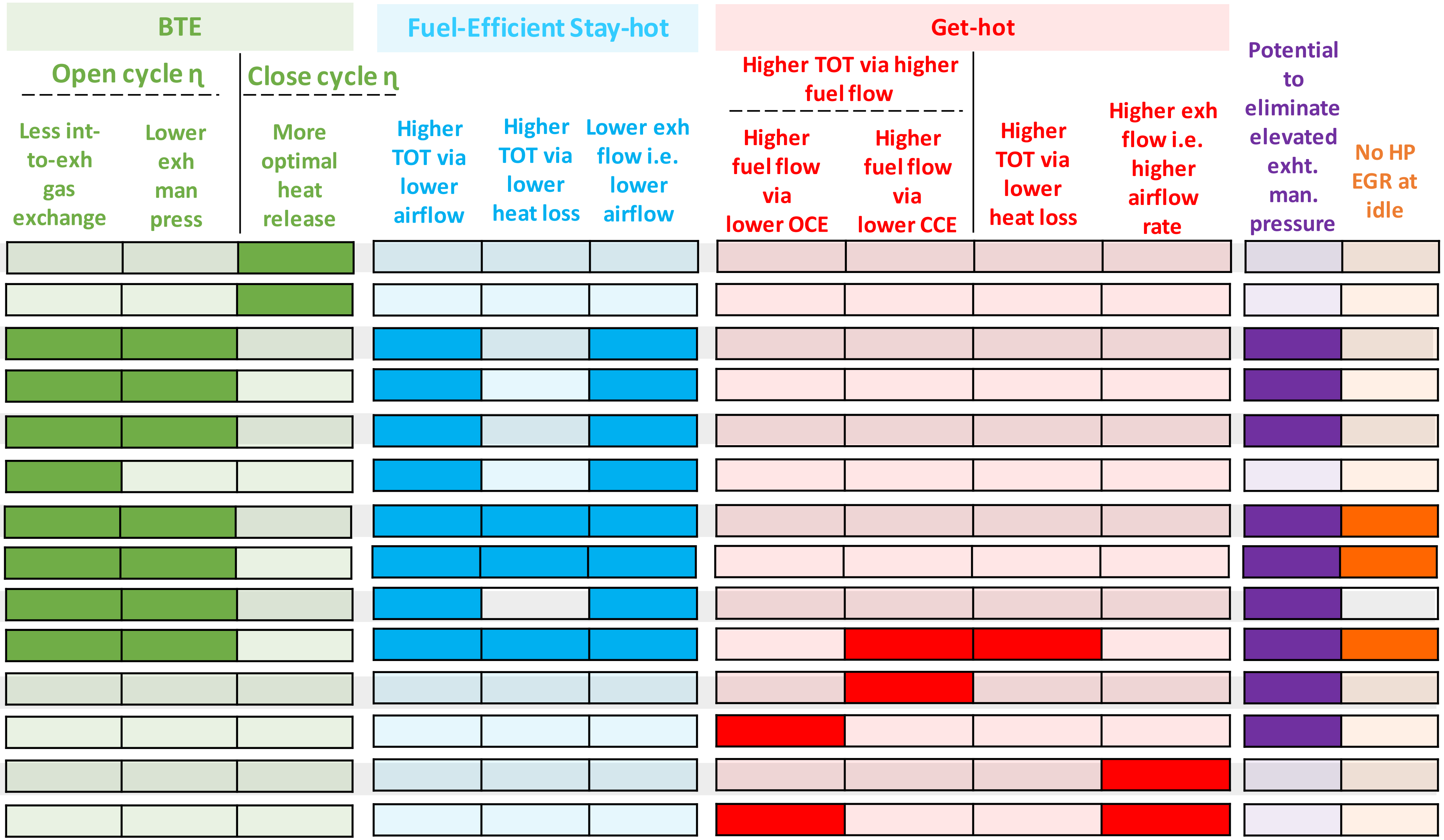


6 cyl mode throughout
CDA (4 CF) → 6 cyl mode
CDA (3 CF) → 6 cyl mode
CDA (2 CF) → 6 cyl mode

VVA improves diesel engine fuel efficiency and aftertreatment thermal management.

