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Adaptive Real-Time Extremum-Seeking Optimization for Low-Emission Control of Marine RCCI Engines

23rd IFAC World Congress 2026, Busan, Korea

Session ThC08 - Extremum Seeking and Model Free Adaptive Control

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27.08.2026

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- RCCI Optimization and Control Challenges
- On-Board Extremum Seeking Optimization
- Experimental Methodology & Optimization Design
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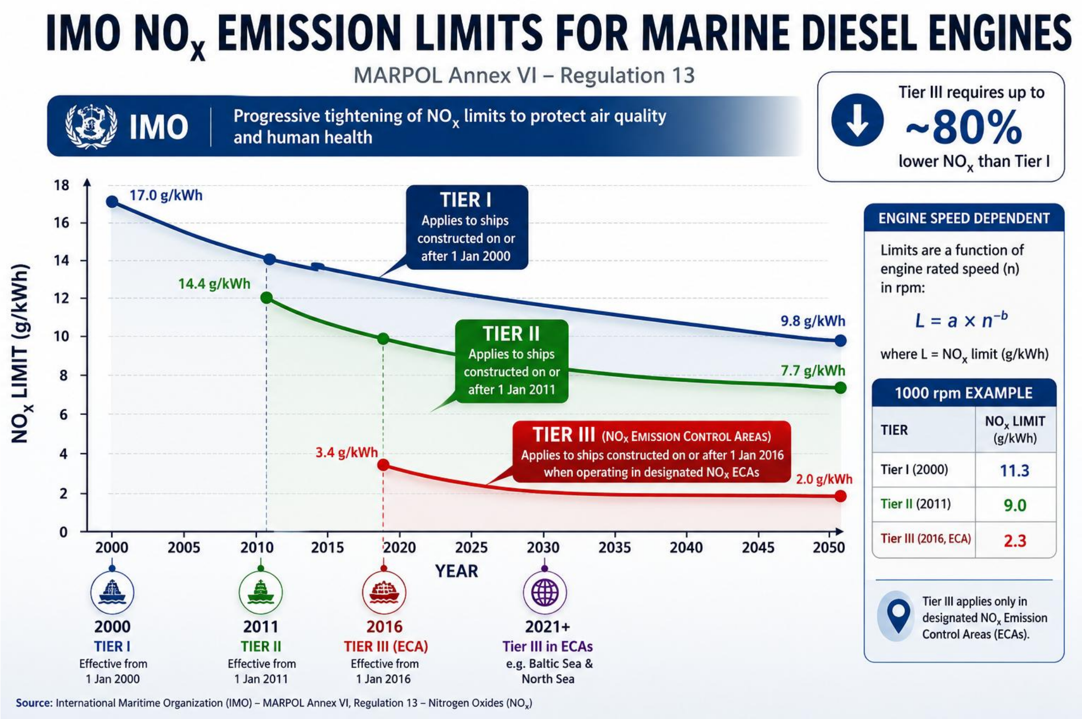
1. Reactivity Controlled Compression Ignition (RCCI)

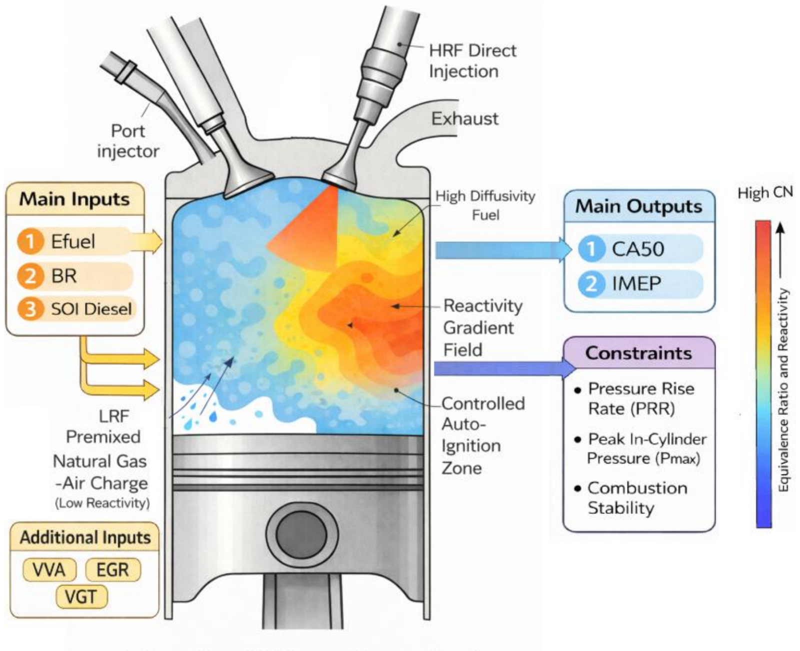
Marine Emission Challenge

- Maritime transport is essential, but emission-intensive.
- Stricter IMO limits + limited electrification demand cleaner combustion.



