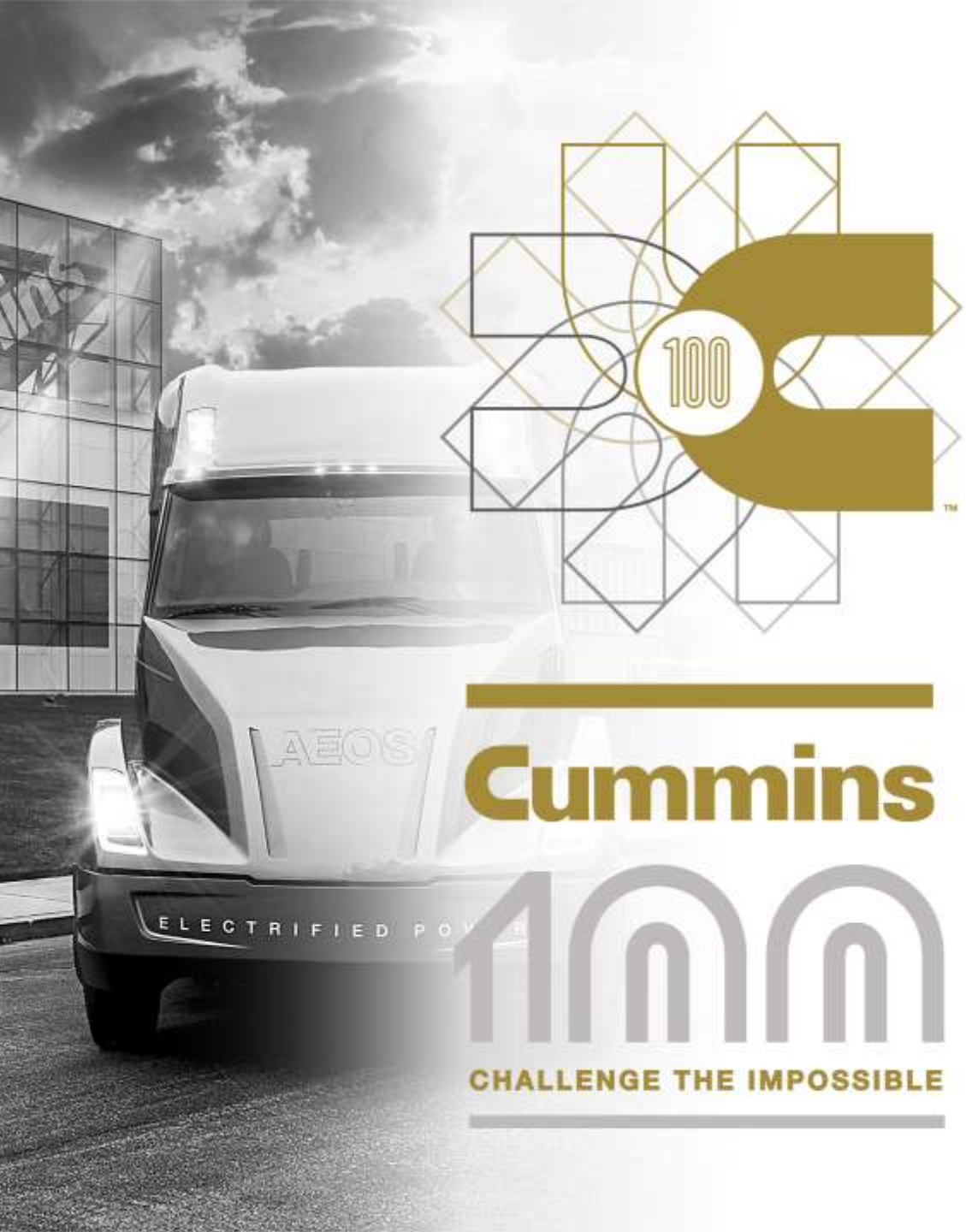

System Simulation for Robust Calibration & Diagnostics

Cummins Inc.

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April 30, 2019

Public

Agenda

- Product Development Challenges
- Investment for System Simulation
- Process Integration of System Simulation
- Pure Simulation
- Approach to System Simulation
- Model Accuracy Assessment
- Clustering
- Data Analysis
- Virtual OBD
- Closing Comments
- Acknowledgements

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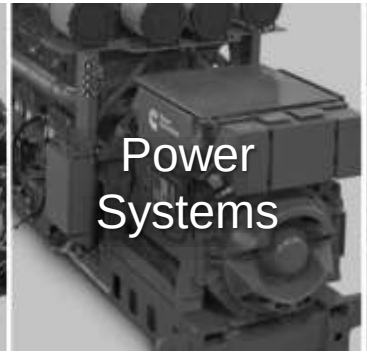


Cummins Inc., a global power leader, is a corporation of complementary business segments that design, manufacture, distribute and service a broad portfolio of power solutions

Dynamic Systems & Controls (DS&C) Engine Integration

- Under Corporate Technical function, DS&C is the centralized controls group providing software for world wide Cummins products

