Drivers for Industrial CFD: CFD Vision 2030, Grand Challenges, and Certification by Analysis

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Outline

- **Some recent activities in USA towards accelerating CFD technologies**
  - CFD Vision 2030 Study
  - Certification by Analysis Study
  - AIAA CFD2030 Integration Committee
    - Community activities
    - Grand Challenge Problems
- **Barriers and Challenges**
  - Technical
  - Logistical and organizational
- **Conclusions**

NASA Vision 2030 CFD Code

Final Technical Review

Contract # **NNL08AA16B** (Order # NNL12AD05T)

Deliverable # 6

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NASA Langley Research Center

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Overview of Study

- "...Address(es) the long-range planning required by NASA's Revolutionary Computational Aerosciences (RCA) …
- Create a comprehensive and enduring vision of CFD technology and capabilities:
- Develop and execute a comprehensive CFD community survey to refine the technical requirements, gaps, and impediments
- Based on the refined vision, hold a CFD workshop among subject matter experts within industry, government, and academia
- Develop and deliver a final report summarizing findings and recommendations

Overview of Study

- **"...Address(es) the long-range planning required by NASA's Revolutionary Computational Aerosciences (RCA) ...**

  "...provide a knowledge-based forecast of the future computational capabilities ..."

  "...and to lay the foundation for the development of a future framework/environment where physics-based, accurate predictions of complex turbulent flows, including flow separation, can be accomplished routinely and efficiently in cooperation with other physics-based simulations to enable multi-physics analysis and design."

Overview of Study

- **Create a comprehensive and enduring vision of CFD technology and capabilities:**
  - Identify shortcomings and impediments
  - Develop a long-term, actionable research plan
  - Develop a detailed technology development roadmap to
    - capture anticipated technology trends and future technological challenges,
    - guide investments for long-term research activities,
    - and provide focus to the broader CFD community for future research activities

Findings

1. Investment in basic R&D for simulation-based analysis and design has declined significantly in the last decade and must be reinvigorated…
2. HPC hardware is progressing rapidly and technologies that will prevail are difficult to predict.
3. The accuracy of CFD is severely limited by the inability to reliably predict turbulent flows with significant regions of separation
4. Mesh generation and adaptivity continue to be significant bottlenecks …
5. Revolutionary algorithmic improvements will be required…
6. Managing the vast amounts of data generated by current and future large-scale simulations will continue to be problematic and will become increasingly complex due to changing HPC hardware.
7. Advances required for increasingly multidisciplinary simulations…

CFD Vision 2030

- **Emphasis on physics-based, predictive modeling**

  Transition, turbulence, separation, unsteady/time-accurate, chemically-reacting flows, radiation, heat transfer, acoustics and constitutive models

- **Management of errors and uncertainties**

  Quantification of errors and uncertainties arising from physical models, mesh and discretization, and natural variability

- **Automation in all steps of the analysis process**

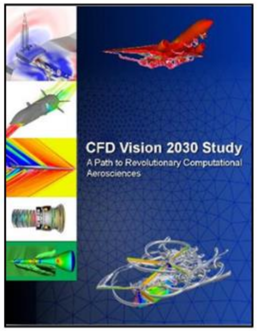
  Geometry creation, meshing, large databases of simulation results, extraction and understanding of the vast amounts of information

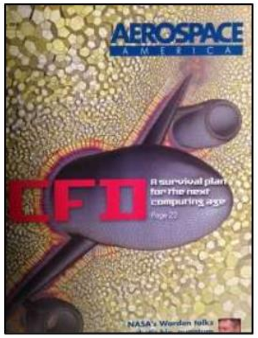
- **Harness exascale HPC architectures**

  Multiple memory hierarchies, latencies, bandwidths, programming paradigms and runtime environments, etc.

- **Seamless integration with multi-disciplinary analyses and optimizations**

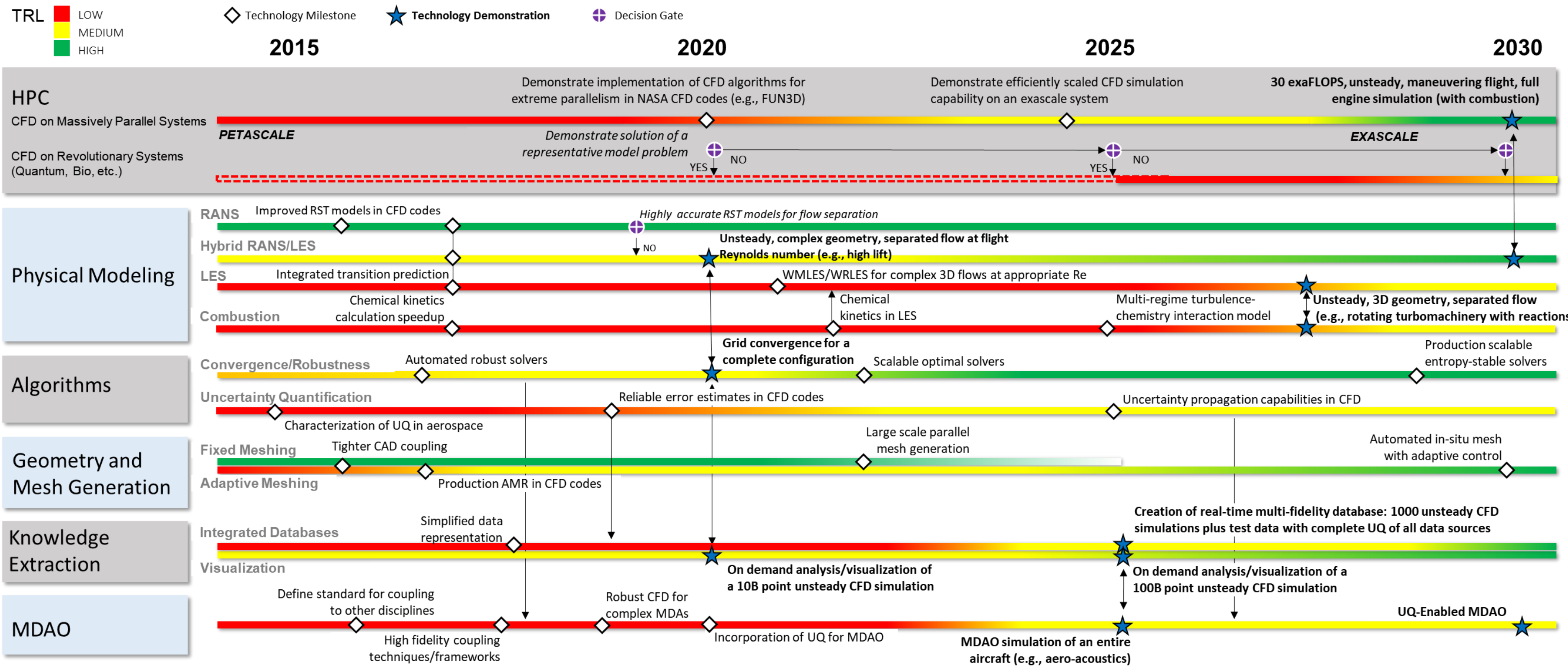
  High fidelity CFD tools, interfaces, coupling approaches, the science of integration, etc.





Slotnick, et al., "CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences," NASA/CR-2014-218178, 2014

Original CFD Vision 2030 Roadmap (2014)



Recommendations

1. NASA should develop, fund and sustain a base research and technology (R/T) development program for simulation-based analysis and design technologies.
2. NASA should develop and maintain an integrated simulation and software development infrastructure to enable rapid CFD technology maturation.
3. NASA should make available and utilize HPC systems for large-scale CFD development and testing.
4. NASA should lead efforts to develop and execute integrated experimental testing and computational validation campaigns.
5. NASA should develop, foster, and leverage improved collaborations with key research partners and industrial stakeholders across disciplines within the broader scientific and engineering communities.
6. NASA should attract world-class engineers and scientists.

Grand Challenge Problems

- **Represent critical step changes in engineering design capability**
- **May not be routinely achievable by 2030**
- **Representative of key elements of major NASA missions**

1. Large Eddy Simulation (LES) of a powered aircraft configuration across the full flight envelope
2. Off-design turbofan engine transient simulation
3. Multi-Disciplinary Analysis and Optimization (MDAO) of a highly-flexible advanced aircraft configuration
4. Probabilistic analysis of a powered space access configuration

Engineering, Test & Technology
Boeing Research & Technology

A 20-year Vision for Virtual Flight and Engine Testing

Subtopic 2.1.1 – Requirements for Aircraft Certification by Analysis (CbA) NNL16AA04B-80LARC19F0018

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Boeing/Raytheon Technologies Research Center/Stanford/U. of Wyoming
4 March 2021

An Overview Certification & Flight Testing

Certification is the last stage of a process that starts long before the airplane is ever built

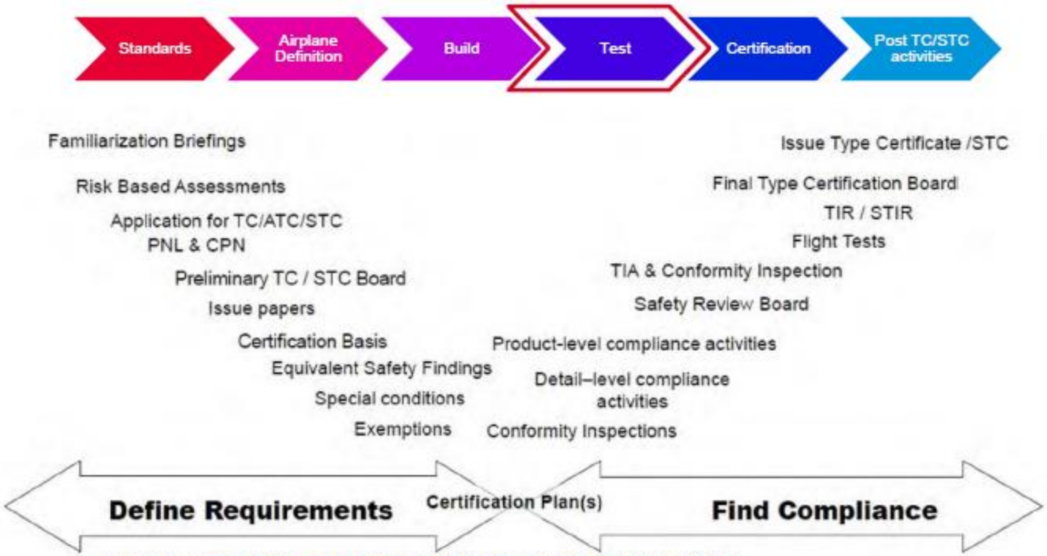


Figure from "The FAA and Industry Guide to Product Certification," 3rd Ed.

- ➢ **Compliance with highlighted subparts encompasses nearly 60 flight maneuvers or engine test scenarios**
- ➢ **Certification efforts for a new airplane program can last over a year and represents a significant portion of the total cost of development**

Applicable FAA Airworthiness Standards

- Transport Aircraft
  - Title 14, Part 25, Subpart B (Flight)
- Engines
  - Title 14, Part 33, Subpart F (Block tests; turbine aircraft engines)

Full Part 25/33 listing

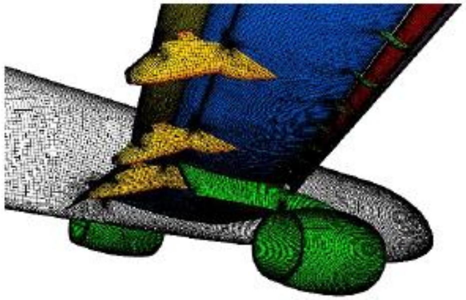
What is Certification by Analysis?