Summary

1. Miller cycling
2. Dynamic charging
3. Cylinder deactivation
4. Dynamic cylinder activation
5. Non-fired cyl. ventilation
6. Cylinder cutout
7. Reverse breathing
8. Intake rebreathing
9. IVC modulation
10. Internal EGR
11. Early exhaust valve opening
12. Late exhaust valve opening
13. 2-stroke breathing + VVA
14. High speed idle + VVA



15. Challenges with CDA?

- CDA during transient operation
- Oil accumulation study
- Charge trapping study
- Vibration with CDA

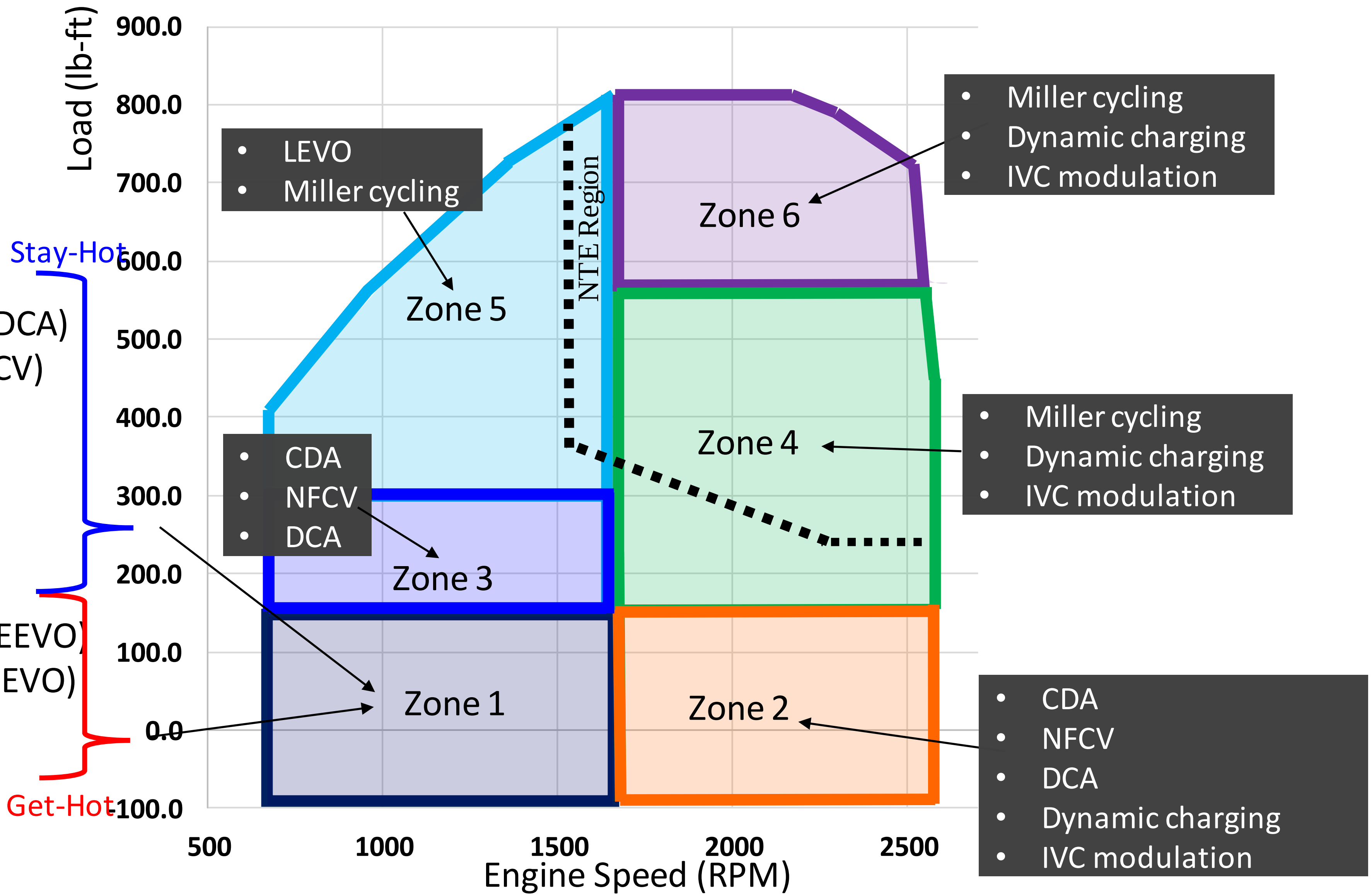
VVA improves diesel engine fuel efficiency and aftertreatment thermal management.

