Ensemble Averaging Method for Efficient Transient Simulations of External Automotive Aerodynamics

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ŠKODA

What do we mean by noise?





- The system's response to a negligible perturbation
- There should be no effect at all, yet a significant effect is observed
- This limits precision when comparing small aerodynamic differences
- We observe that any change, however small, causes an error to accumulate over time

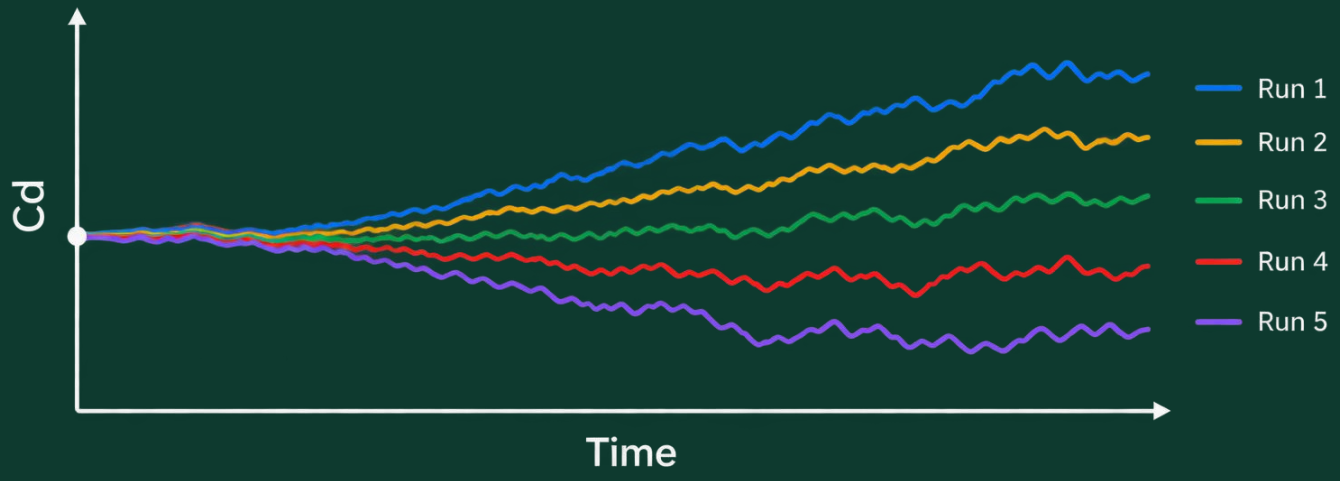


Initially identical → **Diverging** → **Independent**

All runs start from the same point

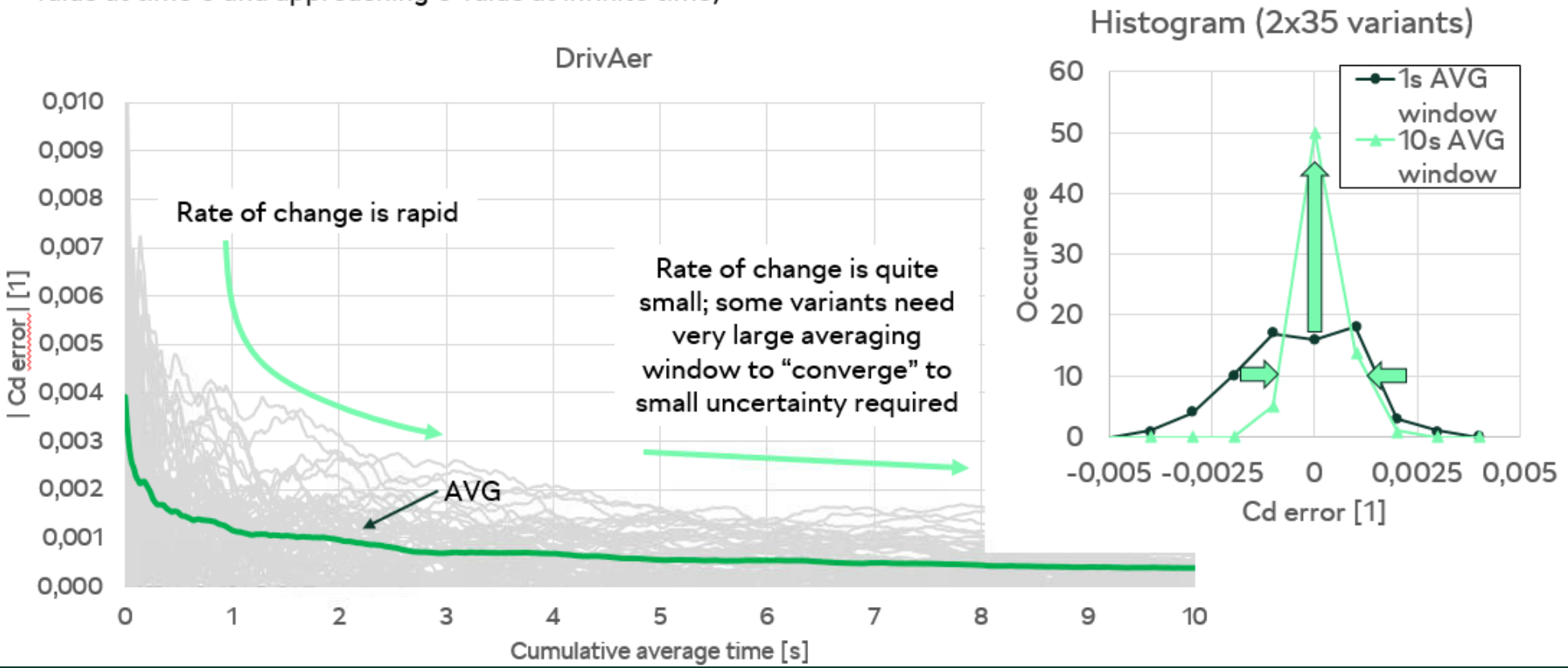