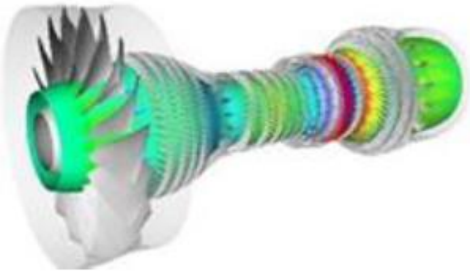
- An alternate means of compliance for airplane and engine certification based on analysis
- "…flight modeling or engine modeling, where analysis (such as numerical or wind tunnel methods) and/or simulation methods are used to obtain results for certification compliance that have traditionally been acquired using physical testing, such as flight testing or ground-based testing for engines."*

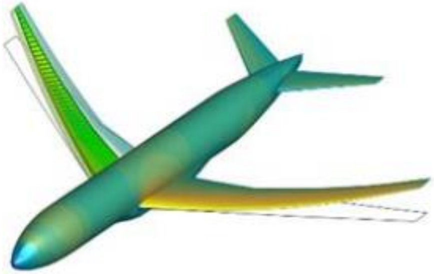
* "When Flight Modelling is Used to Reduce Flight Testing Supporting Aircraft Certification", AIAA Recommended Practice, R-154-202x

Why invest in Certification by Analysis?

- Efficient and optimized certification process
- Discovery and elimination of performance surprises typically discovered during flight test
- Analysis capabilities for concept & configuration development also lead to better designs
- Acceleration of product development schedule and time-to-market



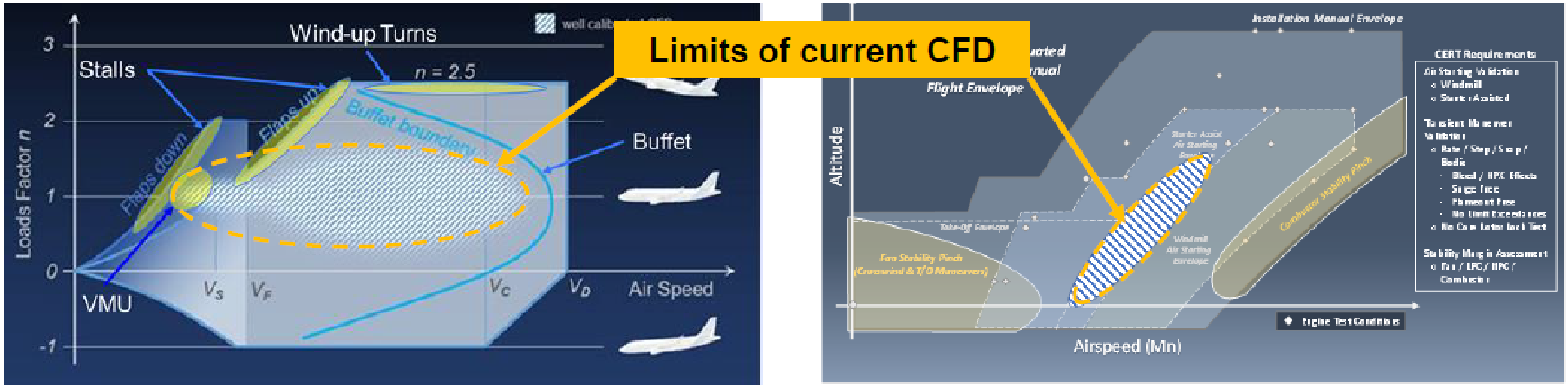




Certification compliance through analytical means

Why is Certification by Analysis challenging?

- **A high bar for proof of compliance**
  - "…by tests upon an airplane of the type for which certification is requested, **or by calculations based on, and equal in accuracy to**, the results of testing" (§ 25.21)
- **Many of the maneuvers occur at the edges of the envelope**
  - **High Speed: buffet, flutter, vibration**
  - **Low Speed: stall, min. control speed, takeoff/landing**
  - **Engine: Engine vibrations and engine operability**
- **Complex flow features at these conditions historically challenging for numerical methods and simulation**
- **Multidisciplinary methods are often involved**
- **Complex systems level interaction required to model full airplane/engine response**
- **Volume of analysis required poses challenges for computing resources and data storage**



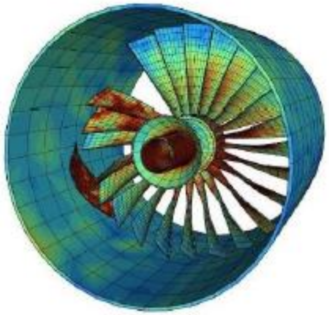
Analysis must be equal in accuracy to testing!

Project Background & Objectives

Objective:

Develop detailed requirements and procedures for certification by analysis pertaining to advances in computational simulation capability (e.g., CFD, CSD, etc.):

- Establish detailed requirements and procedures for certification by analysis,
- Assess the capability of the existing computational tools,
- Identify technical and logistical gaps
- Recommend best approaches to overcome the deficiencies.



Expected Outcomes:

Establishment of requirements for certification by analysis/computations.

A research roadmap to develop computational technology for fulfilling the requirements.

CbA 2040 Vision

Four key elements:

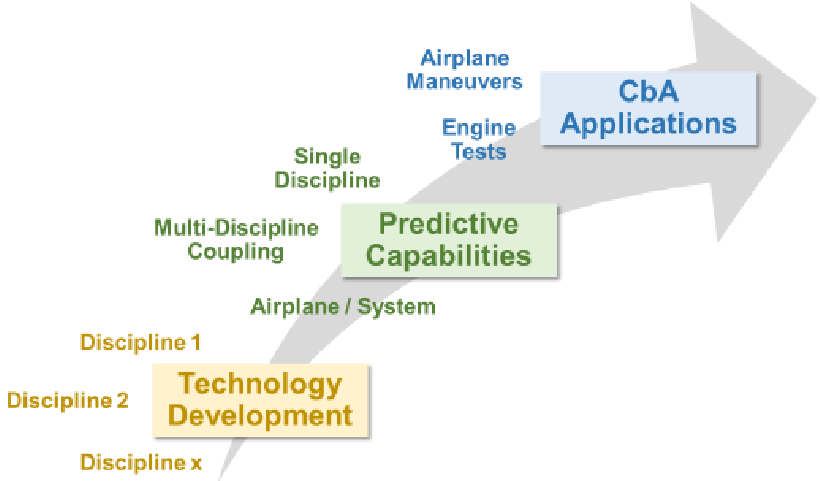
1	2	3	4
The ability to numerically simulate the **integrated system performance and response** of **full-scale airplane and engine configurations** in the **flight and/or ground-test environment** in an **accurate, robust, and computationally efficient manner**.	The development and implementation of quantified **flight and engine modeling uncertainties** to **establish appropriate confidence** in the use of numerical analysis for certification.	The **rigorous validation** of flight and engine modeling capabilities against **full-scale data** from critical airplane and engine testing.	The use of flight and engine modeling to enable **Certification by Simulation***.

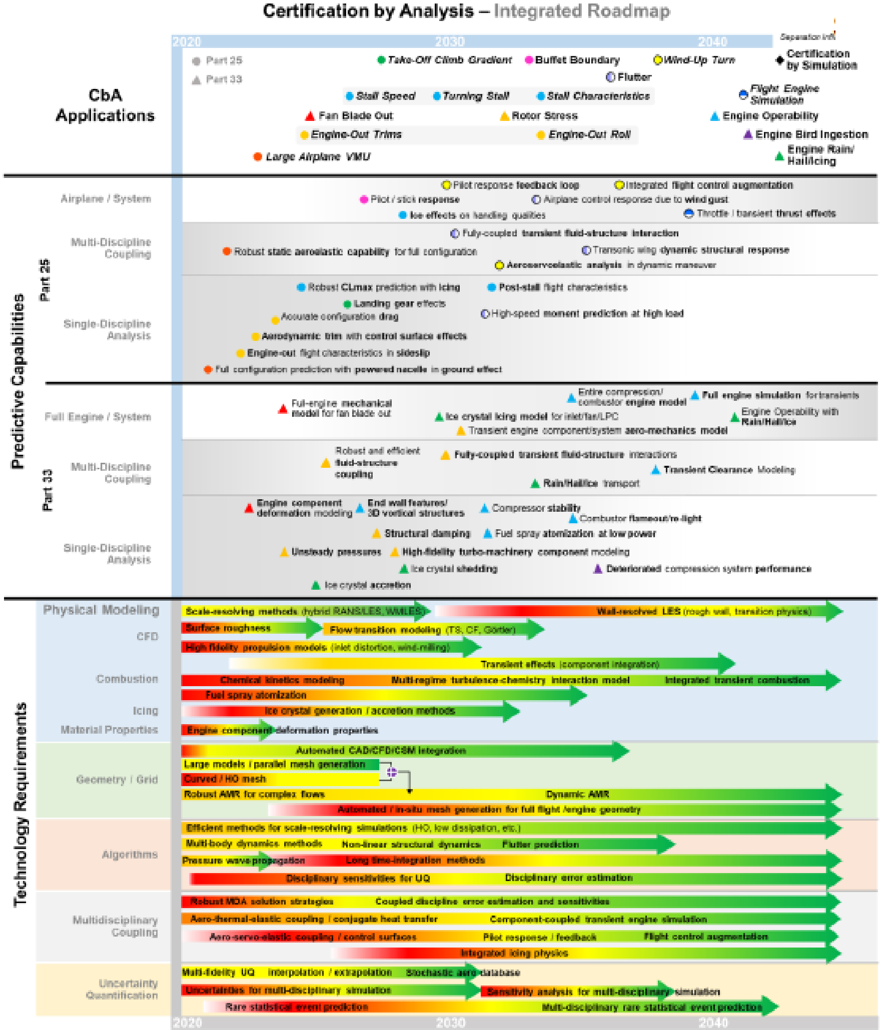
* Flight characteristics of airplane/engine product **fully described by the simulator**, and only **validated with flight test**