Summary	BTE			Fuel-Efficient Stay-hot			Get-hot					
	Open cycle η		Close cycle η				Higher TOT via higher fuel flow					
	Less int-to-exh gas exchange	Lower exh man press	More optimal heat release	Higher TOT via lower airflow	Higher TOT via lower heat loss	Lower exh flow i.e. lower airflow	Higher fuel flow via lower OCE	Higher fuel flow via lower CCE	Higher TOT via lower heat loss	Higher exh flow i.e. higher airflow rate	Potential to eliminate elevated exht. man. pressure	No HP EGR at idle
1. Miller cycling												
2. Dynamic charging												
3. Cylinder deactivation												
4. Dynamic cylinder activation												
5. Non-fired cyl. ventilation												
6. Cylinder cutout												
7. Reverse breathing												
8. Intake rebreathing												
9. IVC modulation												
10. Internal EGR												
11. Early exhaust valve opening												
12. Late exhaust valve opening												
13. 2-stroke breathing + VVA												
14. High speed idle + VVA												
15. Challenges with CDA?												

VVA improves diesel engine fuel efficiency and aftertreatment thermal management.

Summary

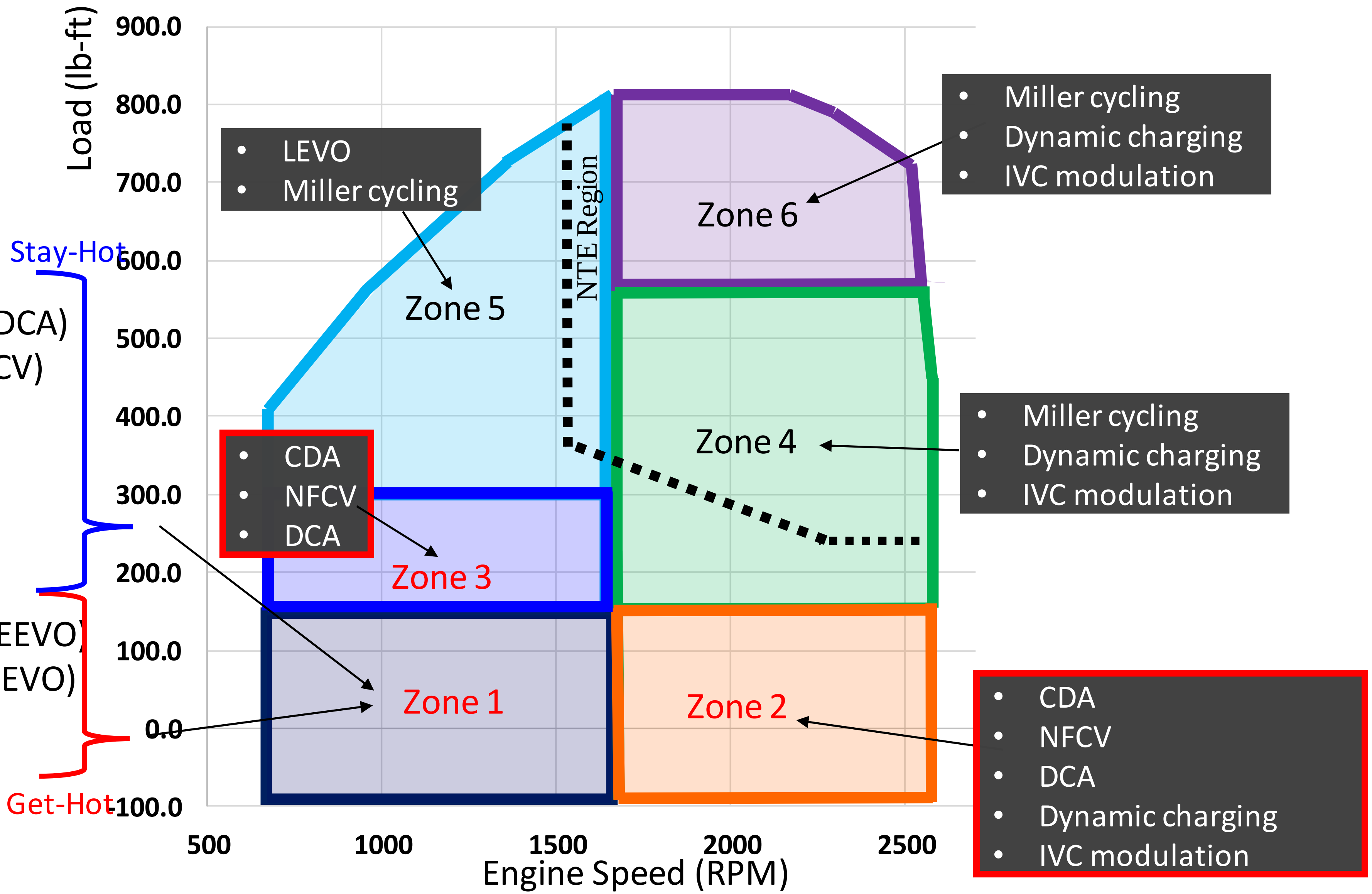
1. Miller cycling
2. Dynamic charging
3. Cylinder deactivation (CDA)
4. Dynamic cylinder activation (DCA)
5. Non-fired cyl. ventilation (NFCV)
6. Cylinder cutout
7. Reverse breathing
8. Intake rebreathing
9. IVC modulation
10. Internal EGR
11. Early exhaust valve opening (EEVO)
12. Late exhaust valve opening (LEVO)
13. 2-stroke breathing + VVA
14. High speed idle + VVA



