A Methodology for Integrated Conceptual Design of Aircraft Configuration and Operation to Reduce Environmental Impact

ATIO/ANERS
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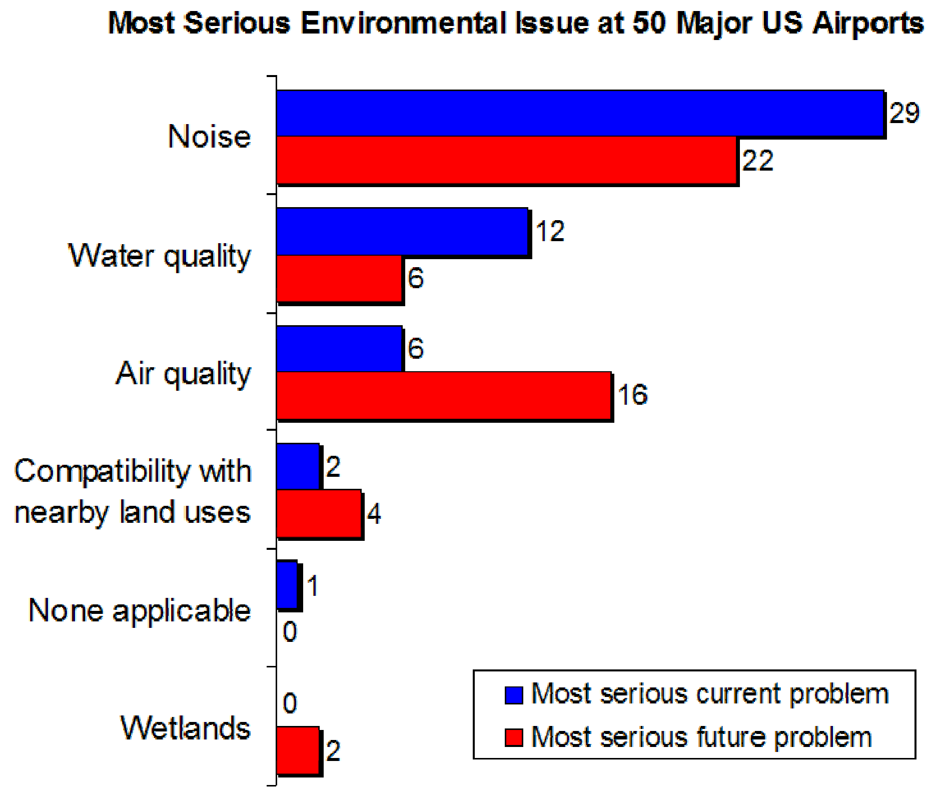
Motivation

- Over the last 35 years
  - Six-fold growth in air-travel capacity
  - Reduction in people impacted by aviation noise
  - 60% improvement in aircraft fuel efficiency
  - Reductions due to improved technology
- Pace has slowed
  - Often trading impacts
  - Need new ways to reduce environmental impacts
- Study interaction of aircraft and operation



Source: GAO's survey of the nation's 50 busiest commercial service airports.