Long term vision provides direction and emphasis

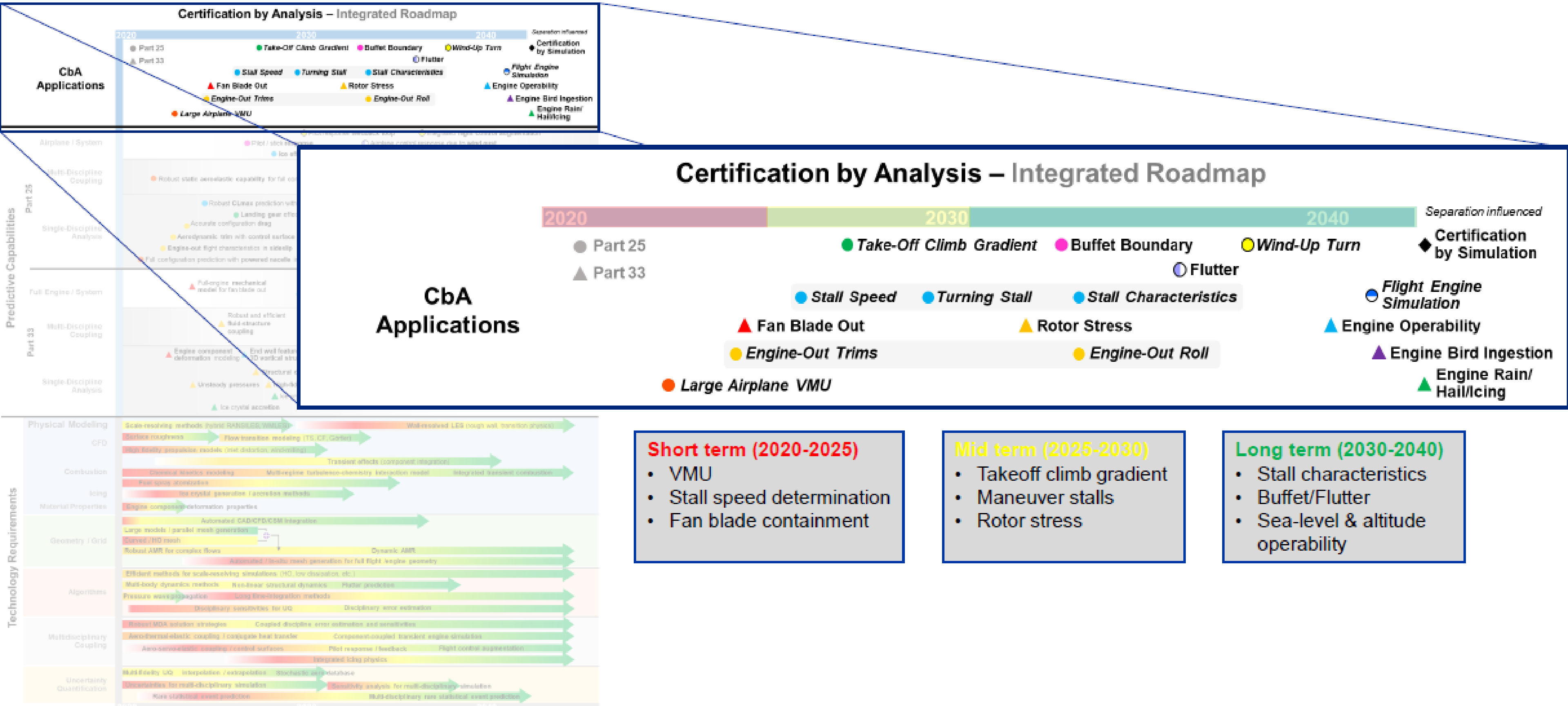
Integrated Technology Roadmap

- Developed an integrated framework for enabling Certification by Analysis
  - Key Technology Development enables critical predictive capabilities
  - Predictive Capabilities support specific CbA Applications
  - Verification, validation, and uncertainty quantification is a requirement at all stages
- Roadmap driven by broad community inputs
  - Certification by Analysis survey
  - Workshop results





Certification by Analysis Applications

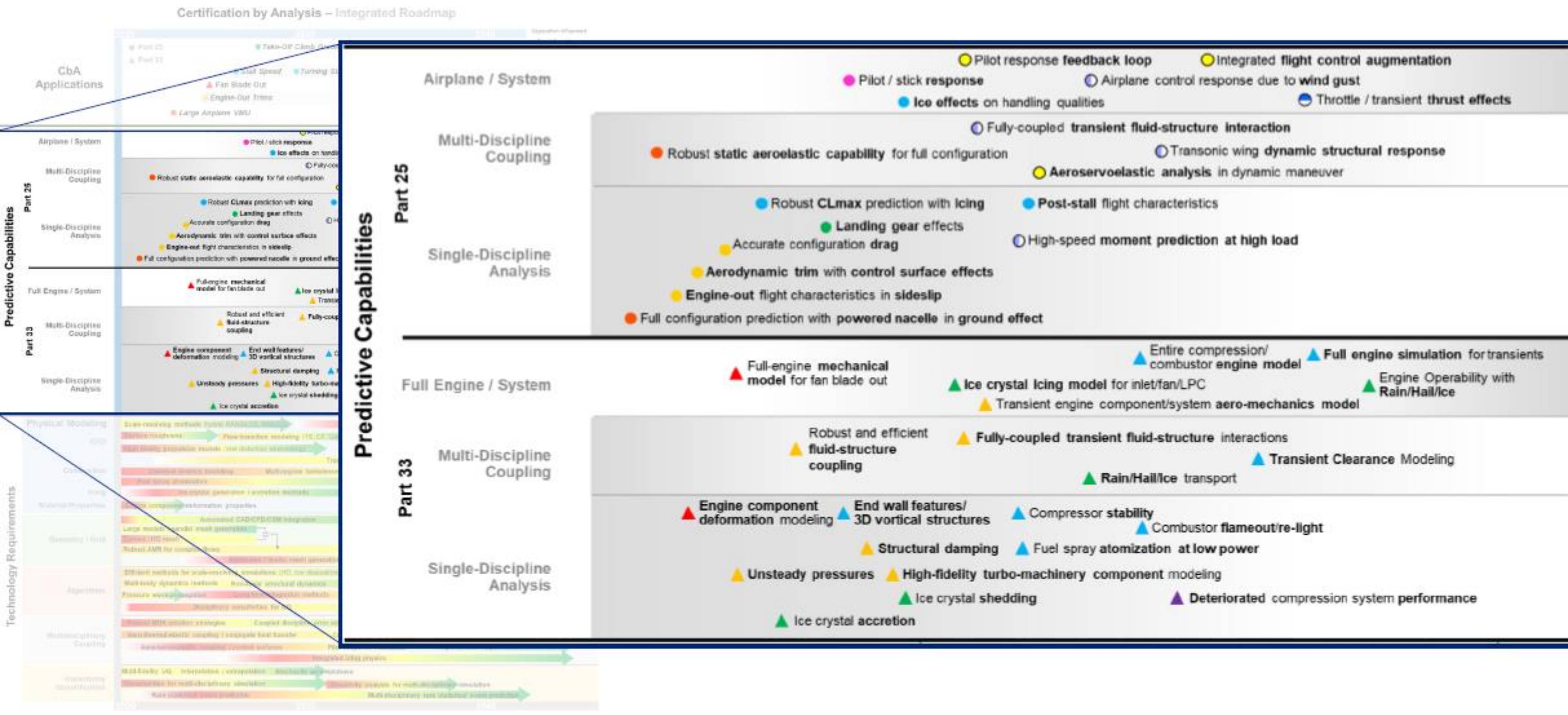


Short term (2020-2025)
- VMU
- Stall speed determination
- Fan blade containment

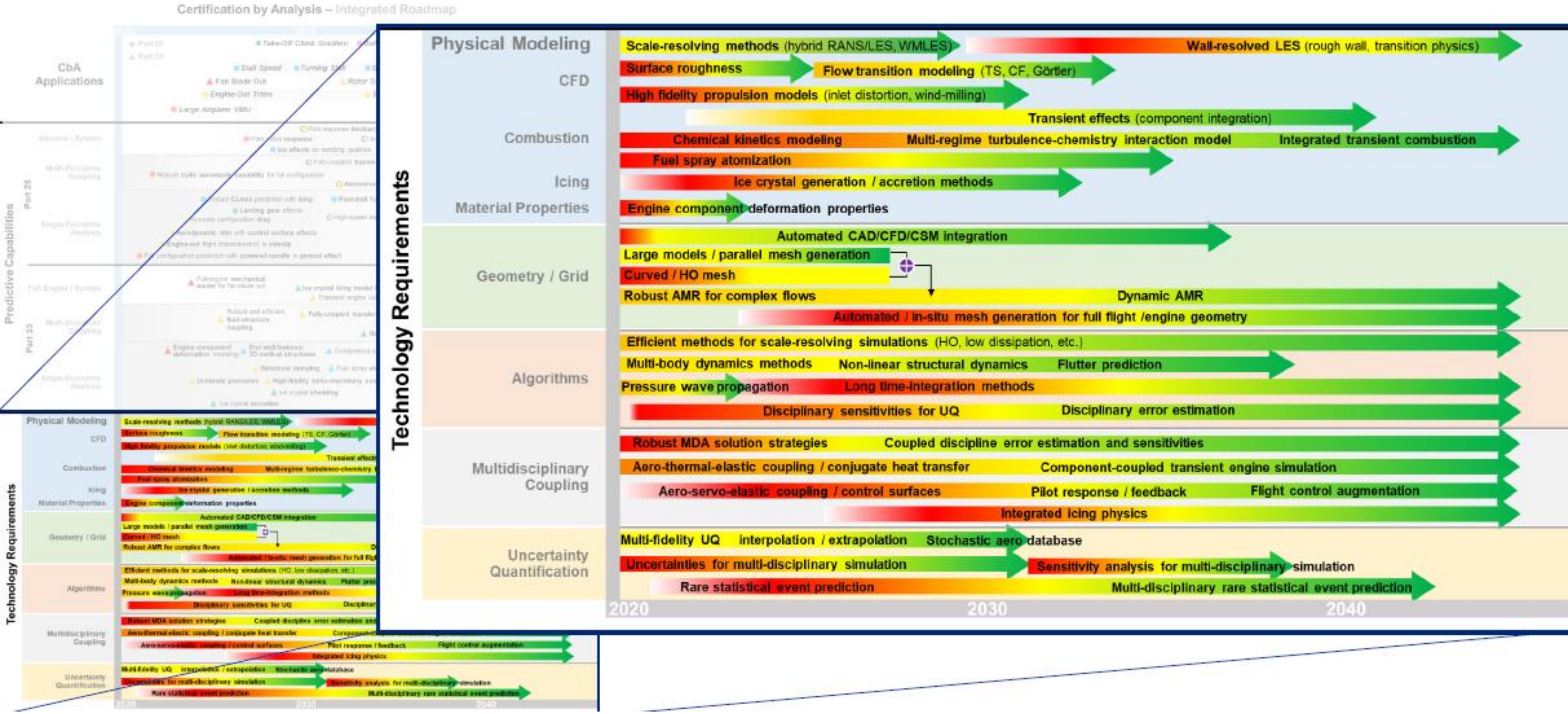
Mid term (2025-2030)
- Takeoff climb gradient
- Maneuver stalls
- Rotor stress

Long term (2030-2040)
- Stall characteristics
- Buffet/Flutter
- Sea-level & altitude operability