Small perturbations grow over time

Runs are no longer correlated and behave independently

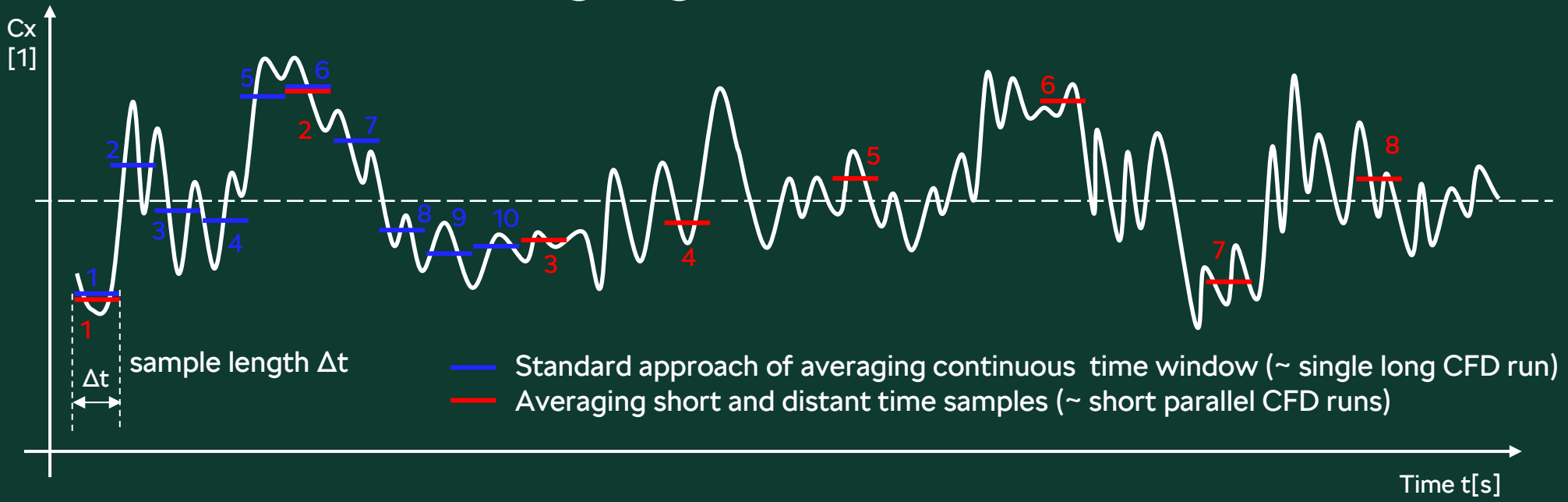


Normal-distribution hypothesis (AutoCFD4)

Hypothesis: The Cd (noise) error is decreasing nonlinearly with increasing length of averaging window (starting at high value at time 0 and approaching 0 value at infinite time)



Ensemble Averaging Method (EAM)



- Multiple short simulations run in parallel, replacing one long simulation
- Each simulation is infinitesimally perturbed so that it evolves independently in time
- The signals become uncorrelated after a period much shorter than the full simulation