Need for Clean, Efficient fuel-flexible Combustion

RCCI: A Promising Solution



Schematic of RCCI reactivity stratification

Key Advantages

- ☑ Advanced dual-fuel Low Temperature Combustion (LTC)
- ☑ High efficiency (55%) & fuel-flexible operation
- ☑ Reactivity stratification enables combustion phasing control
- ☑ Overcomes the classic soot–NO_x trade-off in CDC

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2. RCCI Optimization and Control Challenges

- Highly nonlinear, coupled, and fuel-dependent behavior challenges RCCI real-time optimization.
- Strong NOx–stability trade-off complicates optimal RCCI operation.
- Conventional calibration is time-consuming and non-adaptive

Adaptive, Model-free Optimization

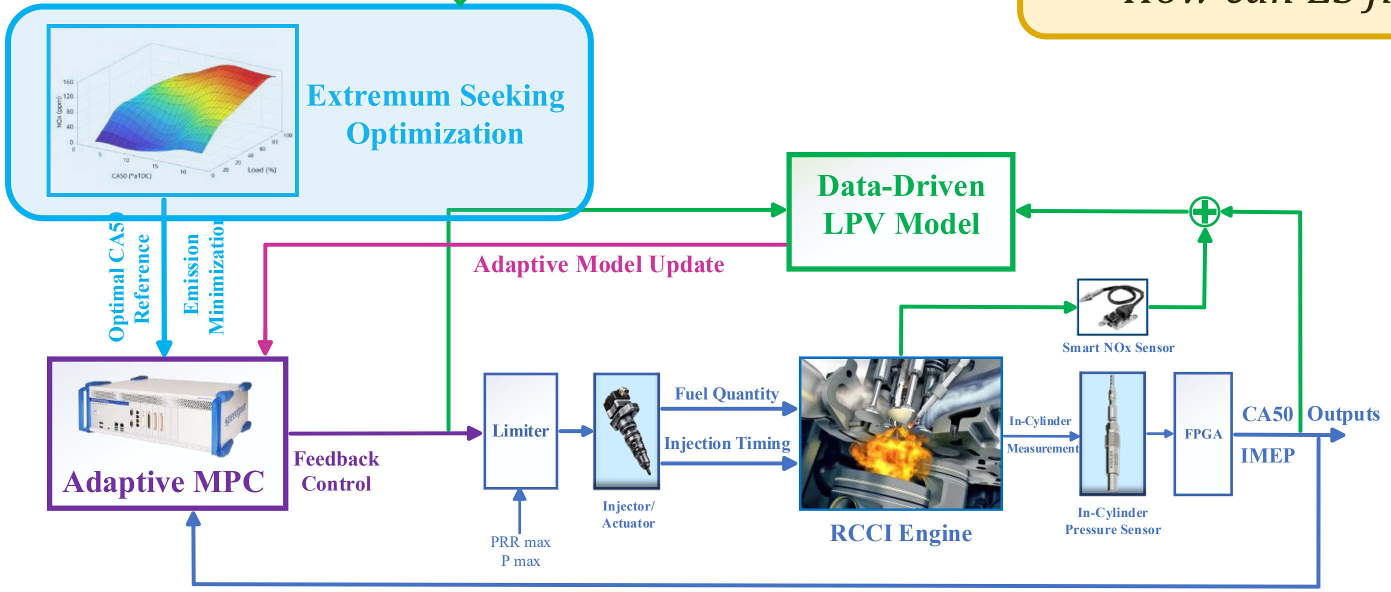
Solution

Extremum Seeking for Optimal RCCI Operation

- ❑ Real-time Onboard Optimal CA50 Reference Generation
- ❑ Self-learning adaptation to operating conditions
- ❑ NOx minimization with combustion stability constraint

Why CA50?

How can ES find the optimum?



Overall Adaptive RCCI Control Framework

3.1 On-Board Extremum Seeking Optimization

Why optimal combustion phasing must be identified online

- Optimal CA50 is operating-condition dependent and not known beforehand.
- CA50 strongly governs the NOx–efficiency–stability balance in RCCI.

↑ ADVANCED CA50 (Early)

↑ Improved efficiency

↑ Higher peak pressure

↑ Higher in-cylinder temperature

↑ Accelerated thermal NOx

↑ Mechanical stress & durability risk

↓ RETARDED CA50 (Late)

↓ Reduced NOx

↓ Lower peak pressure & temperature

↑ Incomplete combustion, high UHC & CO

↑ Reduced efficiency

↑ High cycle-to-cycle variability (COV_{IMEP})

★ OPTIMAL CA50 (Target)