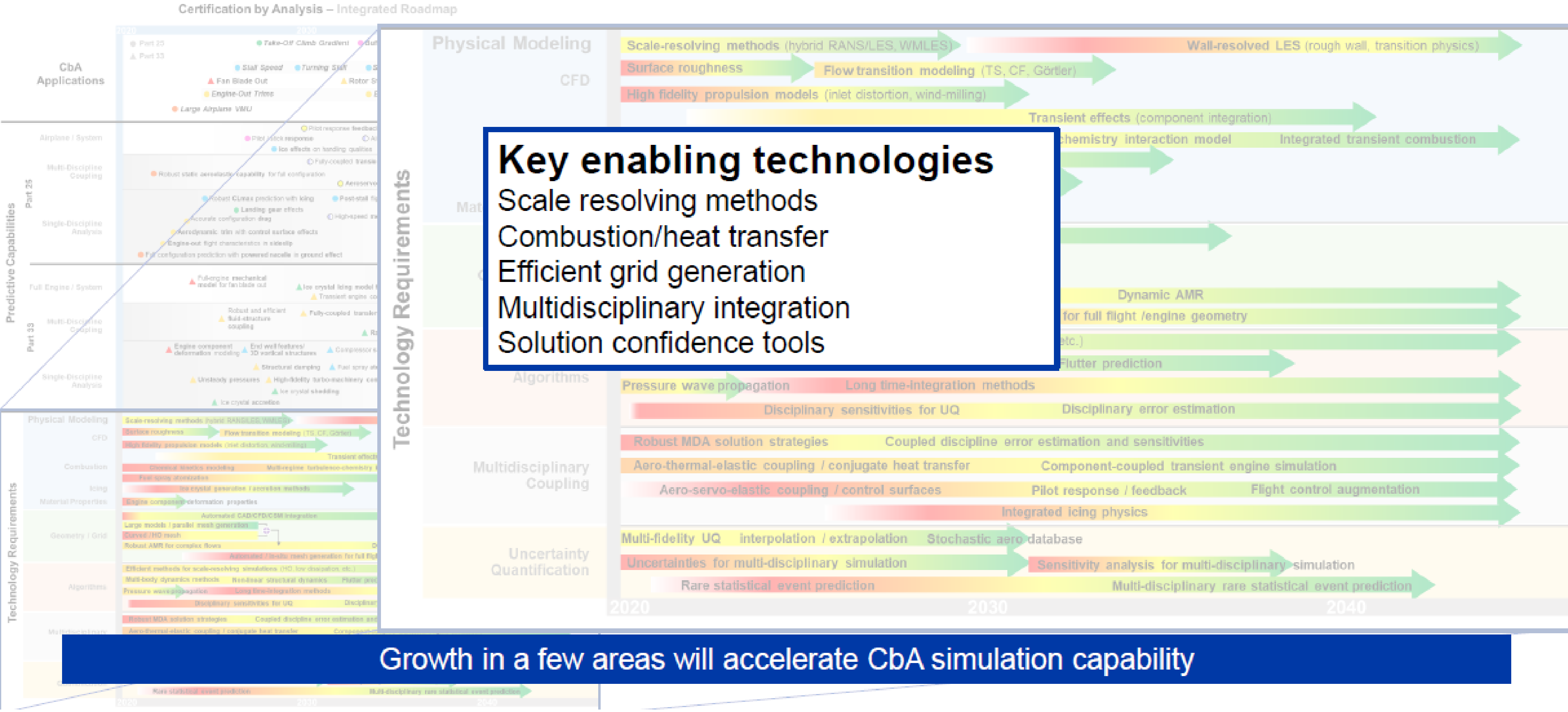
Predictive Capabilities



Technology Requirements



Technology Requirements



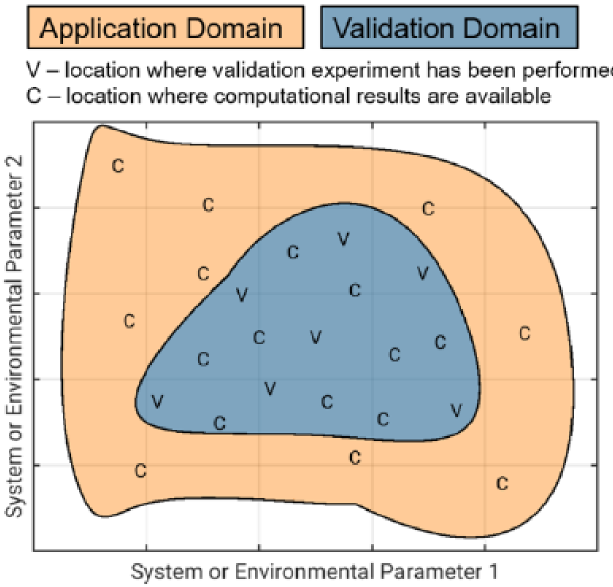
Key enabling technologies
- Scale resolving methods
- Combustion/heat transfer
- Efficient grid generation
- Multidisciplinary integration
- Solution confidence tools

Growth in a few areas will accelerate CbA simulation capability

Solution Confidence Tools

Key challenges for CbA in verification, validation and uncertainty quantification

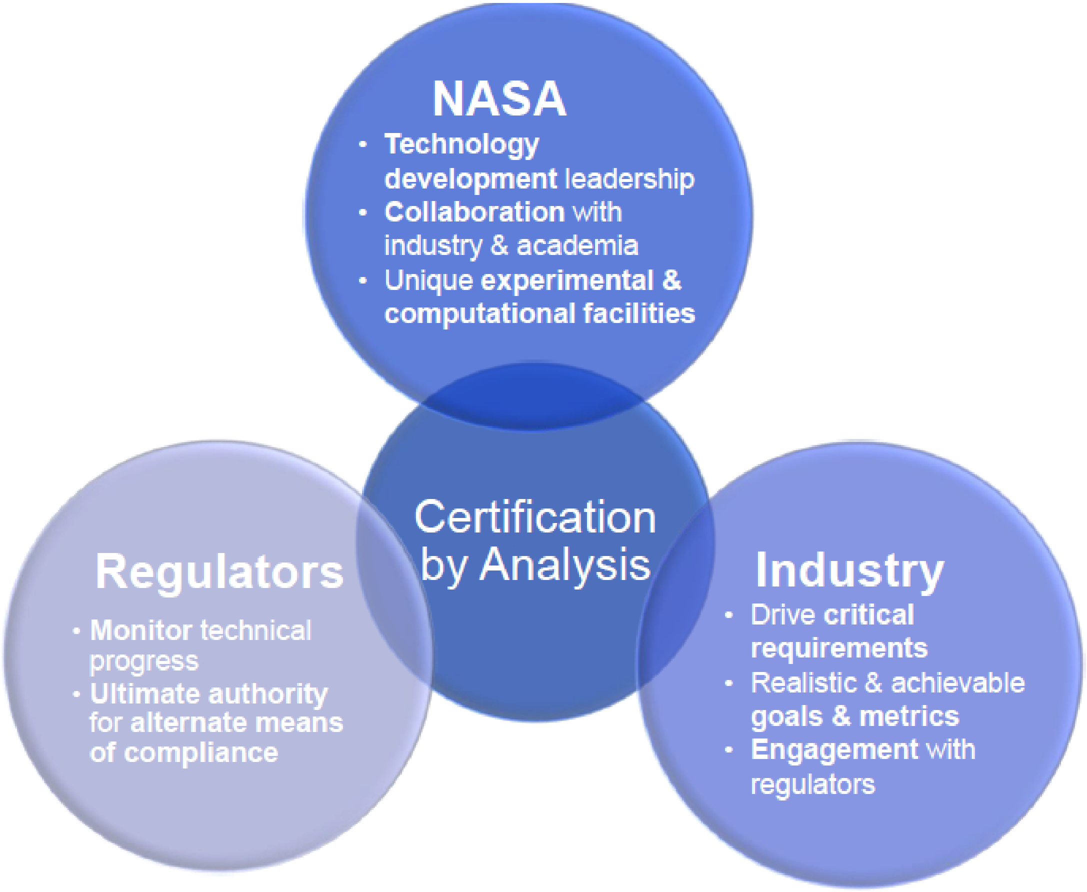
1. Developing and applying methods for **comprehensive verification of tools for single and multiple discipline analysis**, including **estimation of numerical uncertainties** for representative cases
2. Obtaining **validation data** for specific full scale applications with sufficient knowledge of test articles and measurements **to estimate model form uncertainties**
3. Demonstrating appropriate techniques for **estimating changes in uncertainty** from a relevant validation data set to an application problem
4. Creating efficient **uncertainty quantification methodologies** and standards **applicable to certification metrics** including both aleatory and epistemic uncertainties appropriately.
5. Establishing standards for **communicating and interpreting uncertainties** in general, but specifically **with respect to regulations**.



Ensure accurate solutions and provide confidence

Recommendations

- A series of recommendations has been distilled from this study to NASA and other CbA stakeholders including industry, regulators, and academia
- The requirements for accurate and appropriate simulation capabilities for certification by analysis extend well beyond CFD
- Multidisciplinary nature and system-level aspects of CbA require tight coordination between industry, regulators, and government/research organizations
- Each stakeholder has unique capabilities and roles in a concerted effort

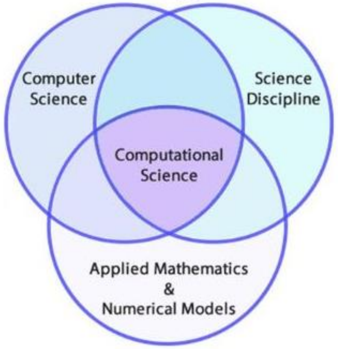


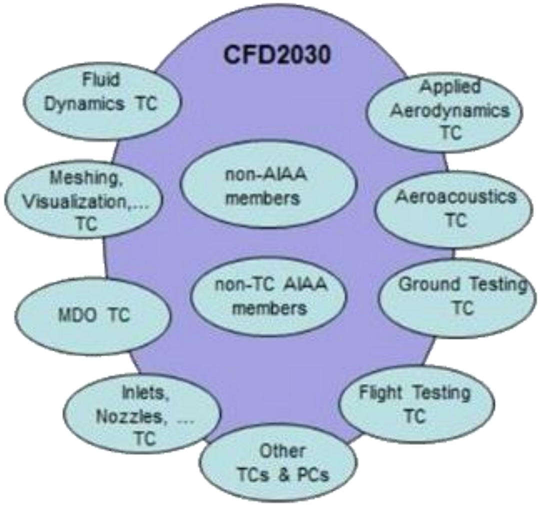
Each Stakeholder has unique capabilities and roles to advance CbA

CFD2030 Integration Committee (IC)

- **Established in 2017**
- **Hosted by AIAA**
- **Objectives:**
  - ***Promote a community of practice*** *engaged in developing methods, models, physical experiments, software, and hardware for revolutionary advances in computational simulation technologies for analysis, design, certification, and qualification of aerospace systems*
  - ***Leverage and integrate enabling technologies*** *such as high-performance computing, physical modeling, numerical methods, geometry/grids, validation quality experiments, multidisciplinary analysis and optimization, with quantified uncertainties.*
  - ***Communicate with other Committees*** *to assure that the AIAA membership engages with their peers and external constituencies in shaping the future of simulation-based engineering.*

Computational Science Venn Diagram



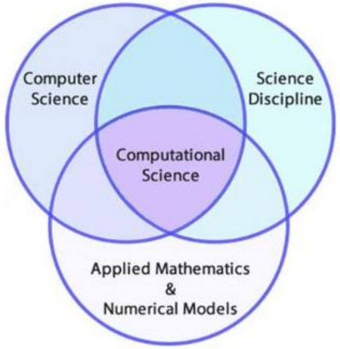


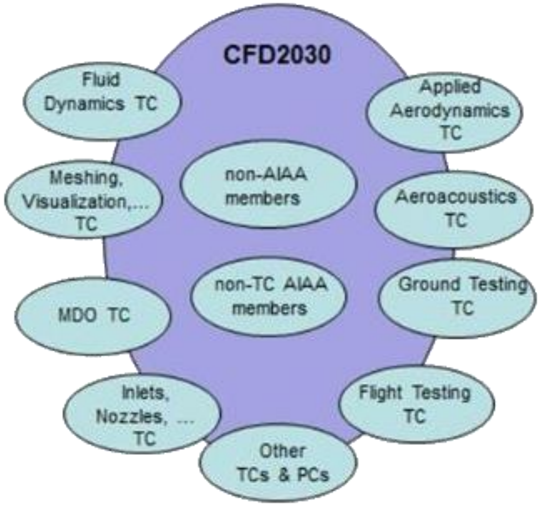
CFD2030 Integration Committee (IC)

- **Established in 2017**
- **Hosted by AIAA**
- **Paid membership in AIAA is <u>not</u> required for participating as a member of IC**

- **http://www.cfd2030.com**
- **44 current members (48% government, 36% industry, 16% academia)**
  - All US-based, but the IC is open to international participation

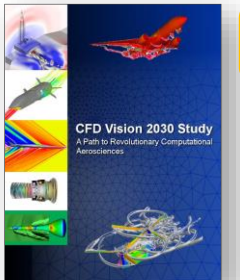
Computational Science Venn Diagram





Landscape

2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2025 | 2030



F360 Panel **CFD Vision 2030**

NASA · Royal Aeronautical Society · Aerospace America · Pointwise · Department of Energy · Department of Defense