- Component software such as aftertreatment and fuel system is integrated with engine and machine controls in order to be validated at system level before delivering to the application teams for calibration

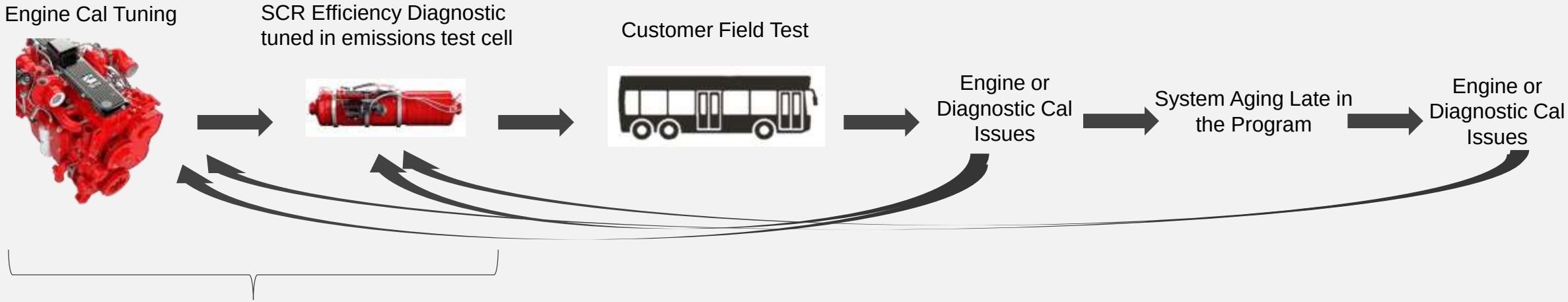
- Within DS&C, Engine Integration group covers air handling and combustion controls software development and calibration for diesel and spark ignited products

Product Development Challenges

System performance calibration development is customer field test centric

30%

of product development cost is spent for
calibration iteration with feedback from customer field test



Opportunity for Robust Cal & Diagnostics development considering noise factors and aging
Target to reduce product development cost by 10% utilizing simulation

Product Development Challenges

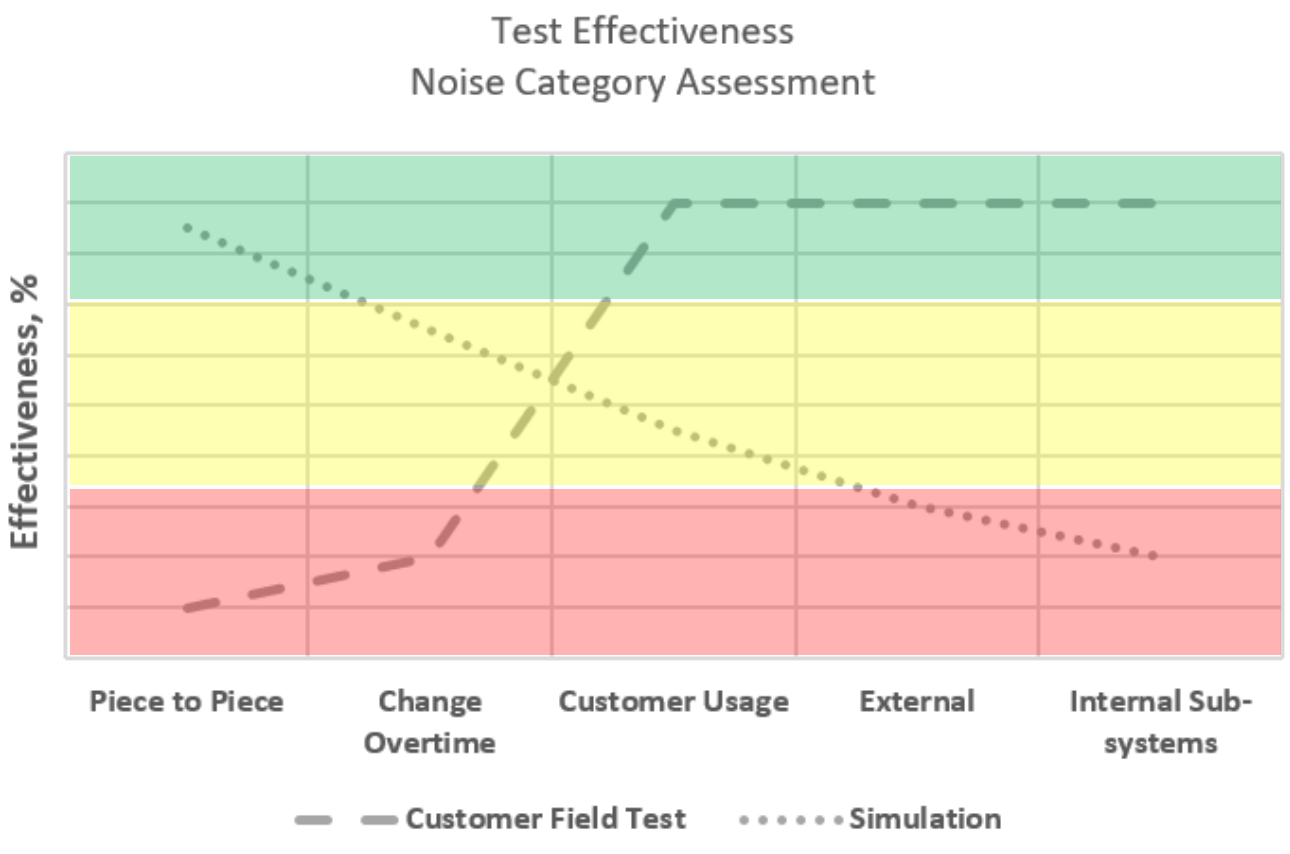
Evaluate all noise factor categories early in the development