VVA improves diesel engine fuel efficiency and aftertreatment thermal management.

Summary

1. Miller cycling
2. Dynamic charging
3. **Cylinder deactivation (CDA)**
4. Dynamic cylinder activation (DCA)
5. Non-fired cyl. ventilation (NFCV)
6. Cylinder cutout
7. Reverse breathing
8. Intake rebreathing
9. IVC modulation
10. Internal EGR
11. Early exhaust valve opening (EEVO)
12. Late exhaust valve opening (LEVO)
13. 2-stroke breathing + VVA
14. High speed idle + VVA



Purdue Team

PI

Greg Shaver

Project Management

Dr. Eric Holloway

Technical Support

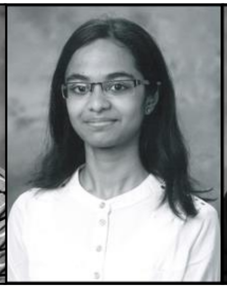
David Meyer

Ryan Thayer

Graduate Students

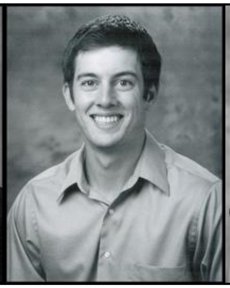
Prof. Cody Allen
U. of Illinois

Dr. Dheeraj Gosala
Cummins



Dr. Mrunal Joshi
Cummins

Dr. Alex Taylor
BTMS



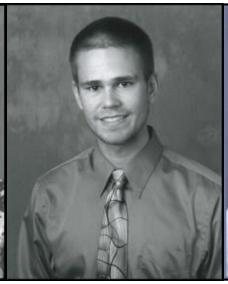
Dr. Kalen Vos
Sandia NL

Shveta Dhamankar

John Foster
DTNA

Leighton Roberts
Eaton

Dr. Chuan Ding
Mathworks



Brad Pietrzak
Ford

Lucius Wang
Faurecia

Mayura Halbe
Cummins

Soumya Nayyar
Cummins

Sylvia Lu
MBA Student

Matt Van Voorhis
Rousch

Troy Odstrcil
Boeing

Dr. Aswin Ramesh
Cummins

Q & A

Powering Business Worldwide

Engage the Experts: free webinars on commercial vehicle engine strategies

September 9 — **The truth about diesel CDA and NVH**
Tom Reinhart, Southwest Research Institute (SwRI)

September 30 — **Achieving 2027 emissions regulations**
Chris Sharp, Southwest Research Institute (SwRI)

October 14 — **The advantages of CDA over real-world drive cycles**
Dr. Mrunal Joshi, Cummins

October 21 — **Understanding diesel cylinder deactivation**
Dr. Greg Shaver, Purdue University

October 28 — **CDA versus cylinder cutout: a technology overview**
Dr. Cody Allen, University of Illinois

Powering Business Worldwide

Powering Business Worldwide