✓ Minimum NOx emissions

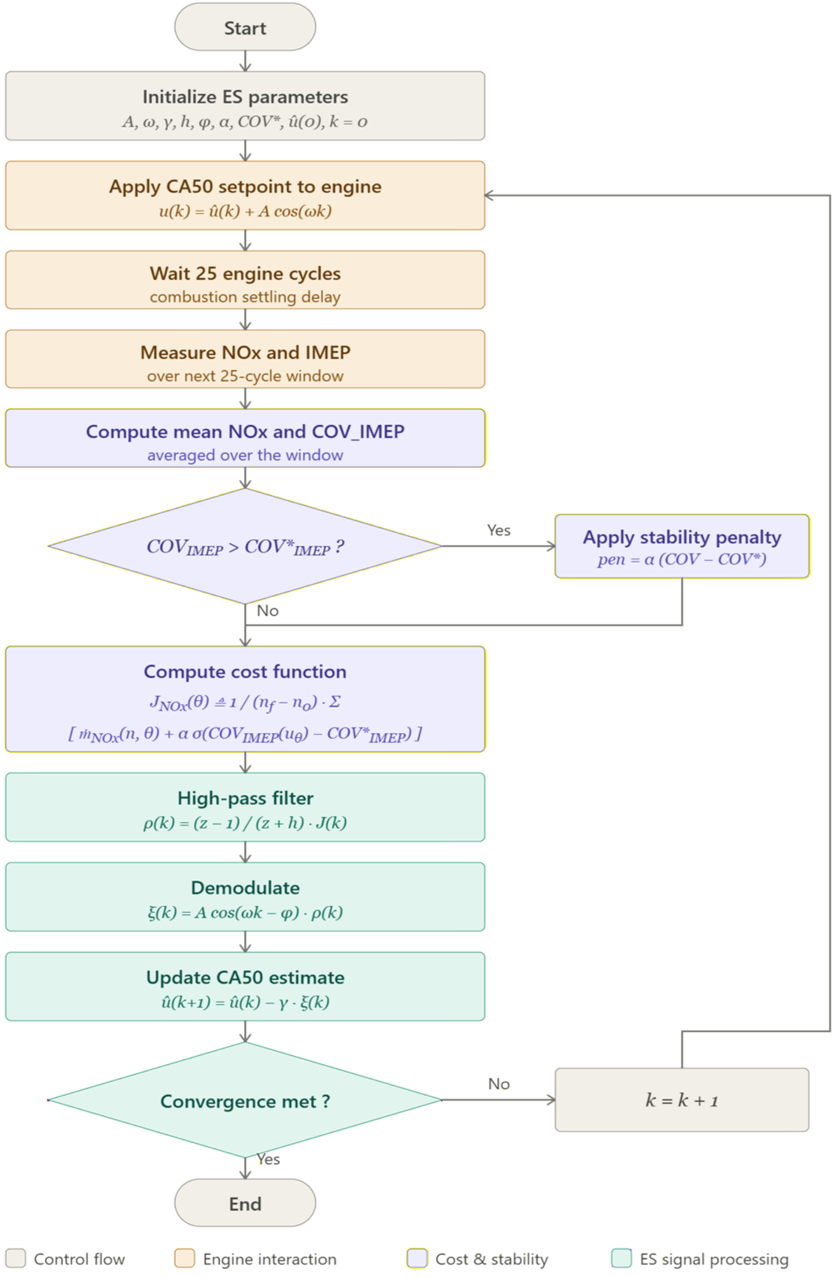
✓ Stable combustion

✓ Balanced efficiency

✓ IMO Tier III compliance

★ Unknown a priori - must be found!

Real-time ES Optimization



Adaptive ES-Based CA50 Optimization for Low NOx RCCI

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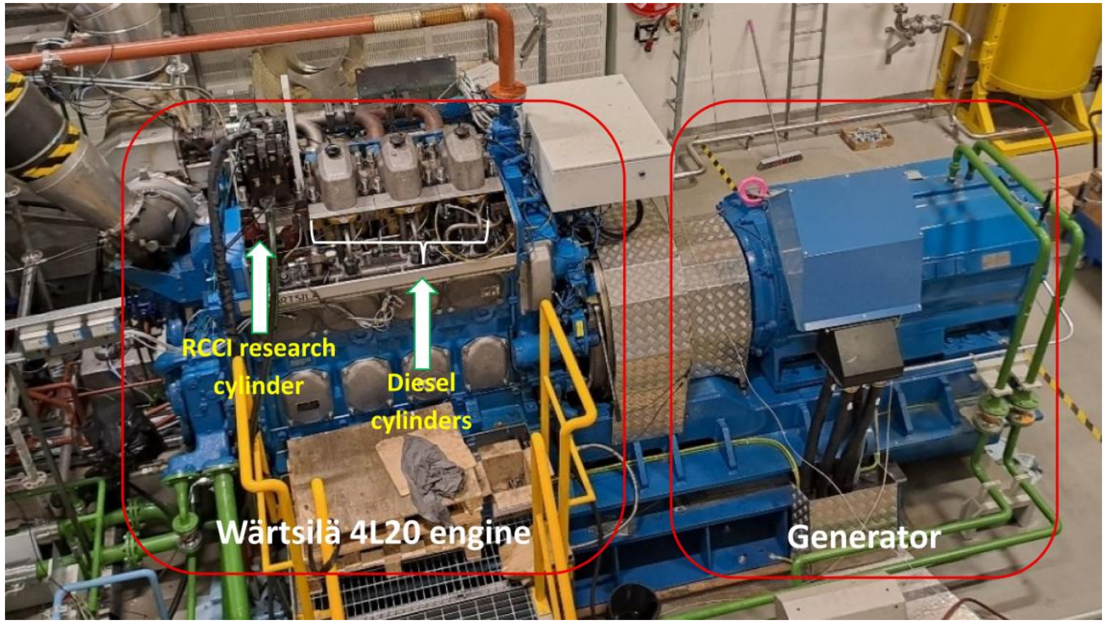
3.2 Experimental Platform