43%

of calibration related quality issues are because customer field test didn't cover all noise factor categories

Compared to customer field test, better opportunity to evaluate piece to piece variation and aged system* performance utilizing simulation

**Still challenging to understand how aged system performs and how to create physical part or model*



Benefits of Simulation

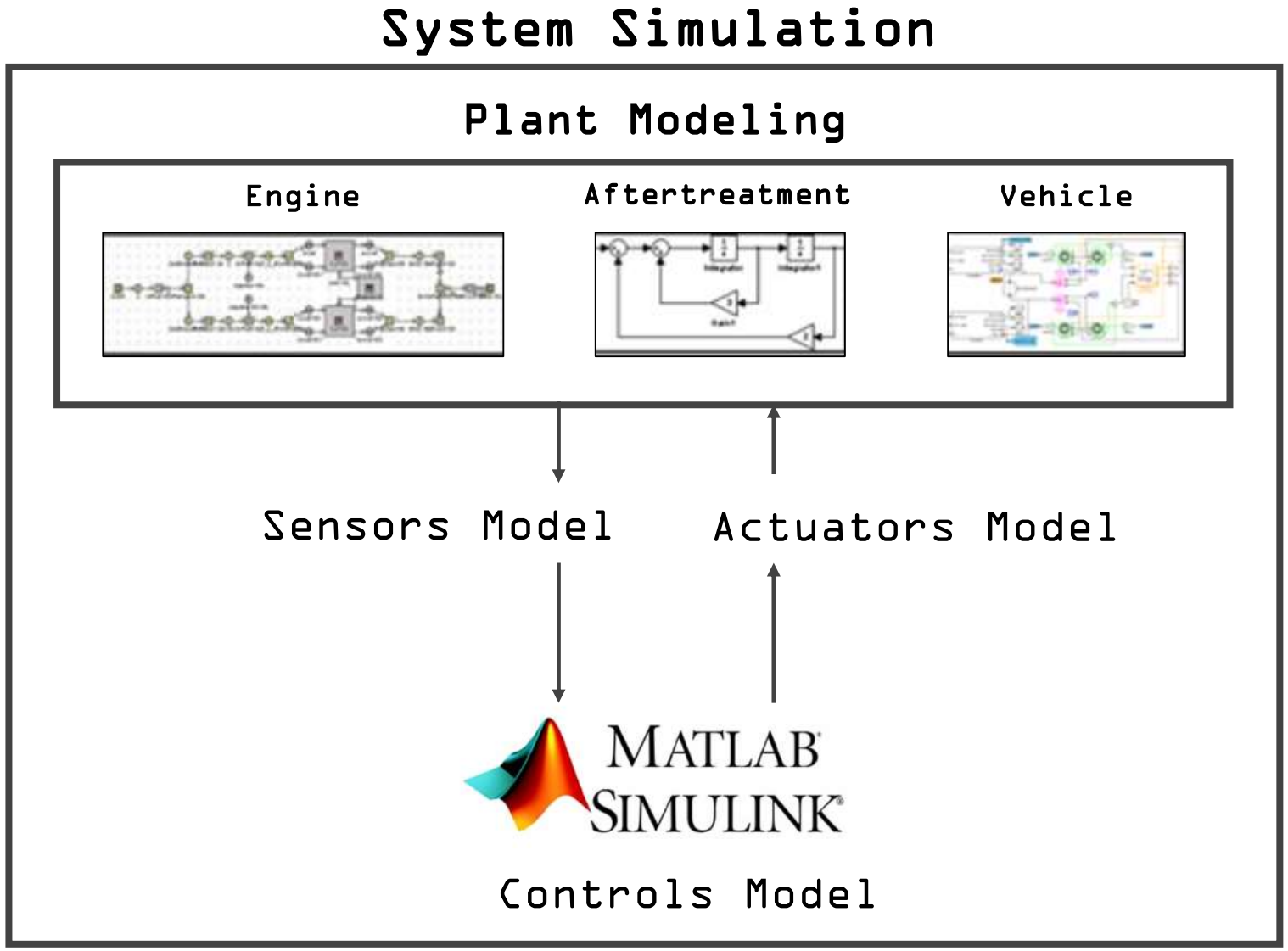
Develop, verify and validate calibrations more efficiently
Faster problem resolution