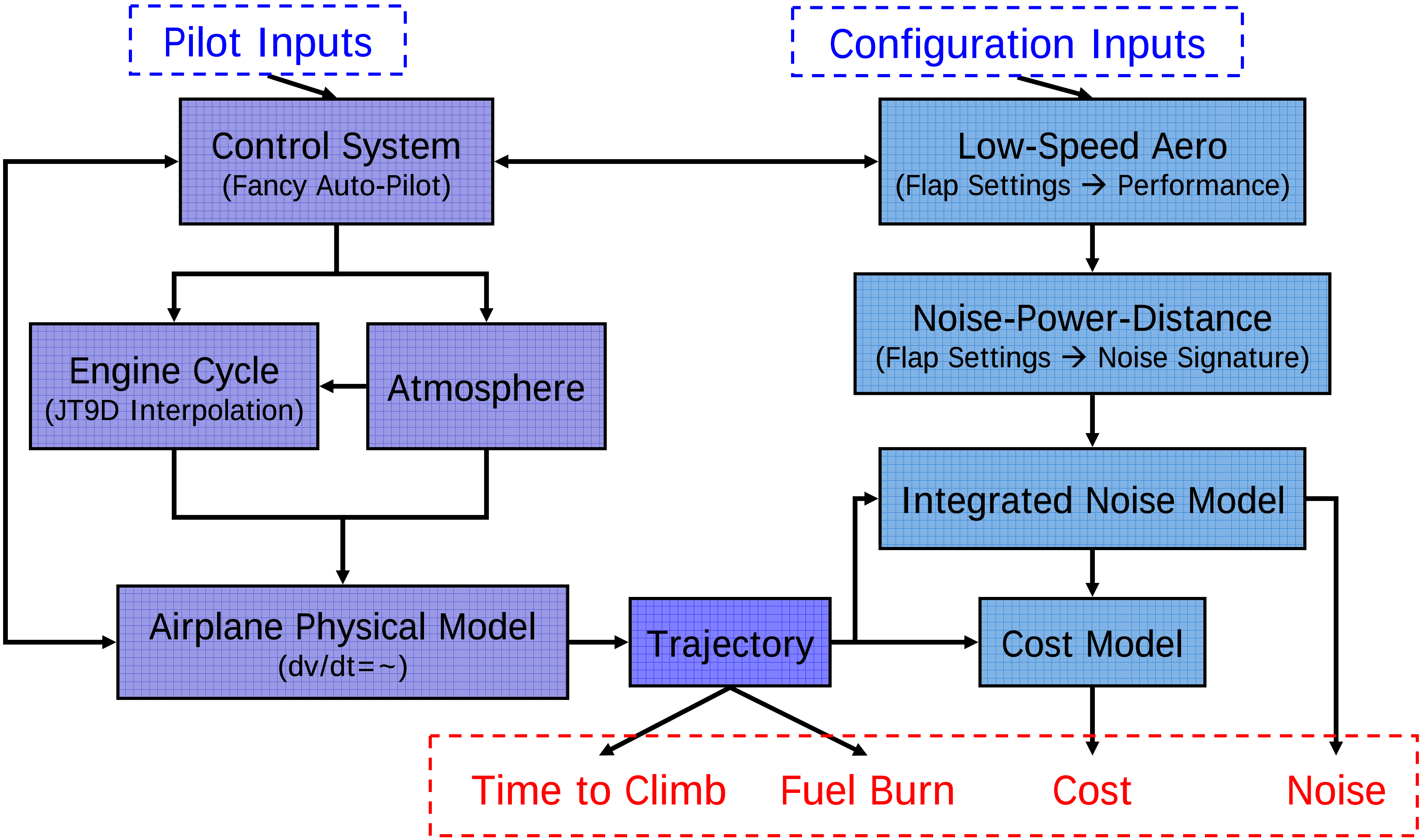
Challenges

- Need to include aircraft operations into early stages of design.
  - Best aircraft will integrate benefits from both configuration and operation.
- Developing configurations and operations simultaneously yields a large design space.
- Require appropriate fidelity such that design space exploration is tractable and meaningful.
  - Generally (not always) a trade between result quality and run-time.