AIAA

AIAA CFD2030
Integration Committee

NASA Workshop **Flight Prediction**

Workshop **Future CFD Technologies**

F360 Panel **HPC**

F360 Panel **Grand Challenges**

Panel **Physical Modeling**

F360 Panel …

F360 Panel …

Special Session **CFD Vision 2030 Progress**

Special Session **Grand Challenges**

Special Session **CFD Prediction Workshops**

Special Session …

Working Groups **Grand Challenges**

CFD Vision **Technology Update**

CFD Vision **Technology Update**

CFD Validation Experiments

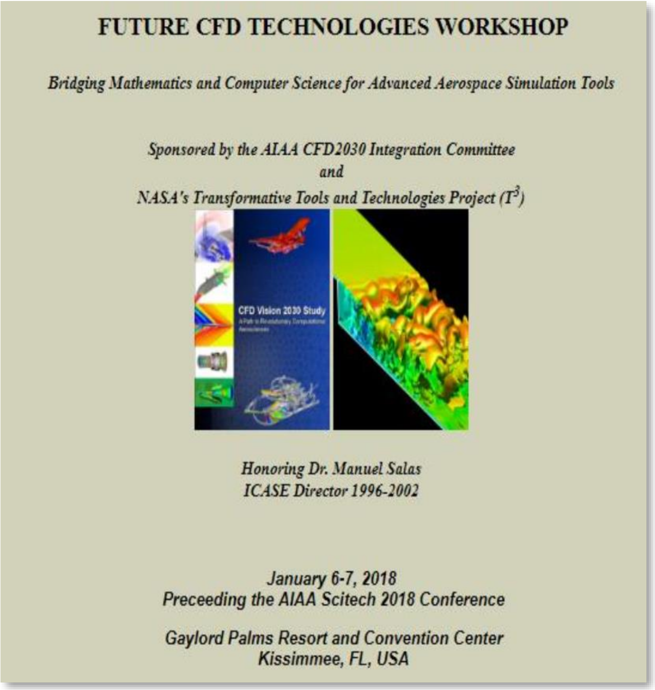
- **High Speed Common Research Model**
- **High Lift (CRM-HL Ecosystem)**
- **Aeroelastic (CRM-AE)**
- **Turbulent Heat Flux (THX)**
- **Aero Propulsion CRMs**
- **Juncture Flow**
- **Canonical Flow Separation Bump Configurations**

CFD Prediction Workshops

- **DPW-5**, **AEPW-1**
- **HLPW-2**
- **PAW-2**, **BANC-3**
- **DPW-6**, **AEPW-2**, **PAW-3**, **BANC-4**
- **HLPW-3**, **GMGW-1**
- **PAW-4**, **BANC-5**
- **GMGW-2**
- **SCPW-1**, **FTPW-1**, **PAW-5**, **BANC-6**
- **Icing-1**
- **HLPW-4**, **GMGW-3**, **LES-1**, **HIFI-1**
- **DPW-7**, **AEPW-2**, **Icing-2**, **PAW-6**, **MFM-6**
- **HLPW-5**

Future CFD Technologies Workshop

- **January 6-7, 2018 – Proceeded AIAA SciTech conference**
  - ➢ **First event hosted by CFD2030**
- **Objectives:**
  - ➢ Bridging **fundamental disciplines** for advanced aerospace simulation tools:
    - ▪ Applied Mathematics/Computer Science/Physical Modeling
  - ➢ **Coordination/collaboration/interaction** with government agencies/professional societies/technical communities
  - ➢ Raise awareness of importance of intersecting disciplines in Aerospace community


FUTURE CFD TECHNOLOGIES WORKSHOP

Bridging Mathematics and Computer Science for Advanced Aerospace Simulation Tools

Sponsored by the AIAA CFD2030 Integration Committee
and
NASA's Transformative Tools and Technologies Project (T^3)

Honoring Dr. Manuel Salas
ICASE Director 1996-2002

January 6-7, 2018
Preceeding the AIAA Scitech 2018 Conference

Gaylord Palms Resort and Convention Center
Kissimmee, FL, USA

Progress Towards CFD Vision 2030

Special Session: Progress Towards CFD Vision 2030

2019 (Aviation)

John Cavolowsky (NASA-TAC Program)
Jeffrey Slotnick (Boeing)
Gorazd Medic (UTRC)
Eric Nielsen (NASA-LaRC)
Scott Morton (CREATE-AV Program)
Dimitri Mavriplis (Univ of Wyoming)
John Chawner (Pointwise) / Nigel Taylor (MBDA)
Philippe Spalart (Boeing) / Michael Strelets (NTS)

Discussion Topics

- Role of NASA Aeronautics
- Industry (airplane/propulsion) perspectives
- Importance of HPC
- Geometry and Mesh Generation
- Turbulence prediction

Roadmap Update

Forum 360: HPC

2020 (SciTech)

Jeffrey Slotnick (Boeing, Moderator)
Roy Campbell (DoD-HPCMP)
Doug Kothe (DoE-ECP Program)
Eric Nielsen (NASA-LaRC)
Scott Morton (CREATE-AV Program)

Discussion Focus

- Drivers: Virtual testing, streamlined product acquisition
- Hardware: Shift to exascale, GPUs, load/system balancing, capability vs capacity
- Software: Toolkits→ stacks→ apps, strategic/long-term code refactoring,
- Algorithms: Asynchronous communication, concurrency, strong scaling, mixed-precision

Panel Session: Physical Modeling

2021 (Aviation)

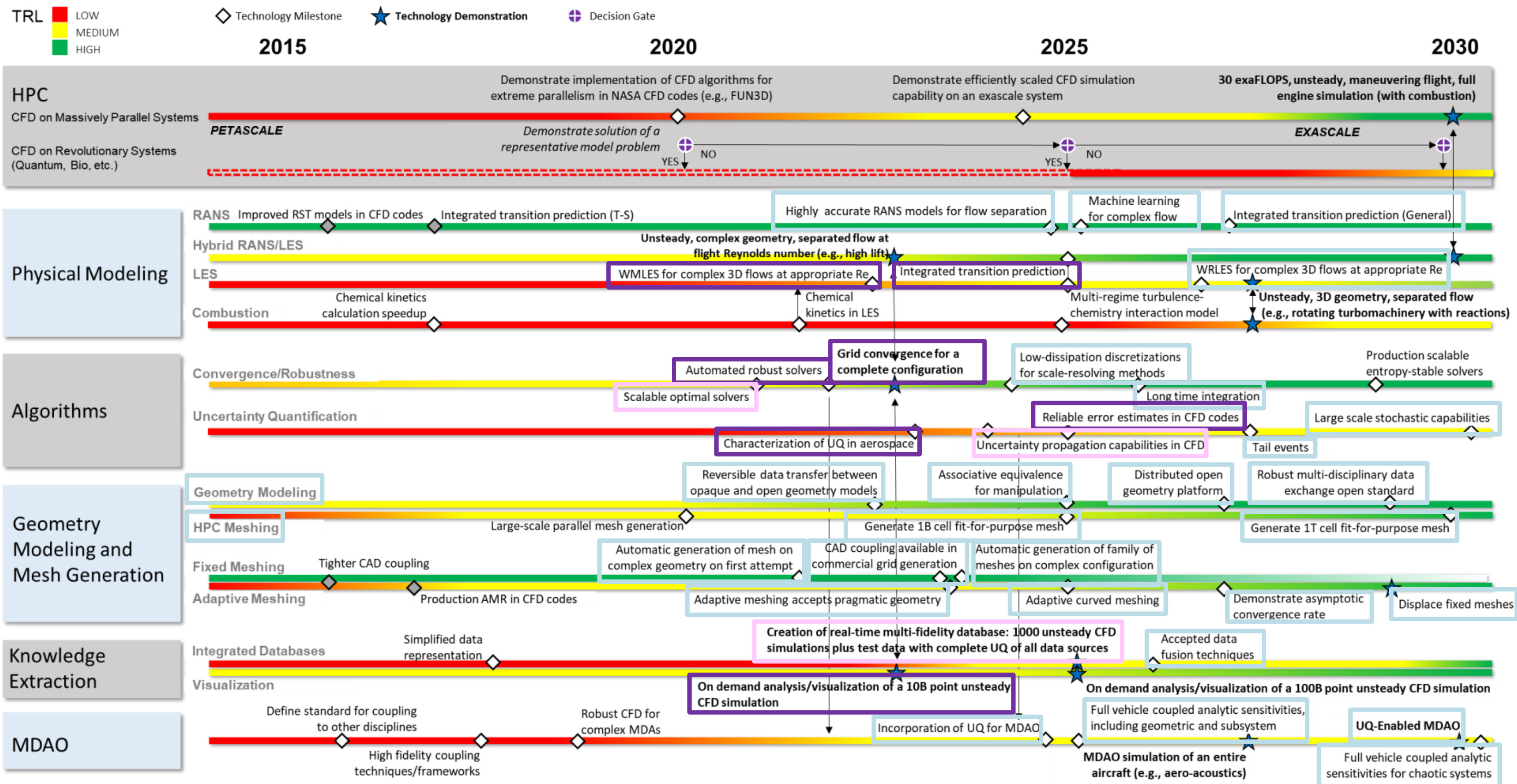
Brian Smith (Lockheed Martin, Moderator)
Florian Menter (Ansys)
Oriol Lehmkuhl (BSC)
Meelan Choudari (NASA)
Venkat Raman (Univ of Michigan)

Discussion Focus

- Scale-resolving simulations and high-fidelity modeling of combustion and flow transition
- Error control and UQ
- Use of AI/ML and data fusion with limited test data
- CFD validation requirements

Roadmap Update (2021)

◆ Milestone achieved
▭ Deferred/reformulated
Accelerated
New



CFD Grand Challenges

F360: Aerospace Grand Challenge Problems for Revolutionary CFD Capabilities

2020 (Aviation)

Juan Alonso (Stanford, Moderator)
John Cavolowsky (NASA-TAC Program)
Ray Gomez (NASA-JSC)
Micah Howard (Sandia)
Om Sharma (UTRC)
Steve Wells (Boeing)

Discussion Focus

- Need and value of Grand Challenge (GC) problems to drive technology innovation
- Overview of 4 GCs described: high-lift, full engine simulation, space access, and hypersonics
- Highlights key technical obstacles and the quantified benefit to industrial product development in overcoming those obstacles.