Cost-effectively verify calibrations by complementing real-world testing

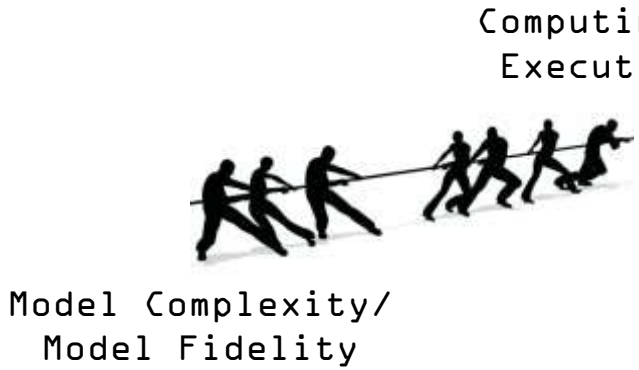
Efficiently evaluate system robustness to noise factors:
Environmental, duty-cycle, part-to-part variability and system aging

Improved customer satisfaction

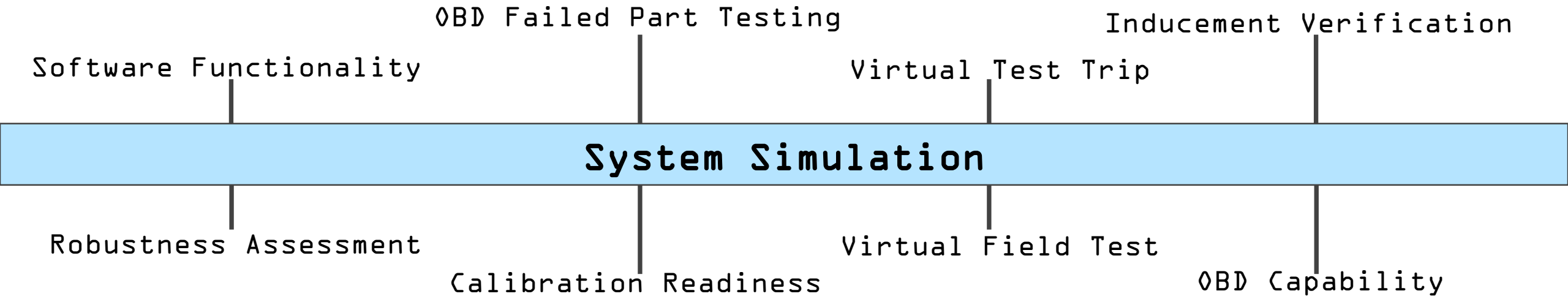
Investment for System Simulation



- Capability to introduce noise factors and failed parts for performance features and over 300 diagnostics
- Empirical transient models for engine out NOx and PM
- Aftertreatment outlet NOx estimation
- Fast running plant models for close to real time execution rate



Process Integration of System Simulation



Calibration Design Reviews | OBD Reviews | Reliability Scorecard | Test Trip Reviews

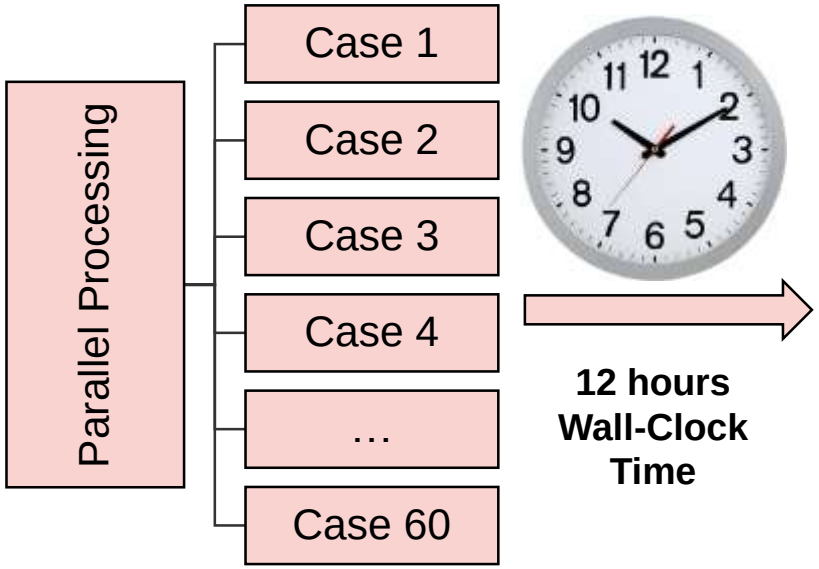
- Simulation Leads are assigned to global major development programs to provide system simulation capability
- Processes and measures are updated
- Benefits to product development efficiency and product quality are being evaluated
  - 6-10% reduction in system performance & OBD product development cost is estimated per program

Pure Simulation

Pure Simulation Benefits

- Allows concurrent execution of multiple test cases
  - Even at Real-Time execution rates running multiple instances in parallel means that the effective number of test hours versus real-time is increased

Pure Simulation opportunity drives for a strategic approach to simulation for robustness assessment