Wärtsilä 4L20 Cutting-Edge RCCI research platform, University of Vaasa Energy Lab

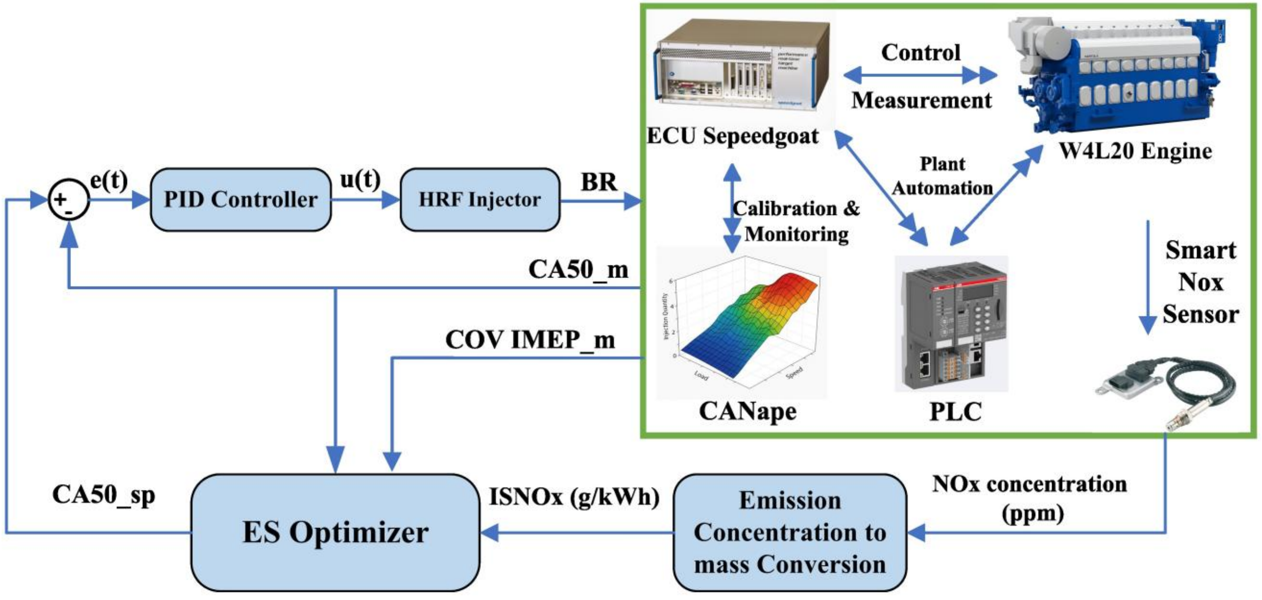
Wärtsilä W4L20 RCCI Cylinder specifications

Parameter	RCCI Cylinder
Nominal speed	1000 rpm
Maximum output	200 kW/cylinder
Bore × stroke	200 × 280 mm
Displacement	8.8 L/cylinder
Compression ratio	13.4
Diesel injection	Independent CRDI, ≤2000 bar
Gas injection	PFI, ≤12 bar

Experimental RCCI Configuration

- **Cylinder 4:** Dual-fuel RCCI research cylinder
- **LRF:** Methane-based gaseous fuel (Port Fuel Injection)
- **HRF:** Bio-Diesel (Direct Injection)
- **Cylinders 1–3:** Conventional diesel combustion (CDC)
- **Dedicated cylinder 4** exhaust sampling for NOx measurement

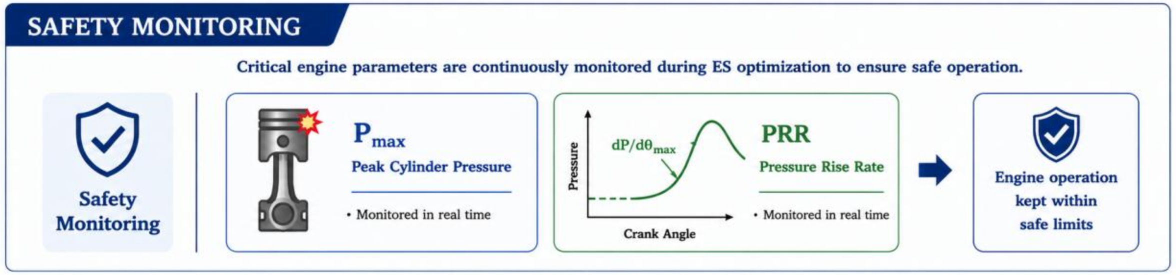
3.3 Real-time On-Board ES Implementation