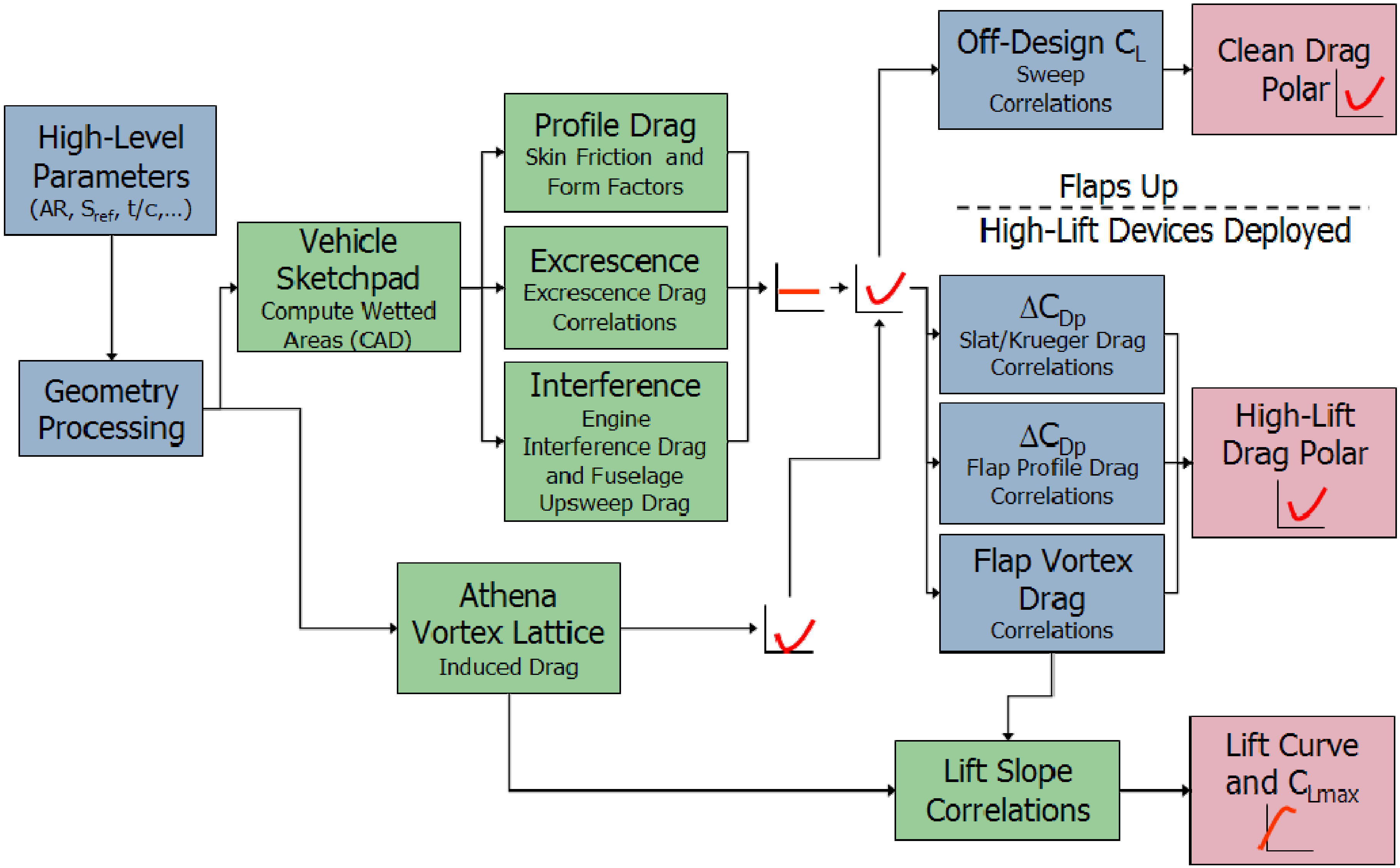
Achievements

- Developed a low-speed aerodynamic tool suitable for integrated design of operating procedure and aircraft configuration.
  - Accuracy similar to industry conceptual design tools
  - Tractable computational complexity and parameter space
- Integrated aircraft performance tools to evaluate operational procedures.
- Used optimization to explore a design space of current aircraft fleet operations.
- Performed a sensitivity study to demonstrate that both configuration and operational procedures can be studied simultaneously.