12 hours Stimulus Cycle @ RT

12 hours Wall-Clock Time

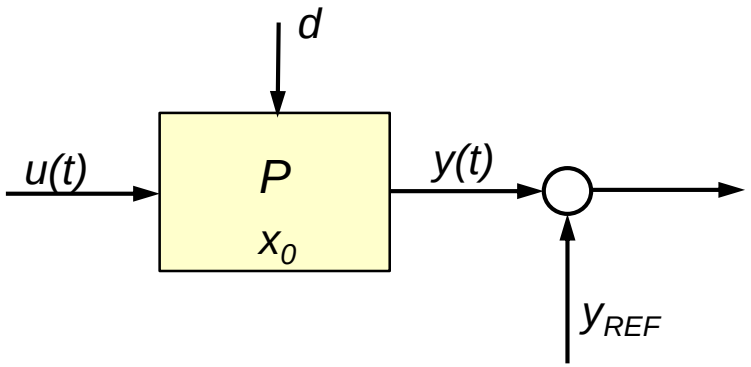
720 hours of Test Data!

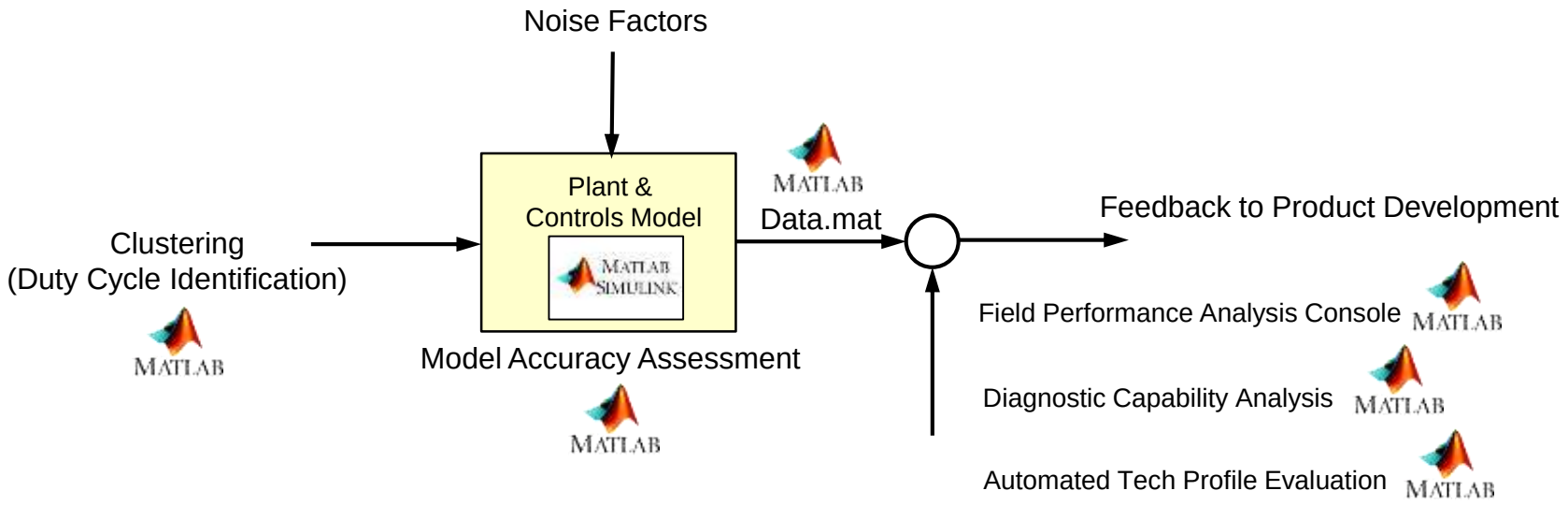
phdcomics.com

Approach to System Simulation

Approach to System Simulation to deliver technical efficiency & effectiveness

1. **Operating Conditions** *(Duty cycle, rating, GCVW…):* ***u(t)***
2. **Initial Conditions** *(Cold start, ash loading…):* ***x_0***
3. **Noise Factors** *(Ambient temp/press, sensor variation, aging…):* ***d***
4. **Outputs of Interest** *(Fluid consumption, Diagnostics…):* ***y(t)***
5. **Requirements on Outputs** *(Tech Profile, Fault Codes…):* ***y_{REF}***
6. **Test Bed** *(Pure Simulation, HIL…):* ***P***