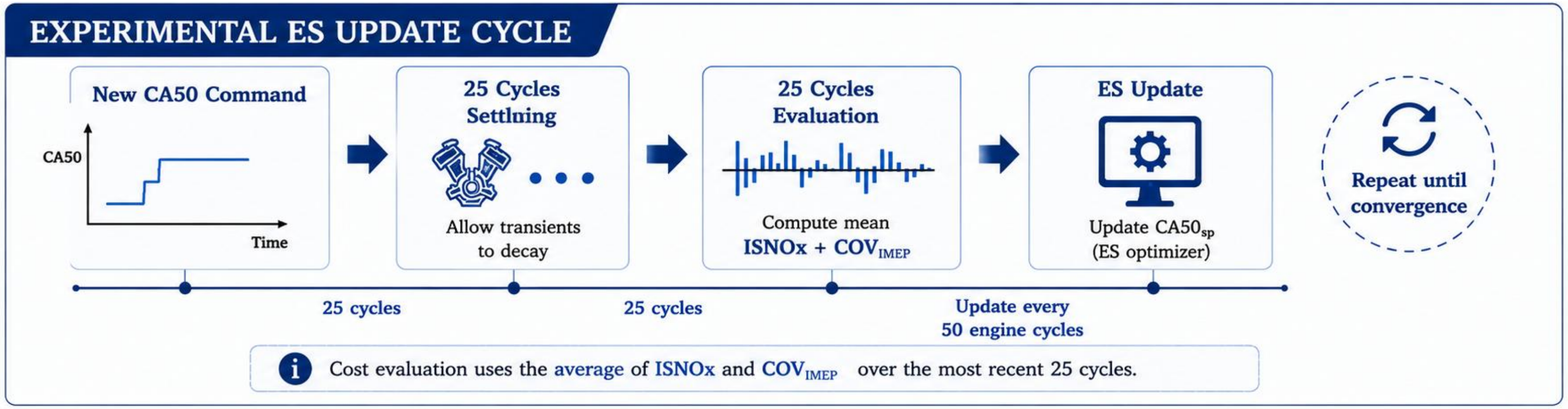


Experimental implementation of the on-board ES-based optimization framework

Real-Time Signal Flow

- **ES output:** $CA50_{sp}$
- **CA50 tracking:** PID controller
- **Control input:** Energy-based BR
- **Feedback:** $ISNO_x + COV_{IMEP}$





3.4 Optimization Objective & Key Definitions

Objective: Minimize NOx while preserving combustion stability

$$J_{NO_x}(\theta) \triangleq \frac{1}{n_f - n_0} \sum_{n=n_0}^{n_f} \left(\dot{m}_{NO_x}(n,\theta) + \alpha\sigma\left(COV_{IMEP}(u_\theta) - COV_{IMEP}^{*}\right) \right)$$

$$\theta \triangleq CA50_{sp}$$

Optimization Terms

$CA50_{sp}$: ES optimization variable
$ISNO_x$: Emission objective
COV_{IMEP} : Combustion-stability metric
COV_{IMEP}^{*} : Allowable stability limit
α: Combustion stability penalty weighting

Control Variable: Energy-Based Blend Ratio

$$\mathrm{BR} = \frac{m_{\mathrm{LRF}}\,\mathrm{LHV}_{\mathrm{LRF}}}{m_{\mathrm{LRF}}\,\mathrm{LHV}_{\mathrm{LRF}} + m_{\mathrm{HRF}}\,\mathrm{LHV}_{\mathrm{HRF}}}, \qquad 0 \le \mathrm{BR} \le 100\%$$

BR: Fraction of total fuel chemical energy supplied by LRF
Higher BR → more LRF / lower mixture reactivity
Lower BR → more HRF / higher mixture reactivity

Combustion Stability

$$\mathrm{COV}_{\mathrm{IMEP}} = \frac{\sigma_{IMEP}}{\mu_{IMEP}} \times 100\%$$

Low $\mathrm{COV}_{\mathrm{IMEP}}$ → stable combustion
High $\mathrm{COV}_{\mathrm{IMEP}}$ → high cycle-to-cycle variability

$$J_{Penalty} = \begin{cases} 0 & , \mathrm{COV}_{\mathrm{IMEP}} \le \mathrm{COV}_{\mathrm{IMEP}}^{*} \\ \alpha(\mathrm{COV}_{\mathrm{IMEP}} - \mathrm{COV}_{\mathrm{IMEP}}^{*}), & \mathrm{COV}_{\mathrm{IMEP}} > \mathrm{COV}_{\mathrm{IMEP}}^{*} \end{cases}$$