Configuration and Operation Integration

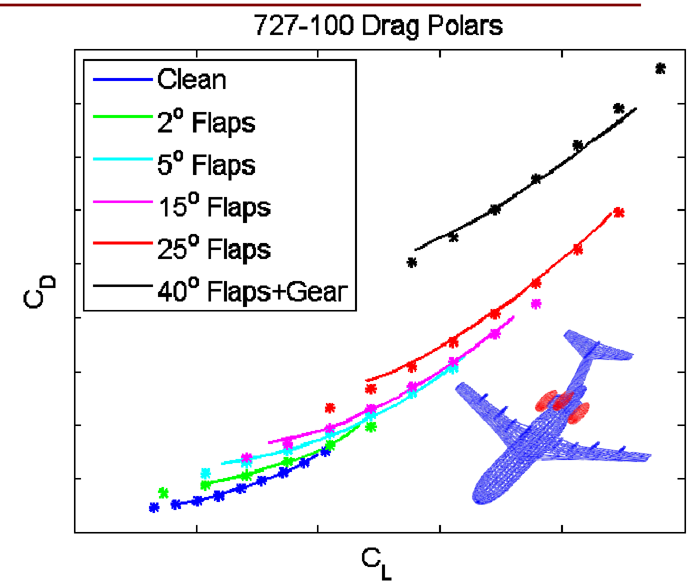


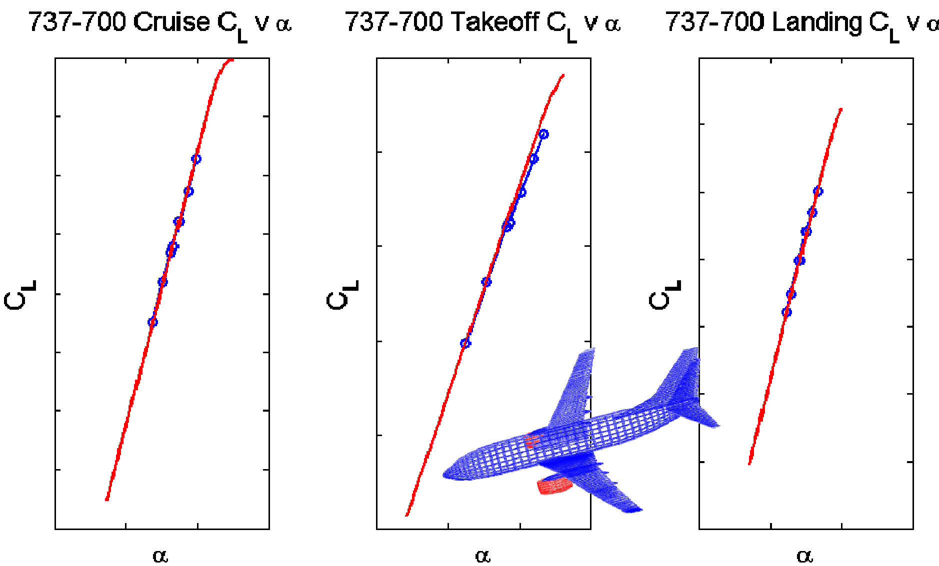
Low-Speed Aerodynamic Model



Aerodynamic Model Fidelity

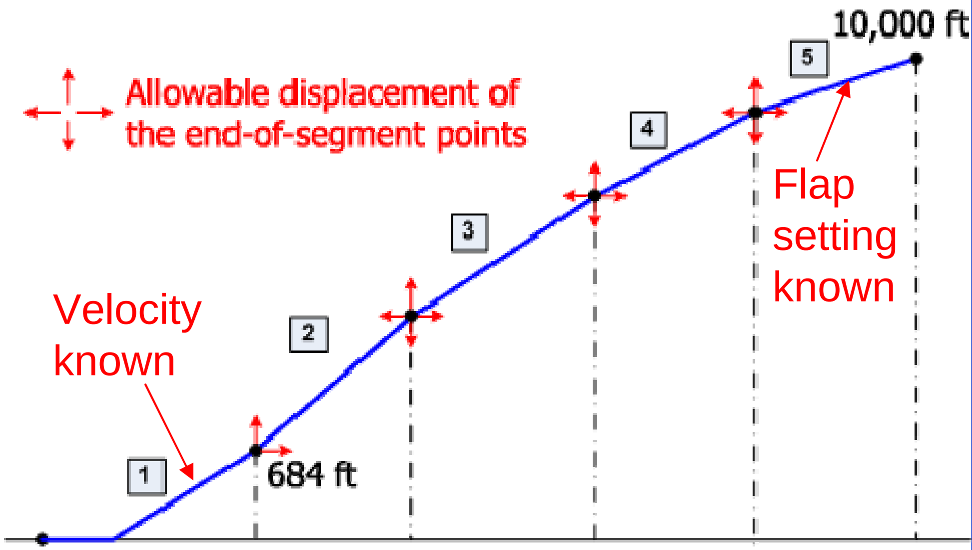
- Estimates drag polars for clean configurations to within ~1%
- High-lift drag polars to within ~10%
- Maximum lift coefficient and lift curve to within ~10%
- Calibration:
  - Boeing flight & wind tunnel tests
  - NASA wind tunnel tests
  - Empirical Lockheed method

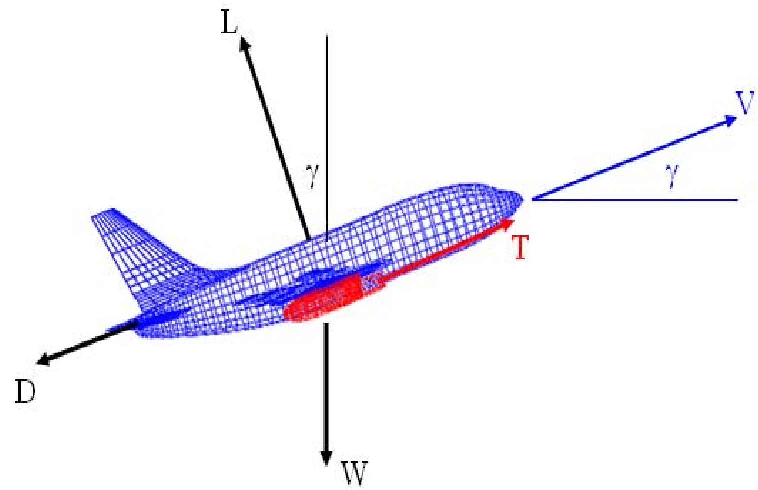




Operational Design Space

- Objectives
  - Time to Climb, Fuel Burn, Noise, Operating Cost
- Parameters
  - Flap setting
  - Throttle setting
  - Velocity
  - Transition Altitude
  - Climb gradient*
  - **18 Total**
- Constraints:
  - Regulations
    - No pilot input below 684 ft
    - Initial climb at V_2+15kts
  - Flap settings
  - Velocity
    - Min: stall
    - Max: max q
  - Throttle
    - Min: engine idle or positive rate of climb
    - Max: full power