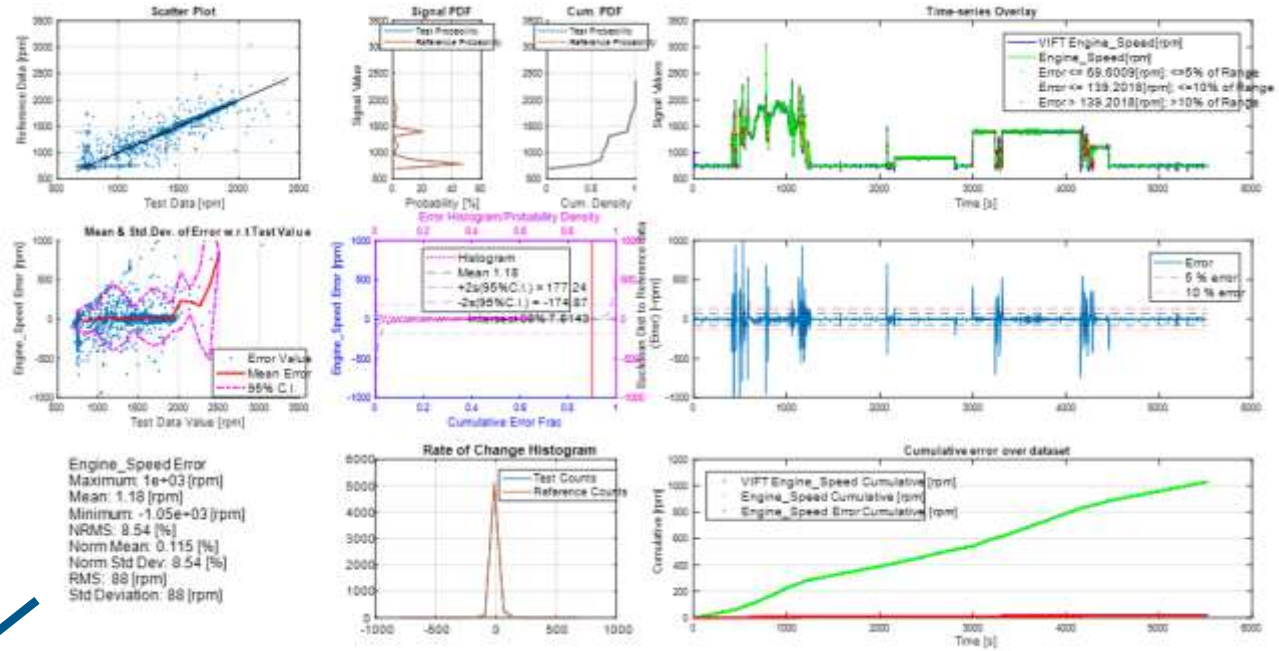
Model Accuracy Assessment

Probability/Cumulative Density Function

Correlation, R^2

Time Series Overlay

Error w.r.t. reference



Error vs Time

Statistics Summary

Rate of Change

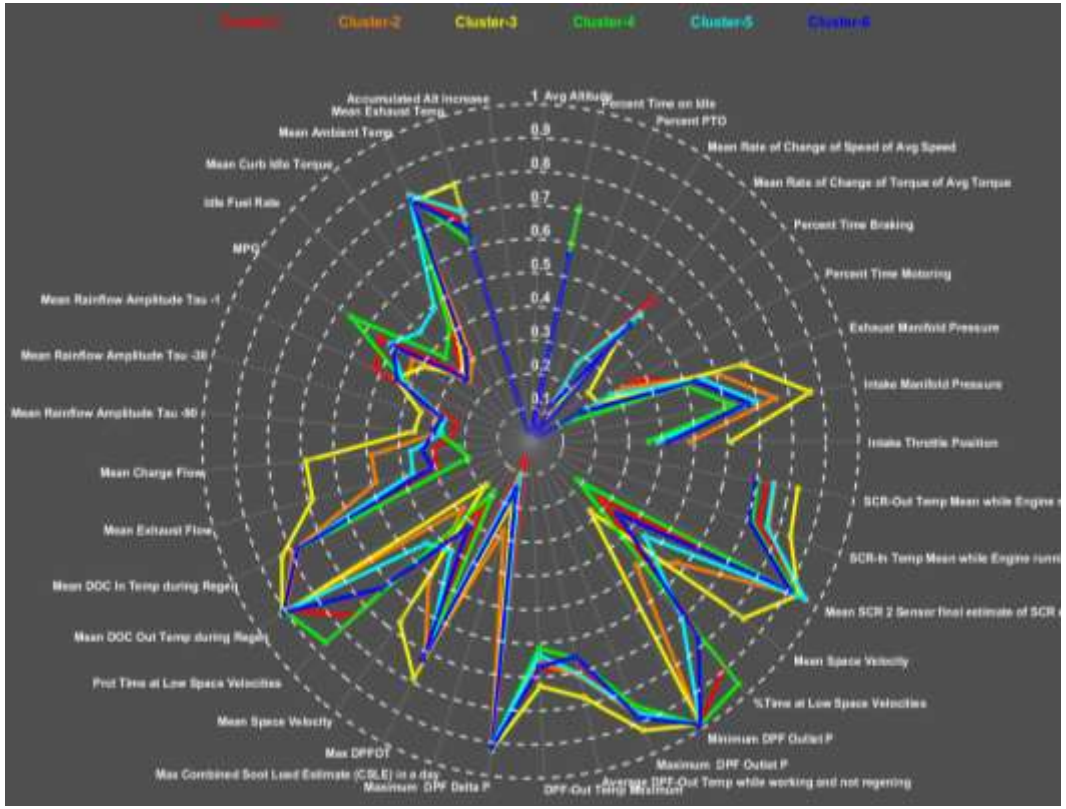
Cumulative Error

Clustering

Clustering is an approach for grouping data using K-Means algorithm

Long term customer data can be processed for various purposes
(identify representative duty cycles or challenge maneuvers for specific failure modes)