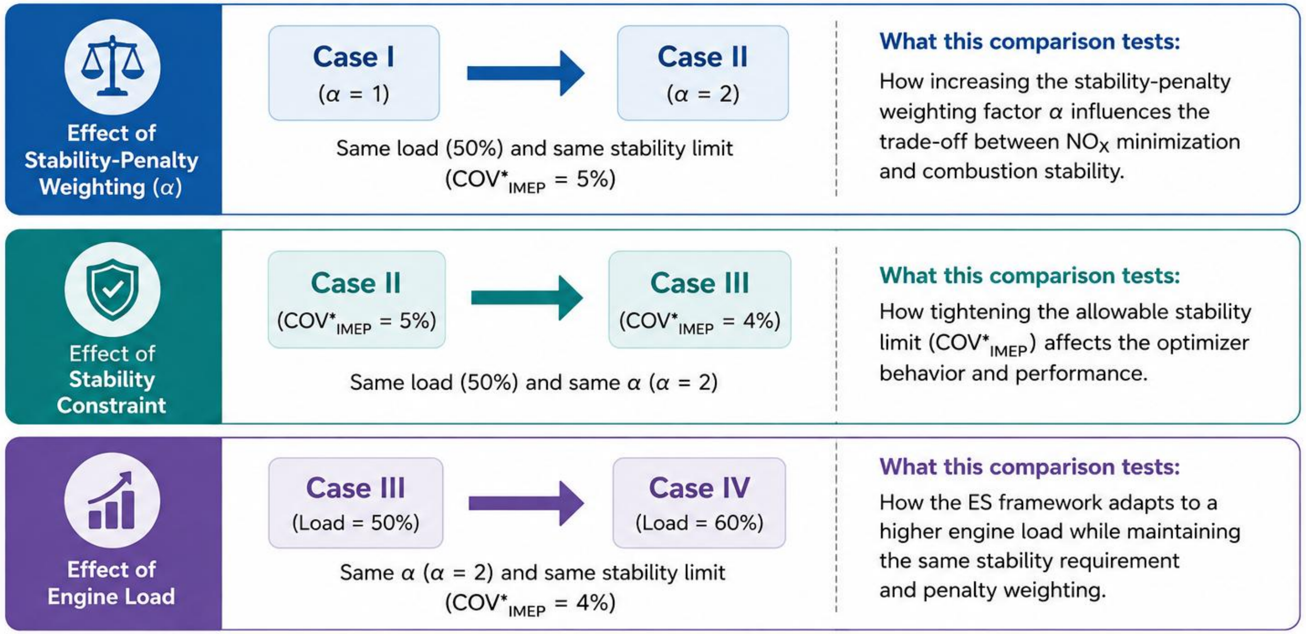
Higher α → stronger penalty for stability-limit violation.

- **PID manipulates BR to track the ES-generated $CA50_{sp}$**

4. Experimental Design and Optimization Cases

Experimental Test Matrix

Case	Load (%)	COV^*_{IMEP} (%)	α	Purpose
I	50	5	1	Weak stability weighting
II	50	5	2	Stronger stability weighting
III	50	4	2	Tighter stability constraint
IV	60	4	2	Higher-load validation



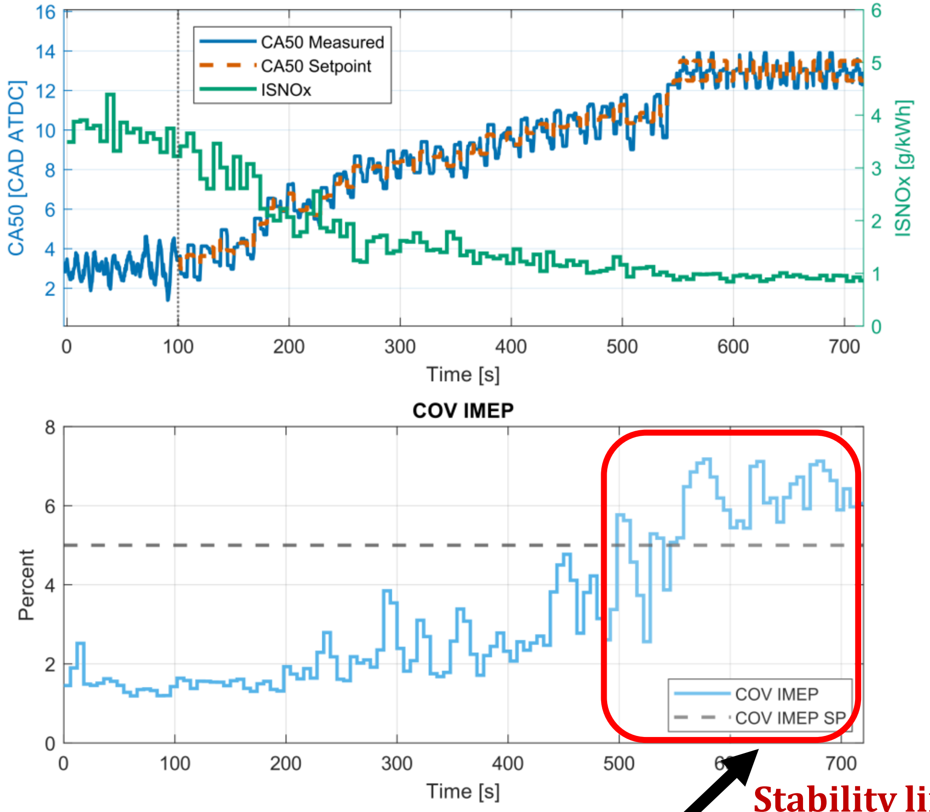
❖ Experimental Strategy

Cases I–IV systematically isolate the effects of stability weighting **α**, stability limit $\mathbf{COV^*_{IMEP}}$, and engine load on ES-based **CA50** optimization.