→

Special Session: CFD 2030 Grand Challenge Problems for Numerical Simulation in Aerospace Engineering

2021 (SciTech)

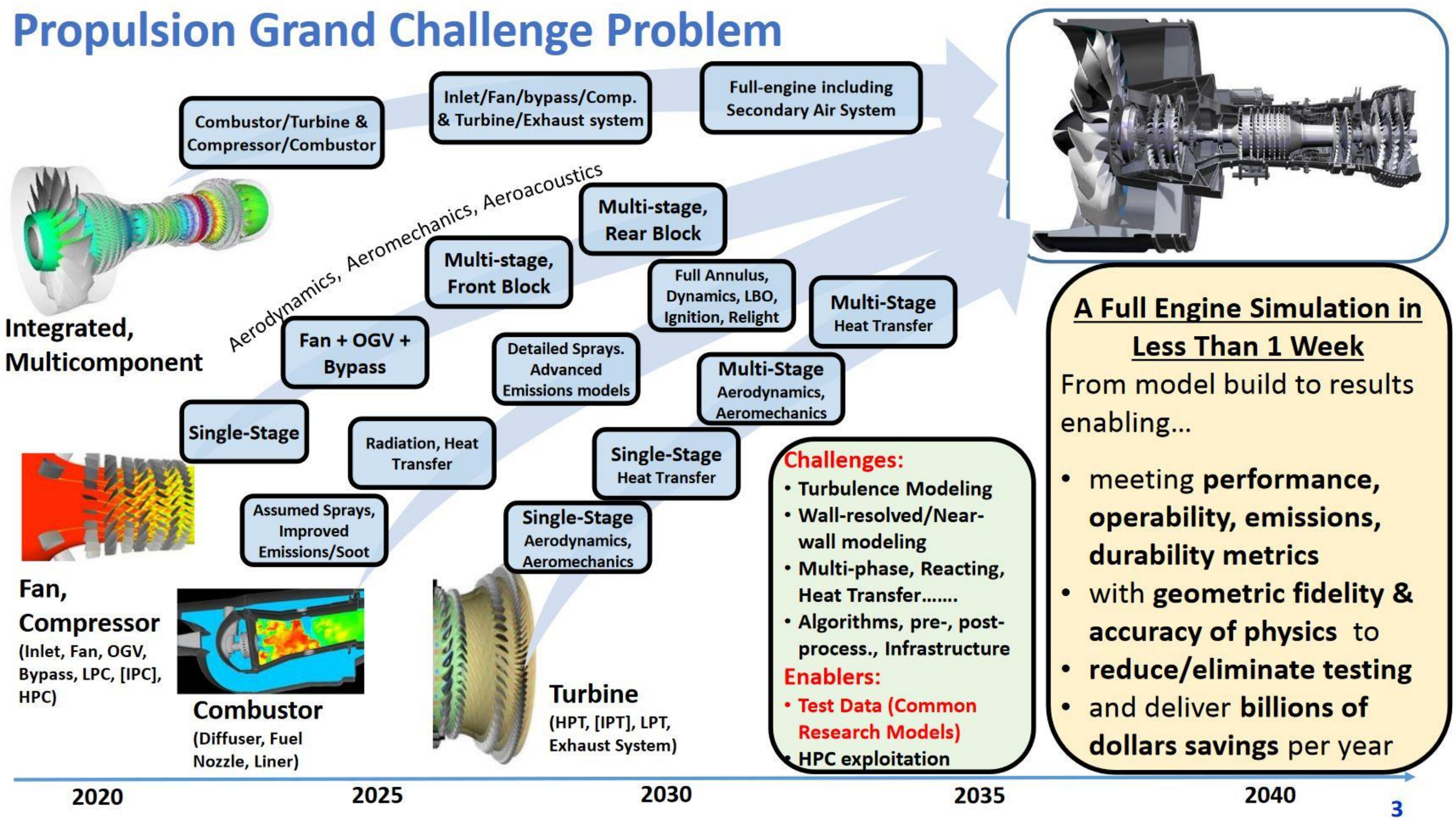
Jeffrey Slotnick (Boeing)
David Schuster (NASA-LaRC)
M. S. Anand (Rolls Royce)
Michelle Munk (NASA-LaRC)
Robert Meakin (CREATE-AV Program)
Doug Kothe (DoE-ECP Program)

Discussion Topics

- Described details of 3 GCs: high-lift, full engine simulation, and space access
- Highlighted key technical obstacles, and the quantified benefit to industrial product development in overcoming those obstacles.
- Experience with GCs within research and government labs

→

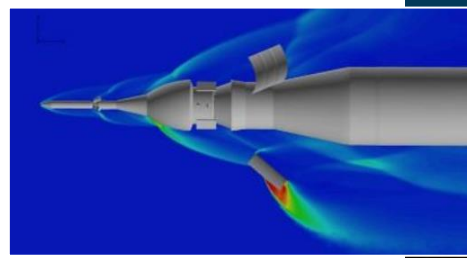
Working Groups
Grand Challenges

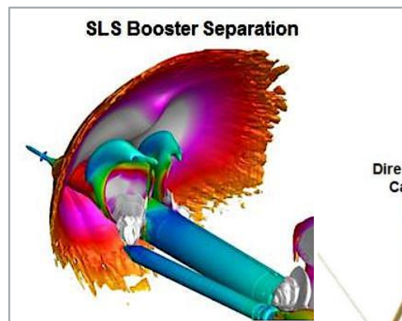


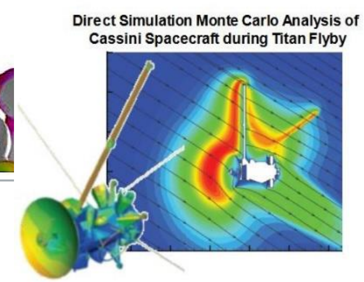
Anand, M. S., et al.,. “Vision 2030 Aircraft Propulsion Grand Challenge Problem: Full-engine CFD Simulations with High Geometric Fidelity and Physics Accuracy”, AIAA 2021-0956, https://doi.org/10.2514/6.2021-0956

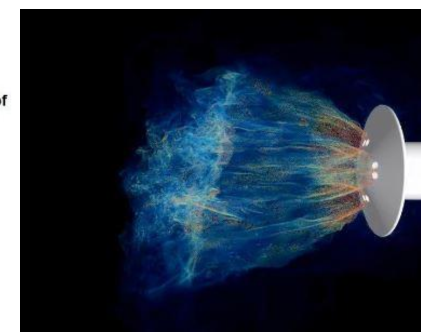
CFD-in-the-Loop Monte Carlo Flight Simulation for Space Vehicle Design

- Detailed analysis is required in two primary flight phases for space vehicles: **Ascent/Abort** and **Entry Descent and Landing (EDL)**.
  - Vehicles not optimized for aerodynamics.
  - Prediction of unsteady flows, plume/surface/aerodynamic interaction, shock effects, heating, and vehicle flight stability are prime requirements.
- Designers regularly deal with unsteady flow –
  - Steady CFD is prone to large variations.
  - Community increasingly turning to DES and LES-based methods for select cases.
- **CFD-in-the-loop MC simulation** has potential to significantly reduce design development time and lessen the cost and schedule impact of vehicle design changes and/or block upgrades
- Challenges to realizing this capability are significant and well-aligned with the goals proposed in the CFD Vision 2030 Study.
- The grand challenge is partially scalable and could be initially **demonstrated on only a segment of a flight simulation**.
  - EDL may be a good choice for demonstrating capability; several initial efforts in free-flight CFD EDL analysis are underway.
- **ROM** and **Machine Learning** techniques may be required for near-term implementation of CFD tools capable of simulating space vehicle flows of interest.









Schuster, D. "CFD 2030 Grand Challenge: CFD-in-the-Loop Monte Carlo Flight Simulation for Space Vehicle Design", AIAA 2021-0957, https://doi.org/10.2514/6.2021-0957

High Lift Grand Challenge

Low-Speed Wind-Up Turn (WUT)

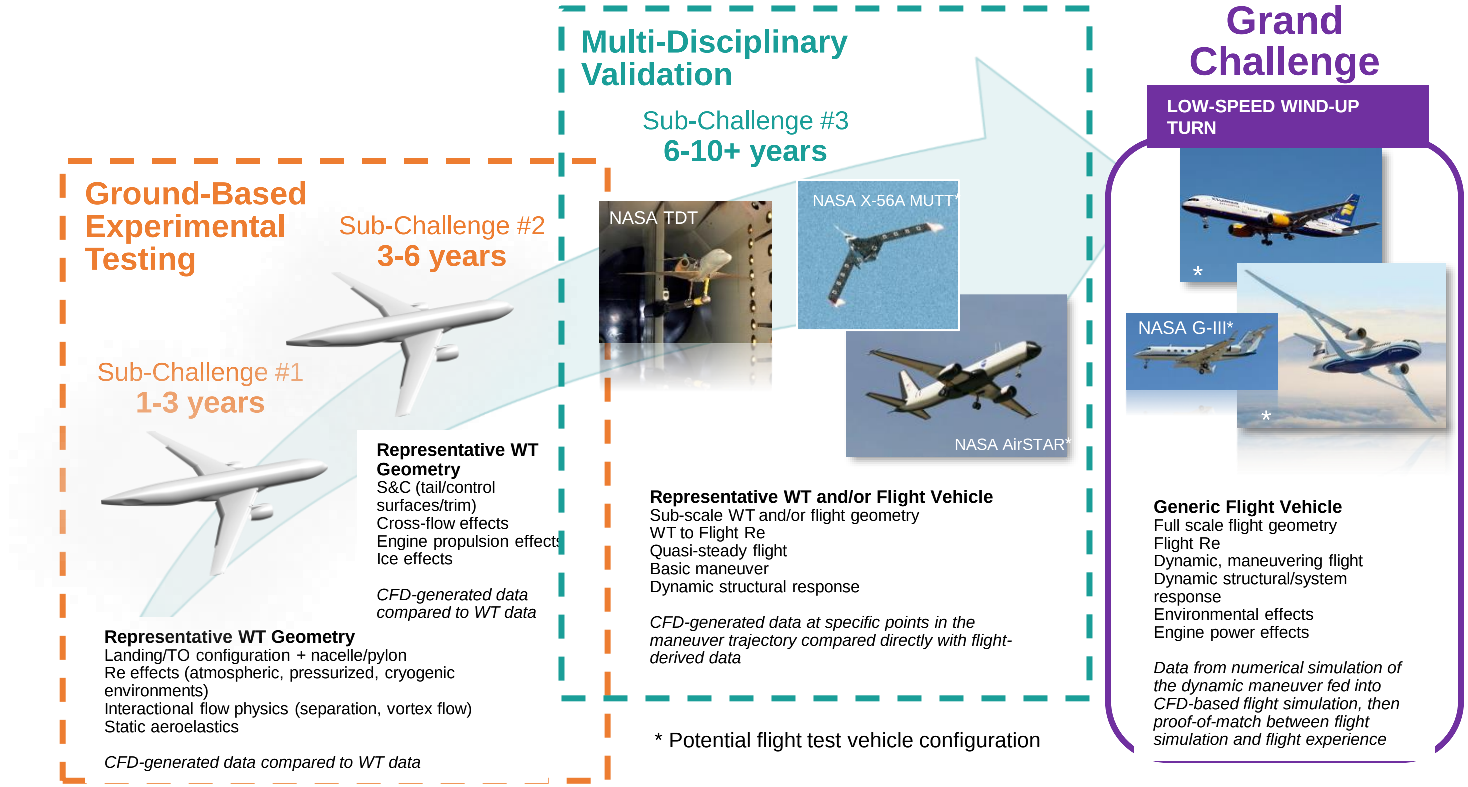
- **Satisfies 14 CFR 25.143***
  - ➢ Airplane must be controllable with increasing load factor at constant speed
  - ➢ Metric: Gradient in "stick force" and/or "stick force/g" must be smooth
- **Maneuver:**
  - ➢ Low-speed (high-lift) configuration
  - ➢ Initiate banked turn at moderate altitude (up to 20K feet AGL) and Mach (~0.35-0.4)
  - ➢ Pull back on stick to increase angle-of-attack (and load factor). Maintain altitude to +/- 500 feet
  - ➢ Increase thrust to maintain speed (to within +/- 5 knots)
  - ➢ Longitudinal stick controls elevator (pitch), lateral stick controls aileron (roll). Rudder pedal not typically used.