Engine Speed & Load traces from clustering analysis are used as input to the System Simulation



Cluster 1: Buses

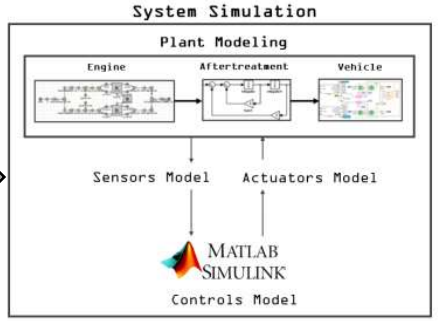
Cluster 2: Truck (Low Load)

Cluster 3: Truck (High Load)

Cluster 4: Refuse Hauler

Cluster 5: Feed Lot Truck

Cluster 6: Waste Hauler



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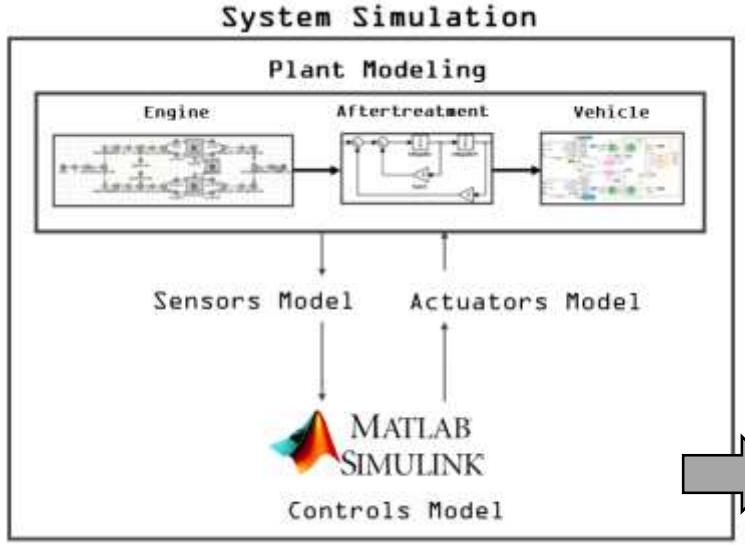
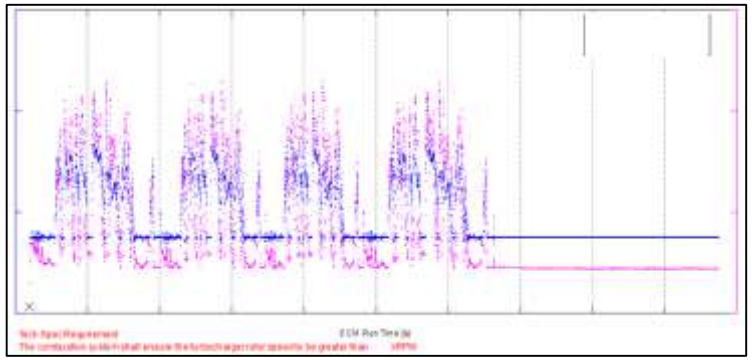
Data Analysis



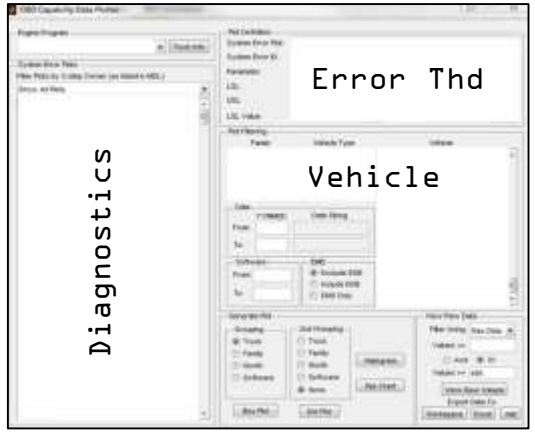
Virtual Field Test

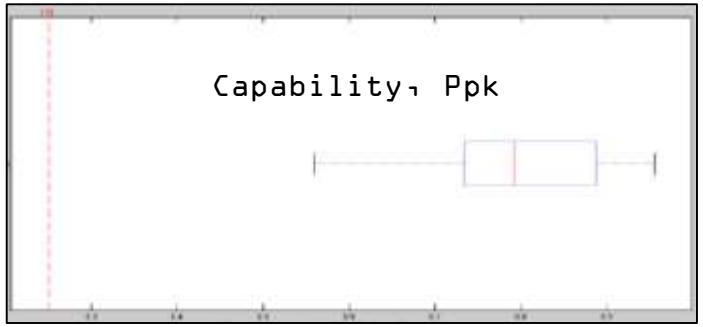
Automated Tech Profile Assessment
Requirements written as scripts for data analysis