❖ Evaluation: CA50 tracking • ISNOx • COV_{IMEP}

5. Results and Discussions: Effect of Stability Weighting

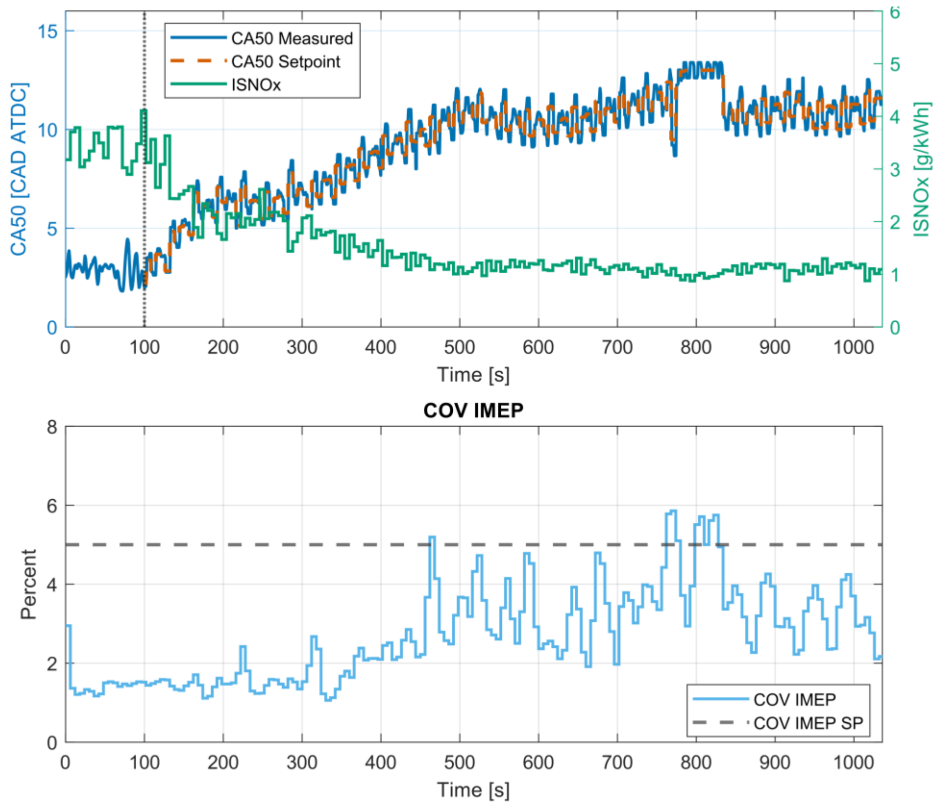
Case I: Weak Stability Weighting (**α=1**)



Stability limit exceeded

- **ISNOx** : ~4 → 0.927 g/kWh
- Aggressive NOx minimization
- **COV_{IMEP}** persistently exceeds 5% → stability compromised

Case II: Stronger Stability Weighting (**α=2**)