Representative turn maneuver

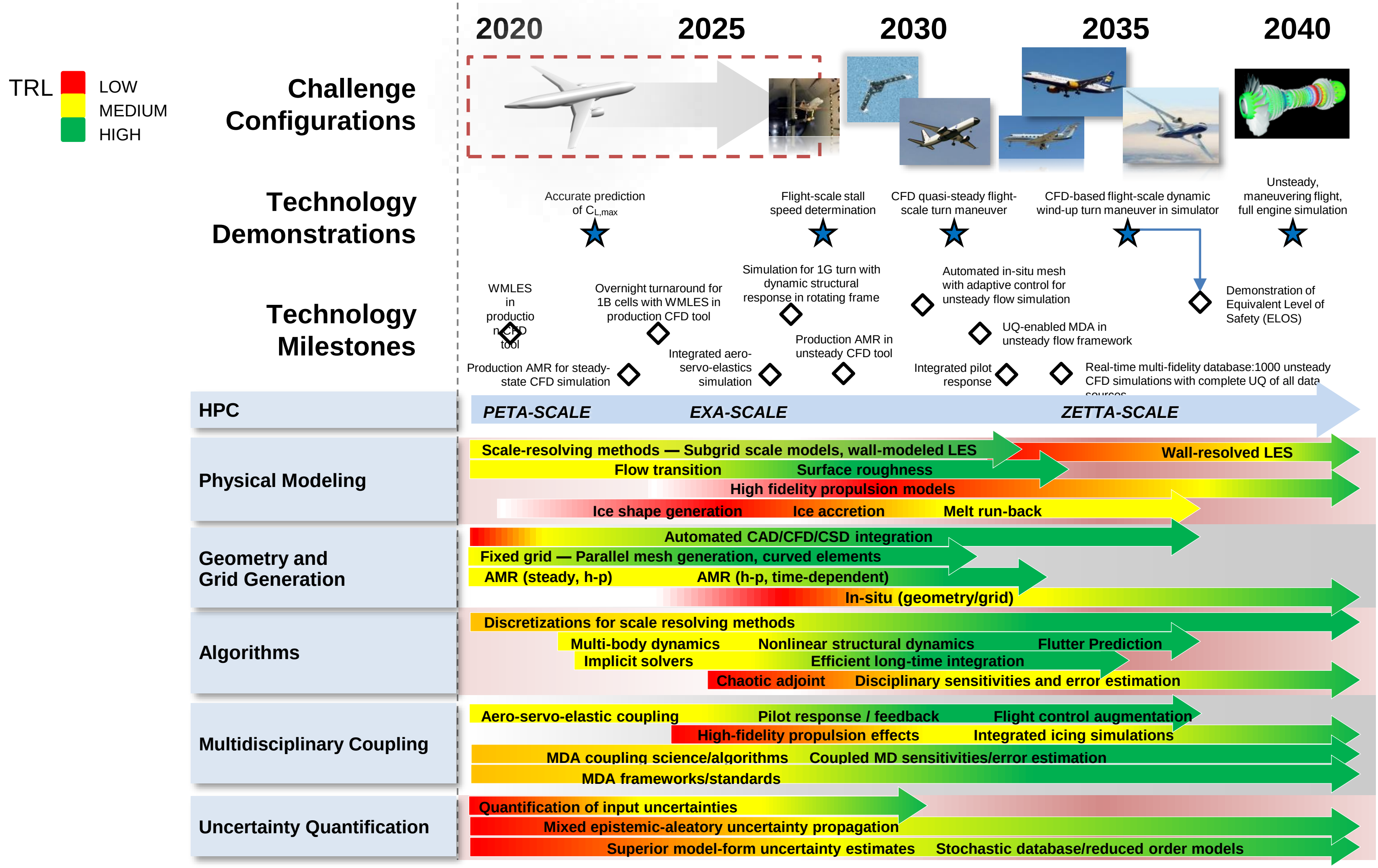
https://www.businessinsider.com/watch-a-dreamliner-maneuver-like-a-fighter-jet-2014-7 (youtube/boeing)

***14 CFR 25.143(g).** When maneuvering at a constant airspeed or Mach number (up to VFC/MFC), the stick forces and the gradient of the stick force versus maneuvering load factor must lie within satisfactory limits. The stick forces must not be so great as to make excessive demands on the pilot's strength when maneuvering the airplane, and must not be so low that the airplane can easily be overstressed inadvertently. Changes of gradient that occur with changes of load factor must not cause undue difficulty in maintaining control of the airplane, and local gradients must not be so low as to result in a danger of over-controlling.

Advancing High Lift Aerodynamic Prediction
Series of Technical Challenges



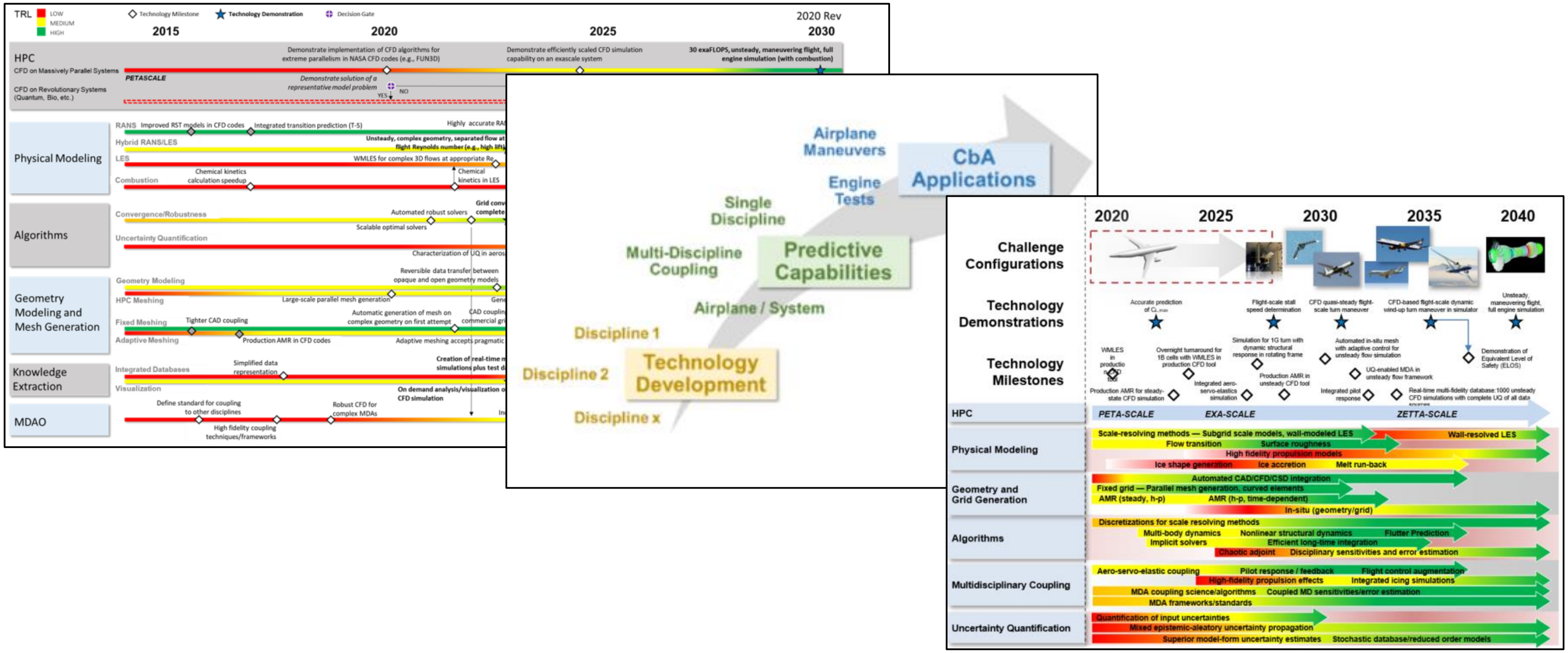
Slotnick, J., and Mavriplis, D. “A Grand Challenge for the Advancement of Numerical Prediction of High Lift Aerodynamics”, AIAA 2021-0955, https://doi.org/10.2514/6.2021-0955


2020
2025
2030
2035
2040
TRL
LOW
MEDIUM
HIGH
Challenge Configurations
Technology Demonstrations
Accurate prediction of $C_{L,max}$
Flight-scale stall speed determination
CFD quasi-steady flight-scale turn maneuver
CFD-based flight-scale dynamic wind-up turn maneuver in simulator
Unsteady, maneuvering flight, full engine simulation
Technology Milestones
WMLES in productio n CFD tool
Overnight turnaround for 1B cells with WMLES in production CFD tool
Simulation for 1G turn with dynamic structural response in rotating frame
Automated in-situ mesh with adaptive control for unsteady flow simulation
Demonstration of Equivalent Level of Safety (ELOS)
UQ-enabled MDA in unsteady flow framework
Production AMR in unsteady CFD tool
Integrated aero-servo-elastics simulation
Production AMR for steady-state CFD simulation
Integrated pilot response
Real-time multi-fidelity database:1000 unsteady CFD simulations with complete UQ of all data sources
HPC
PETA-SCALE
EXA-SCALE
ZETTA-SCALE
Physical Modeling
Scale-resolving methods — Subgrid scale models, wall-modeled LES
Wall-resolved LES
Flow transition
Surface roughness
High fidelity propulsion models
Ice shape generation
Ice accretion
Melt run-back
Geometry and Grid Generation
Automated CAD/CFD/CSD integration
Fixed grid — Parallel mesh generation, curved elements
AMR (steady, h-p)
AMR (h-p, time-dependent)
In-situ (geometry/grid)
Algorithms
Discretizations for scale resolving methods
Multi-body dynamics
Nonlinear structural dynamics
Flutter Prediction
Implicit solvers
Efficient long-time integration
Chaotic adjoint
Disciplinary sensitivities and error estimation
Multidisciplinary Coupling
Aero-servo-elastic coupling
Pilot response / feedback
Flight control augmentation
High-fidelity propulsion effects
Integrated icing simulations
MDA coupling science/algorithms
Coupled MD sensitivities/error estimation
MDA frameworks/standards
Uncertainty Quantification
Quantification of input uncertainties
Mixed epistemic-aleatory uncertainty propagation
Superior model-form uncertainty estimates
Stochastic database/reduced order models

Technology Focus Areas

Physical Modeling	Geometry Grid Generation	Algorithms	Multidisciplinary Coupling	Uncertainty Quantification
➢ Separated flows (smooth body, corner, etc.) ➢ Flow transition (surface roughness) ➢ High fidelity propulsion modeling (engine-out, wind-milling) ➢ Icing physics and accretion, icing effects	▪ Accurate and automatic discretizations for CFD and CSD on flight geometry ▪ Traceable (Digital Thread) ▪ Large grid models and/or HO meshes ▪ Adaptive grid refinement (steady and unsteady flow)	▪ Efficient methods for scale-resolving simulations ▪ Nonlinear structural modeling ▪ Multi-body dynamics (moving control surfaces) ▪ Long time-integration schemes ▪ Sensitivity/error analysis for time-dependent, chaotic systems	▪ Accurate/Efficient/ Stable MD coupling algorithms ▪ Aero-servo-elastic coupling with quantified error estimates ▪ Integration of high-fidelity, time-dependent propulsion capabilities ▪ Icing effects ▪ MDA framework for tight coupling at high-fidelity, data standards ▪ System/pilot response	▪ Identify sources of uncertainty within each discipline ▪ Characterization ▪ UQ frameworks for MDA (uncertainty propagation and aggregation) ▪ Data fusion for flight simulation database with uncertainty