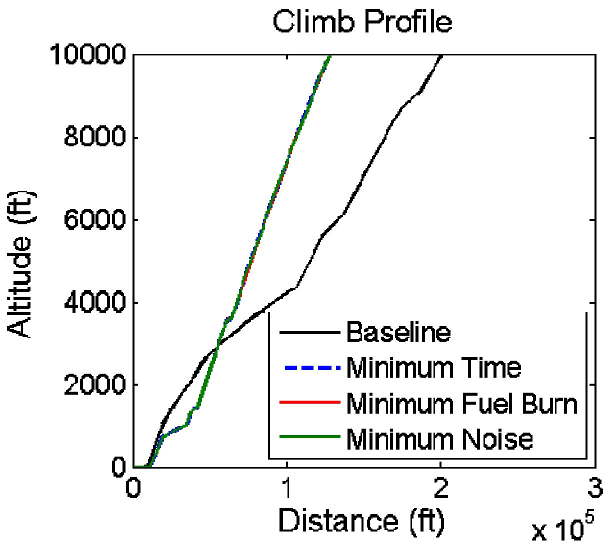


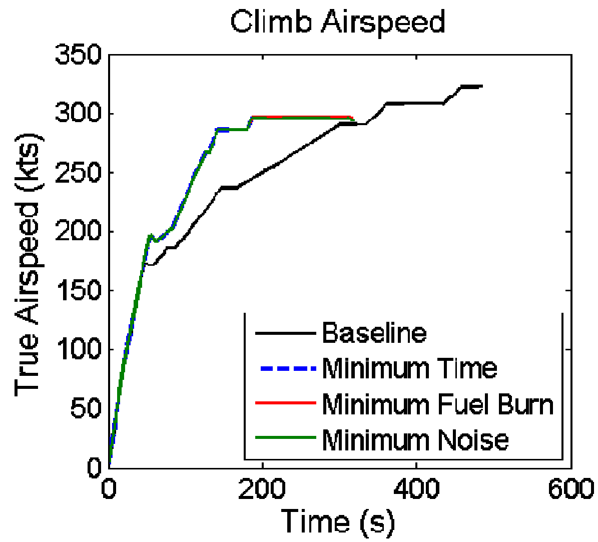
Design Space Exploration Methods

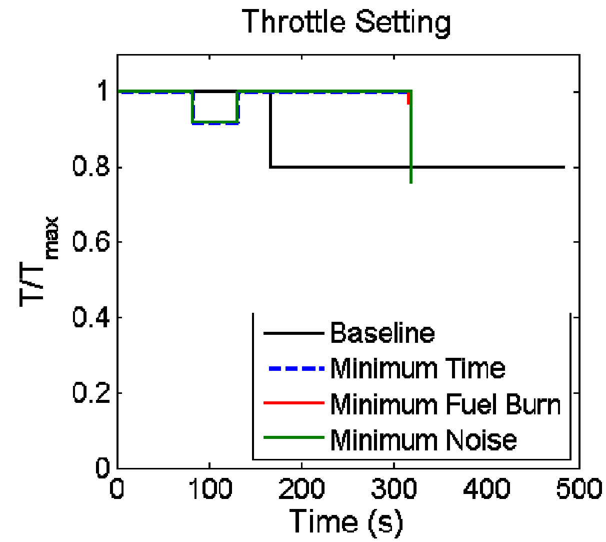
- Exploration Challenges
  - Islands of feasibility
  - Many local minima
  - Mixed discrete/continuous variables
  - Many design variable scales ($10^{-1} \rightarrow 10^{4}$)
  - Long function evaluation time (~2 minutes with noise)

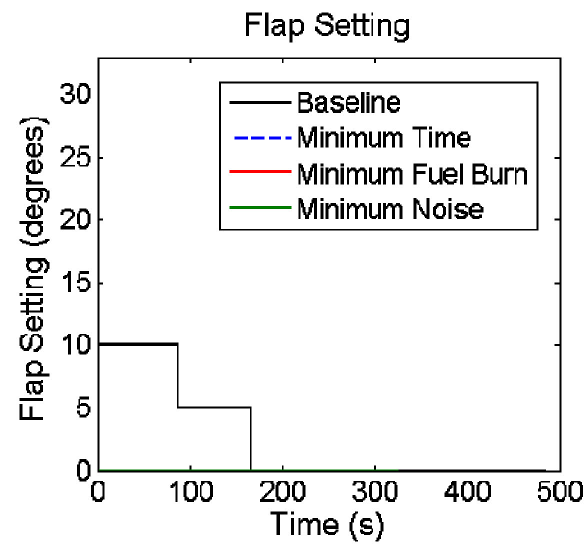
- Sequential Quadratic Programming [Climb time: 312 s]
  - Stuck at local minima
  - Can't handle discrete integers
- Direct Search (Nelder-Mead) [Climb time: 319 s]
  - Similar problems as SQP, but worse results
- Particle Swarming Optimization [Climb time: 319 s]
  - Slow running (8-12 hours), optimum not as good as Genetic Algorithm
- Genetic Algorithm [Climb time: 308 s]
  - No issues with any of the challenges of this problem.
  - No convergence guarantee and SLOW! Run-time ~24 hours.
  - But, best result.