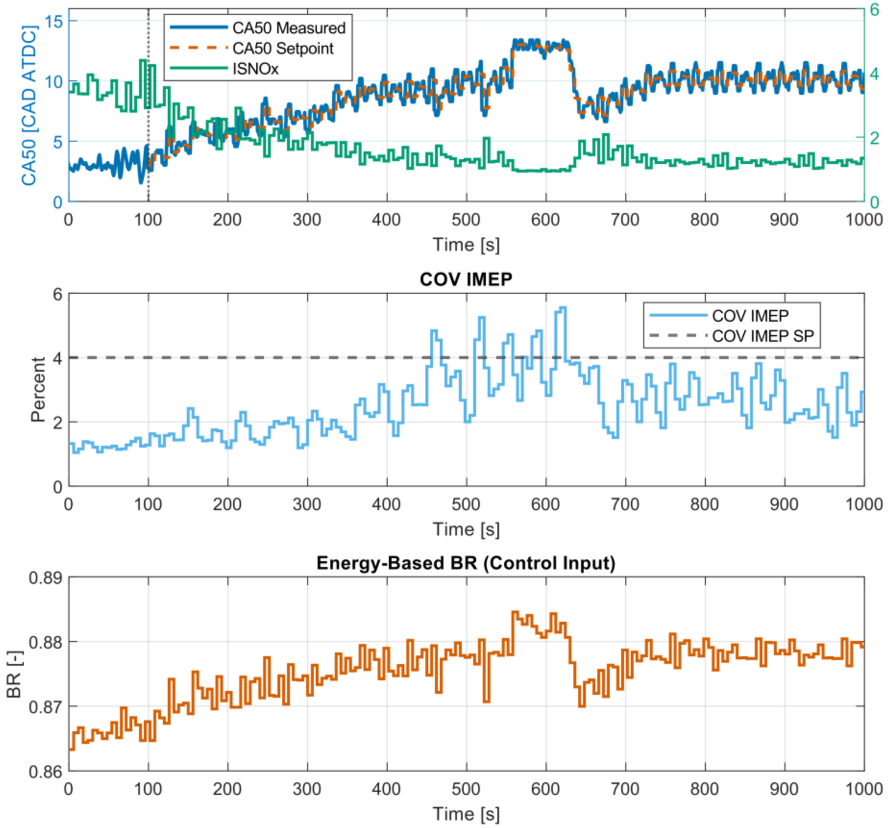


- **ISNOx**: 1.108 g/kWh
- **Stronger** response to instability
- **COV_{IMEP}** better controlled only transient exceedances

☑ **Key Finding:** Increasing **α** from 1 to 2 strengthens stability enforcement with only a modest increase in **ISNOx**.

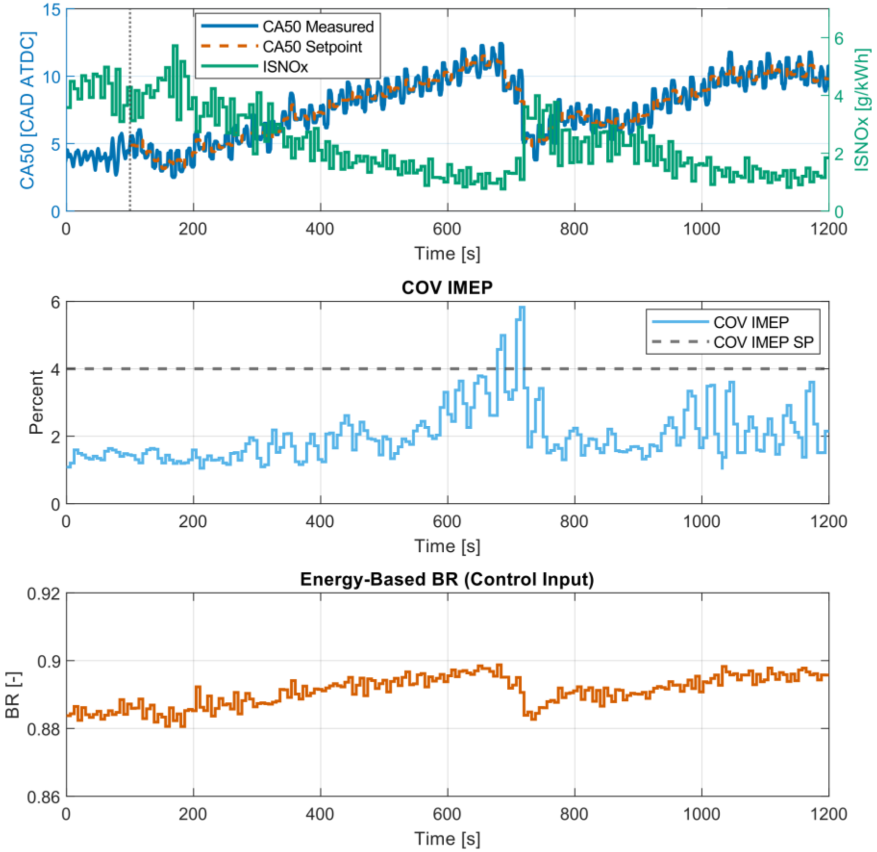
5. Results and Discussions: Stability Constraint & Load Adaptability

Case III: Tighter Stability Constraint (**COV^*_{IMEP}** =4%, **α** =2)



- **ISNOx**: 1.218 g/kWh
- Tighter **COV_{IMEP}** limit: 5% → 4%
- Stronger combustion-stability limit
- Optimal **$CA50_{Sp}$** : 10.15° ATDC

Case IV: Higher-Load Validation (**60%** load, **COV^*_{IMEP}** =4%, **α** =2)



- **ISNOx**: 1.561 g/kWh
- Higher-load increases NOx challenge
- ES adapts **CA50/BR,** enforcing stability
- Optimal **$CA50_{Sp}$** : 10.20° ATDC

☑ **Key Finding:** ES preserves robust CA50 optimization under tighter stability constraints and higher-load operation.

6. Conclusions & Future Work

Key Contributions

- Real-time on-board ES experimentally validated on a large-bore RCCI engine.
- Optimal CA50 references identified online without an explicit RCCI model.
- NOx–Stability co-optimization achieved via COV_{IMEP}-based penalty
- Robust adaptation demonstrated across stability requirements & engine loads.

Future Work

- Extend ES optimization across the full engine speed–load operating space.
- Construct an experimentally validated optimal CA50 reference map.
- Extend the framework to H_2–NG–diesel RCCI for fuel-flexible operation.

Thank You!

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- **This work was conducted within Flexible Clean Propulsion Technologies project (ref. 1309/31/2023), co-funded by Business Finland.**
- **Travel support for participation in this conference was provided by Merenkulun säätiö (Maritime Foundation).**