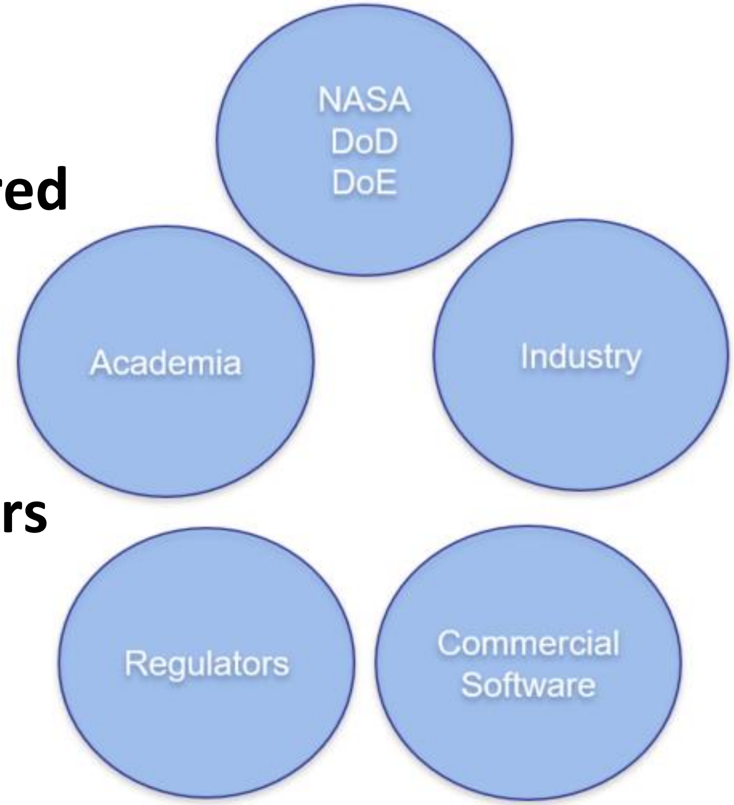
Complementary Roadmaps



- **Overlapping but complementary roadmaps**
  - CFD2030 roadmap originally for NASA program planning
  - CbA roadmap focused on industry end problem: Certification
  - Grand Challenge roadmap specific to GC problem

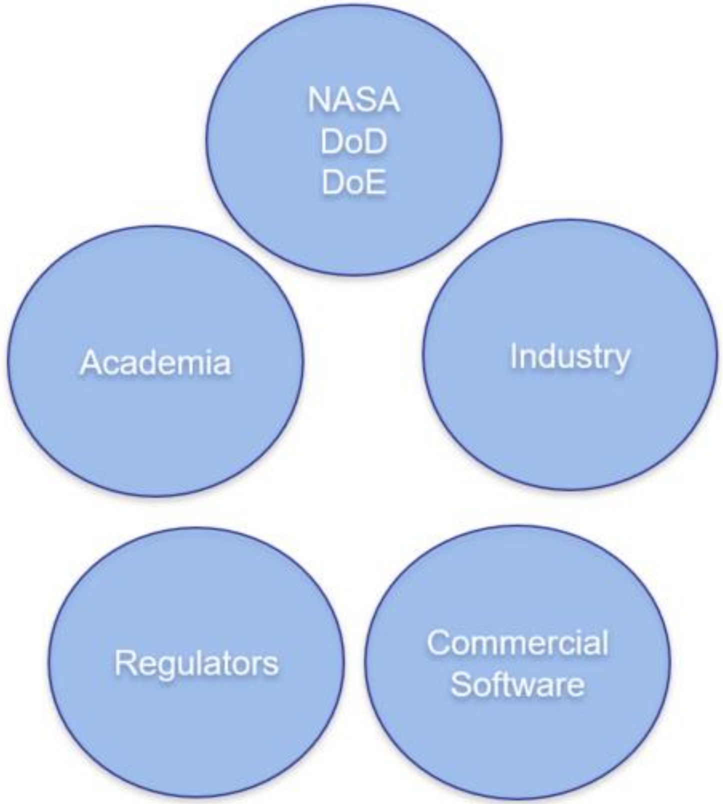
Additional Challenge Areas

- **Roadmaps mainly address technical challenges**
- **Additional challenges must be considered**
  - Logistical challenges
  - Organizational challenges
- **Addressing all areas requires coordination/input from all stakeholders**
  - Government
  - Academia
  - OEM Industry
  - Commercial Software
  - Regulators (for CbA)



Additional Challenge Areas

- **CFD2030 IC seeks to address challenges i all areas:**
  - Technical, Logistical, Organizational
- **CFD2030 IC represents all stakeholders**
  - Participation in IC and on Steering Committee
  - Studies: NASA commissioned, Industry led, Academic participation
- **Objectives include:**
  - Promote understanding between stakeholders
  - Facilitate collaboration between stakeholders
  - Enable consensus
  - Build advocacy backed by community consensus



Community Collaboration Opportunities

Success requires coordinated collaboration within engineering and simulation communities

Courtesy NASA

Courtesy DLR

CFD Validation Partnerships

- Encourages pooling of critical resources (people, time, $) to develop appropriate configurations and/or platforms (e.g. CRM-HL)
- Drives community consensus on data requirements (type, location, etc.)
- Enables joint sharing of data and lessons learned
- Establishes steering of future CFD validation activities

CFD Prediction Workshops

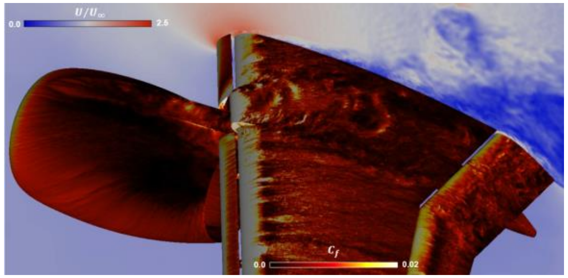
- Growing number within aerospace community – several (e.g. HLPW) directly address issues associated with Grand Challenges (e.g. high lift GC)
- Focuses attention on specific problems of interest
- Encourages newcomers to get involved
- Increasingly tied to the development and testing of common research models (e.g. CRM-HL)

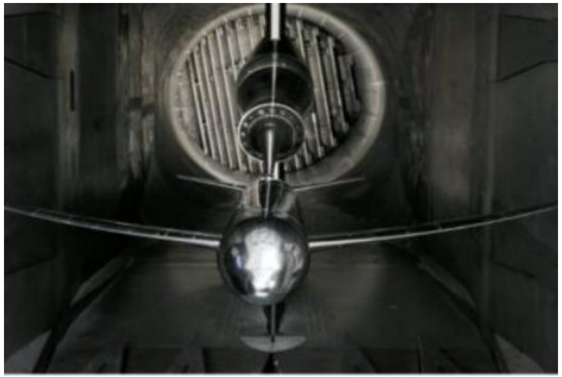
Future Activities

- Increasing emphasis on engine/propulsion simulation technologies → CRMs, workshops
- Integration of simulation and test data to enhance/accelerate product development
- "Digital Flight" workshops focusing on multi-disciplinary coupling strategies using building block approaches
- Formation of Grand Challenge Working Groups

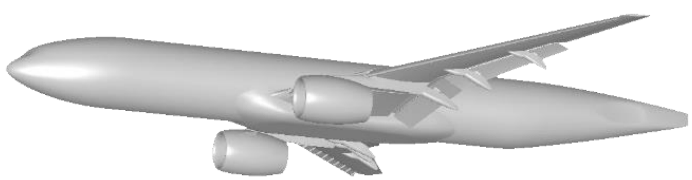
GC: Template for Community Collaboration

- **Industry defines requirements**
- **Industry/Gov/Academia focus on technical requirements/funding advocacy**
- **Academia funded by government focuses on fundamental technologies**
- **Government provides**
  - ➢ Further technical dev. and demonstration
  - ➢ Validation through unique facilities
- **Industry feedback**/adoption
- Regulator approval



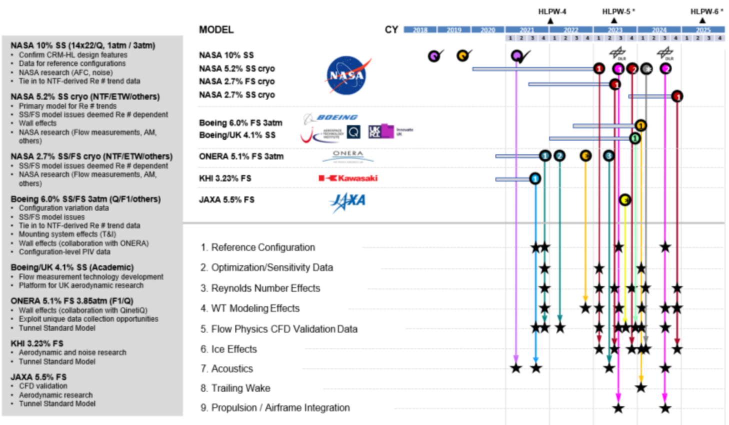


Starting Point: Current High Lift Common Research Model Ecosystem



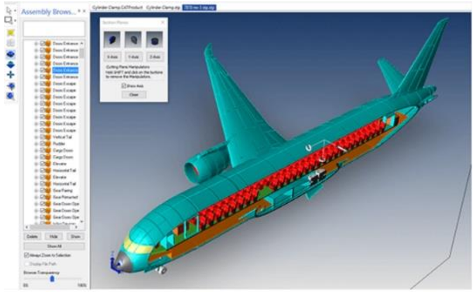
- Provides **industry-relevant** configuration(s) and consistent models.
- Enables **direct assessment and comparison** between CFD flow solvers and modelling approaches.
- Provides a **common standard** to assess the predictive capabilities of emerging computational tools.
- With proper controls, enables the design and fabrication of nearly **identical models in multiple facilities** (for data repeatability).
- Provides a challenging open-source configuration(s) to demonstrate **advanced measurement and sensing techniques**
- Provides a **freely-sharable geometry**, which enables new, and strengthens existing, partnerships to accelerate technology development.
- Provides a geometrically-relevant testing platform to jointly develop, assess, and share **pre-competitive aerodynamic technology** (e.g. Active Flow Control, noise, etc.) with partners
- Drives development of enabling technologies which provide indirect benefits, like improved **test facility capability/utilization** and **workforce development** (e.g. industry/university collaboration).

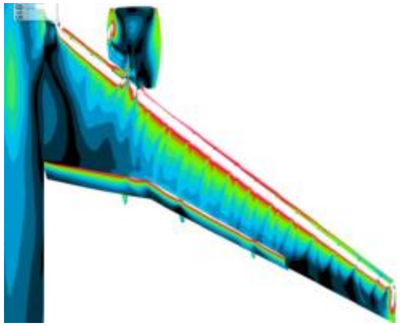
High Lift Common Research Model Ecosystem – Test Plan



Role of Commercial Software

- **Well suited for developing and curating complex software projects**
- **Market driven multidisciplinary efforts underway**
- **Digital thread/Product life cycle software trends**
  - Traceability for CbA
- **Mix of commercial and specialized CFD (HPC) software likely to remain**
  - Will require better integration/cooperation between industry/software stakeholders





Summary

- **CFD2030 Vision Study originally commissioned to help NASA planning activities**
- **CFD2030 Vision Study has strongly influenced NASA and community at large in setting future CFD capability goals**
- **Certification by Analysis study followed similar approach to focus on industry driven application: Certification**
- **CFD2030 Integration Committee within AIAA focuses on sustaining and extending the Vision**
  - Promote understanding and collaboration between stakeholders
  - Provide advocacy backed by community consensus
  - GC problems provide actionable targets and measurable progress

- The CFD2030 IC steering committee **strongly encourages international participation** to help shape and drive efforts to advance CFD simulation technology
  - Desire to leverage **specialized expertise and knowledge**
  - Desire to promote **cross-fertilization of ideas**
  - Desire to assist with **internal national activities**