Results (725,000 lbm)







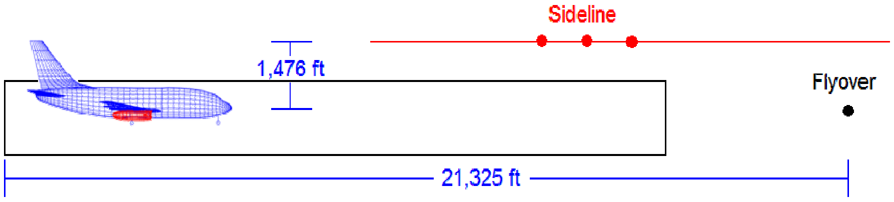


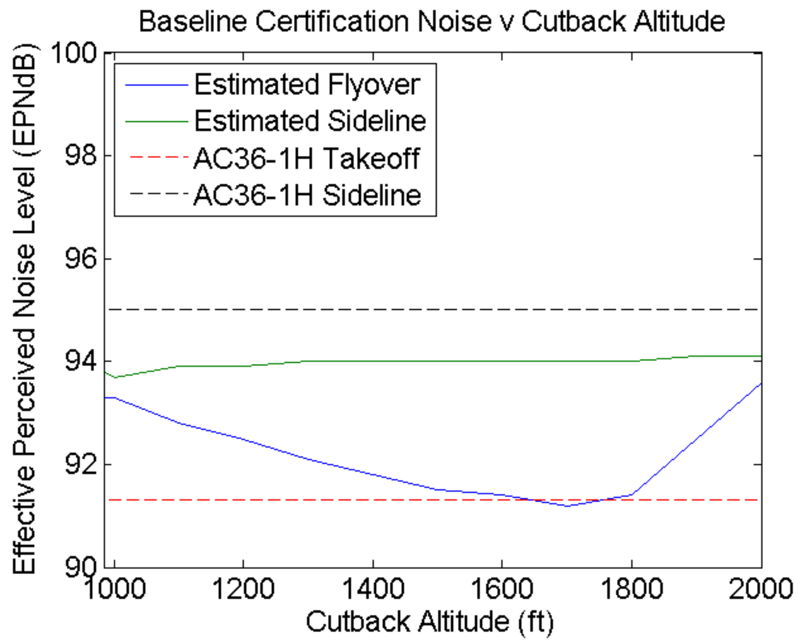
All metrics have improved:

	Time	Fuel Burn	Noise (55 EPNdB)
Baseline	485.5 s	6,817 lbm	477.6 mi^2
Minimum Time to Climb	307.5 s	5,080 lbm	354.2 mi^2
Minimum Fuel Burn	315.6 s	5,125 lbm	357.6 mi^2
Minimum Noise	318.7 s	5,138 lbm	357.4 mi^2

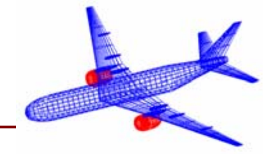
Takeoff Noise Sensitivity Studies

- Ex. Boeing 777-200ER
- Sensitivity study not Optimization
- Takeoff Certification Procedure
  - Full-power until at least 984ft, then cutback
- Simple operational procedure
  - 2 design variables
- Aircraft configuration
  - 60 design variable
  - 16 dominant variables studied
- Sensitivity of noise to each configuration parameter requires an optimization loop for cutback altitude
  - Configuration and operation are coupled