Graphical User Interface for performance analysis plots

OBD Capability Data Plotter





Virtual OBD Experience

- Successful correlation of simulated failure modes to real-world failure modes
  - Benefits → Reduce iterations to find Worst Performing Acceptable / Best Performing Unacceptable failed parts
- Identified emissions shift associated with failure levels
  - Benefits → Reduce iterations to find threshold failed part
- Identified system-level risks due to component level failures
  - Benefits → Catastrophic failure avoidance in test cell

Virtual OBD Failed Part Testing

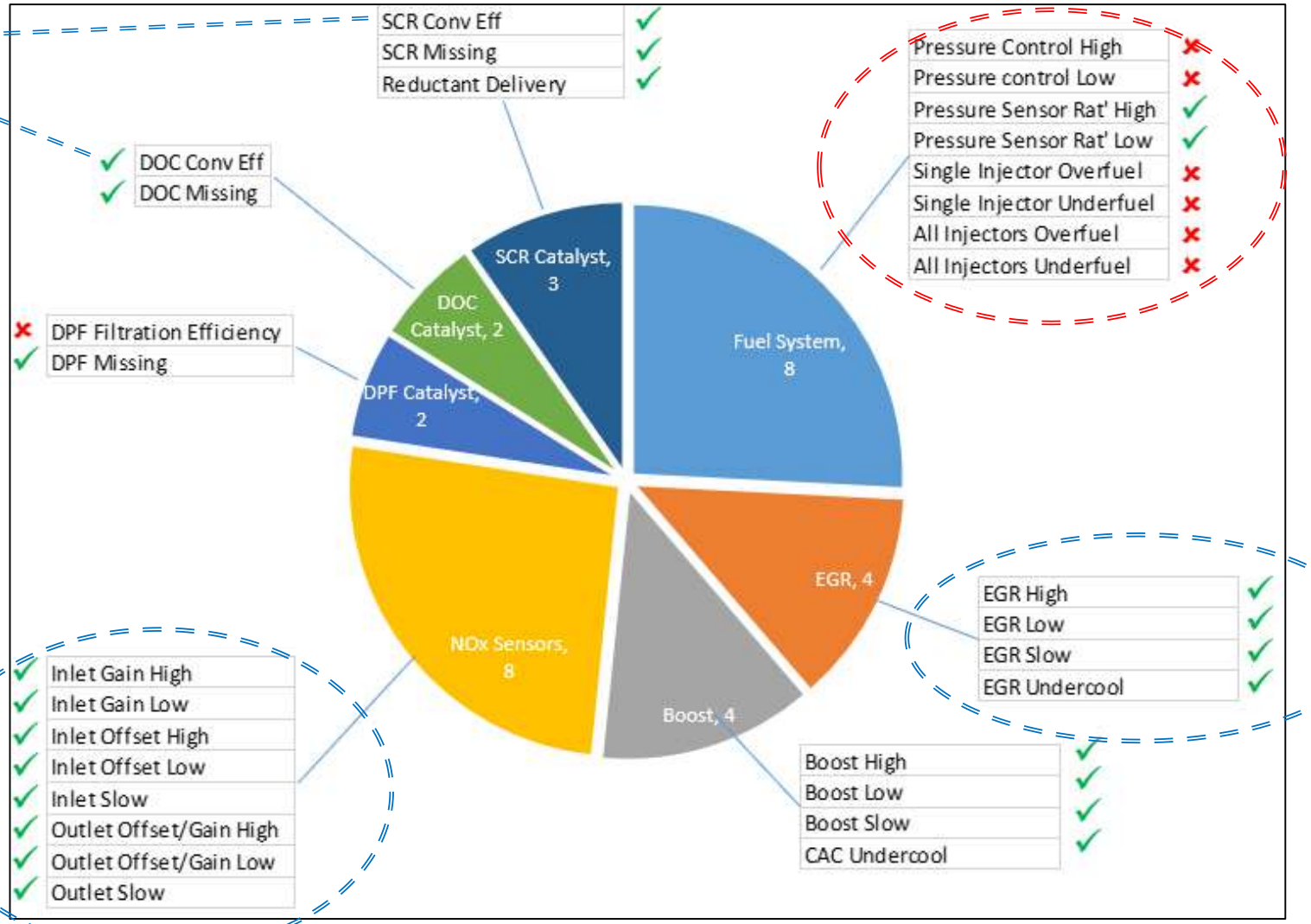
Emissions Threshold Monitors

AVL BOOST Catalyst Model Updates

Fuel System Feedback is not Modeled

GTPower Engine Model Updates

Sensor Shift in Controls Model



✘ Not Capable

✓ Capability Demonstrated

Closing Comments

Remaining Challenges

- Missing simulatable components in Controls Model and modifications required to run System Simulation
- Engine Control Module hardware performance not matching Controls Model performance
- Long duration from Controls Model release to functional System Simulation

Next Steps

- Evaluation of Controls Model development processes to improve completeness and efficiency
- Develop plant modeling requirements for system simulation
- Assignment of Simulation Leads to more development programs
- Monitor product development efficiency and product quality benefits of system simulation

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Q+A


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