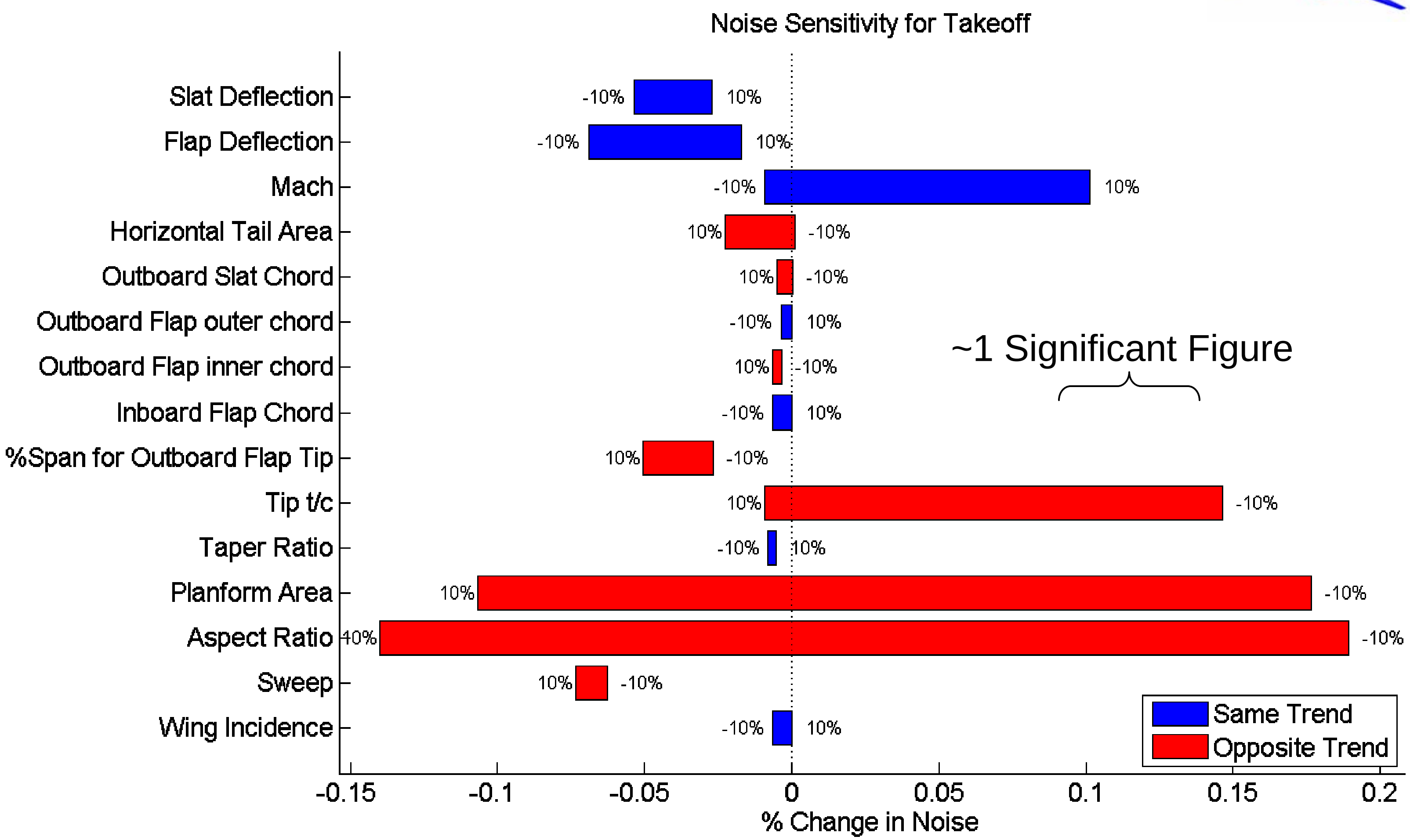




Boeing 777-200ER

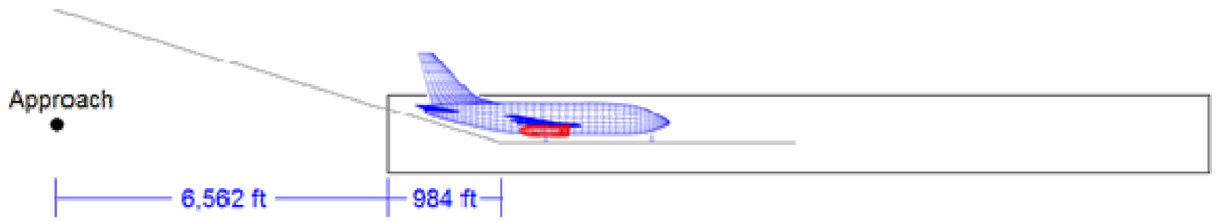


Takeoff Noise Sensitivity



- % change in minimum Sideline+Flyover
- All sensitivities are **small**.

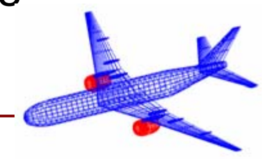
Approach Configuration Analysis

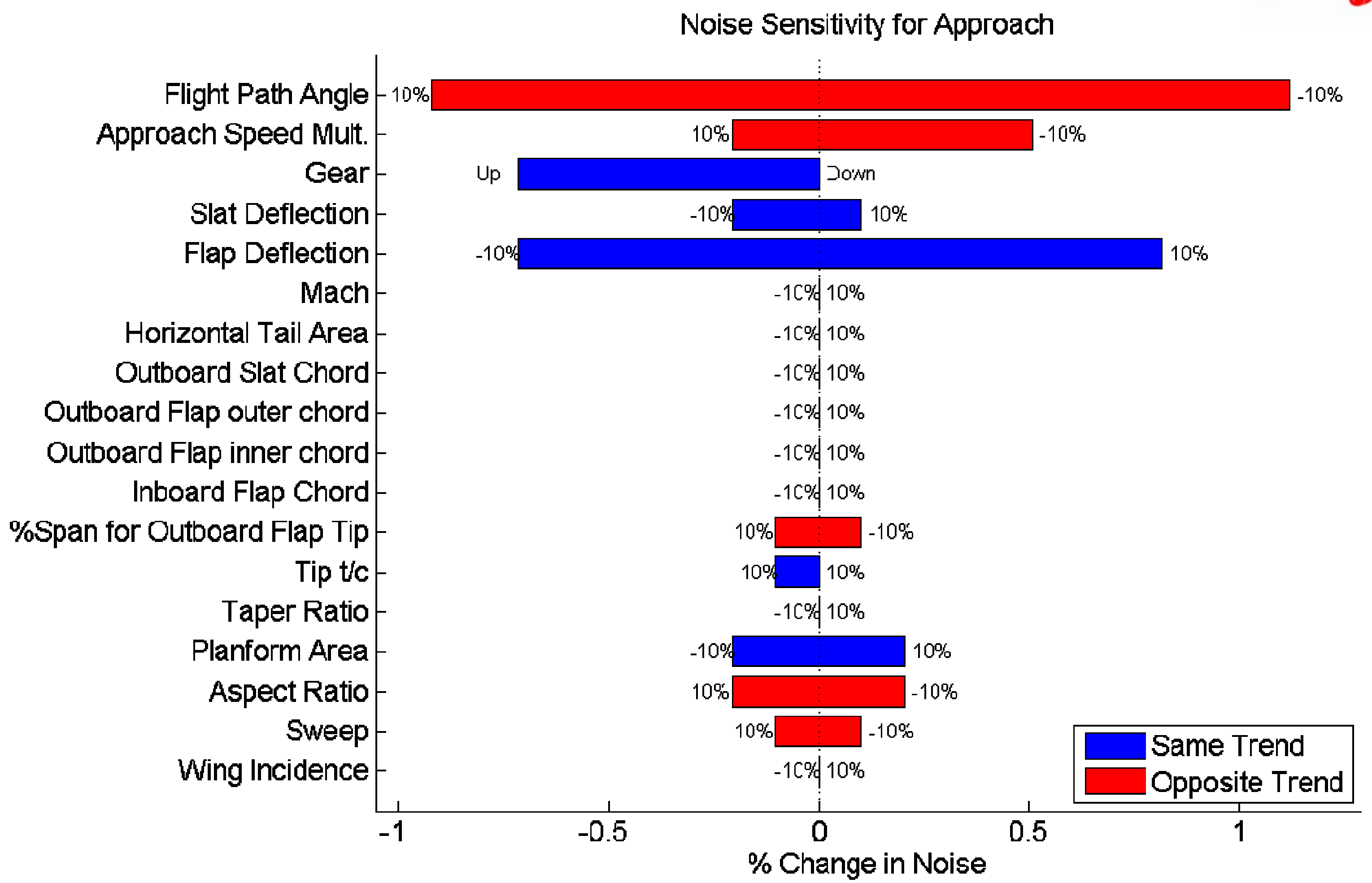


- Ex. Boeing 777-200ER
- Two operational parameters
  - Glide slope
  - Velocity ($k*V_s$)
- 17/60 aircraft configuration parameters studied
- Design Space Exploration:
  - Sensitivity study to determine effect of 10% change in each parameter
    - 19 parameters, 57 runs
  - Full-factorial study of dominant parameters
    - 4 parameters, 81 runs

Approach Noise Sensitivity

Boeing 777-200ER





- Considerably more sensitive than takeoff.
- Best combination: 10% faster and steeper, 1.12%

Conclusion

- An integrated analysis of aircraft configuration and operation shows significant opportunities to reduce environmental impact.
  - Found an optimized departure procedure for the 747-200 that simultaneously reduced:
    - 178 seconds in time to climb. (37%)
    - 1,700 lbm in fuel consumption. (26%)
    - 123 square mile reduction in 55 EPNdB noise exposure area. (26%)
    - $1,800 in operating costs[1] (2.6%)
  - Demonstrated coupling between configuration and operation and that certification noise is sensitive to both.
- This highlights the benefit of multidisciplinary optimization and examining both configuration and operation at the early stages of design.

[1] 2007 dollars

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Questions?