INTERNAL

Wind-tunnel data for EAM development 1/2

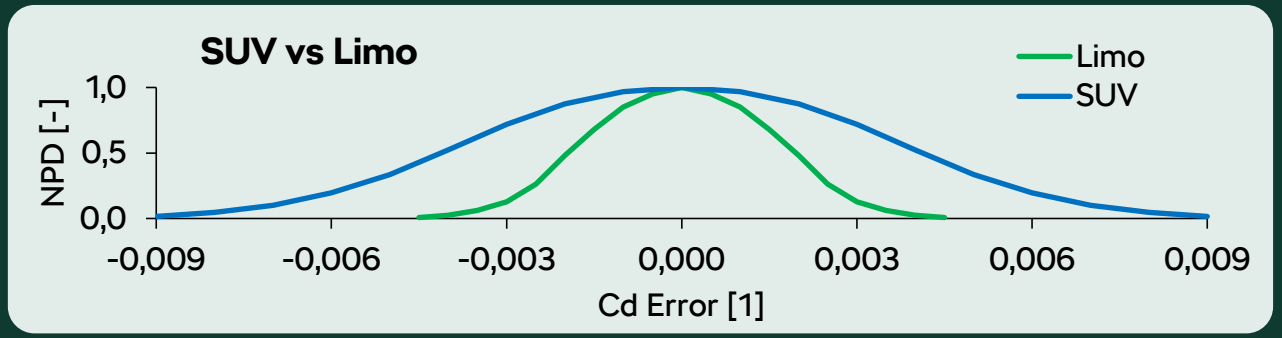
- Due to low-frequency fluctuations, CFD analysis would require a large number of prohibitively long and expensive simulations
  - Approximately 1,000 WT signals were used to to support and substantiate our conclusions before applying it to CFD

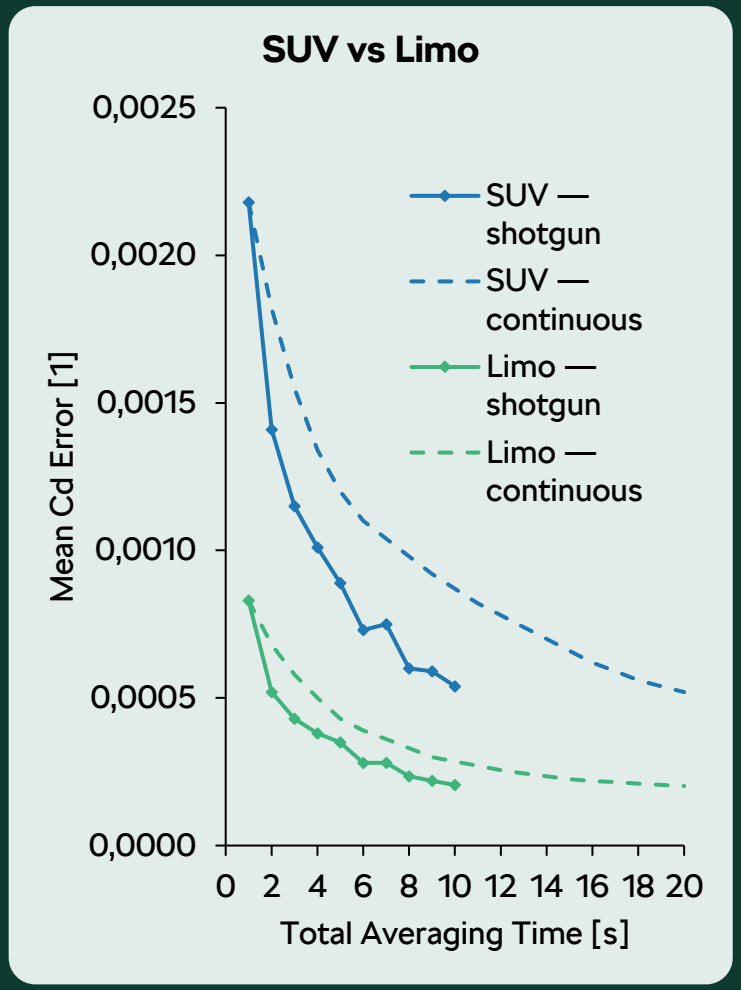
- Measurements and CFD showed consistent behavior
  - A quick Fourier analysis showed sufficient agreement
  - Both methods show similar uncertainty decay and error distributions, including consistent trends across vehicle types



WT data for EAM dev. 2/2

- WT data helped estimate how subvariant duration and decorrelation time affect error
  - Error magnitude and convergence rate depend strongly on the input geometry
  - EAM works for all vehicle types, but it is most effective when the error is larger and decreases more slowly
- After the initial estimate, we also validated EAM using CFD data: five vehicle types, dozens of 10–15 s simulations, and even 60 s long runs





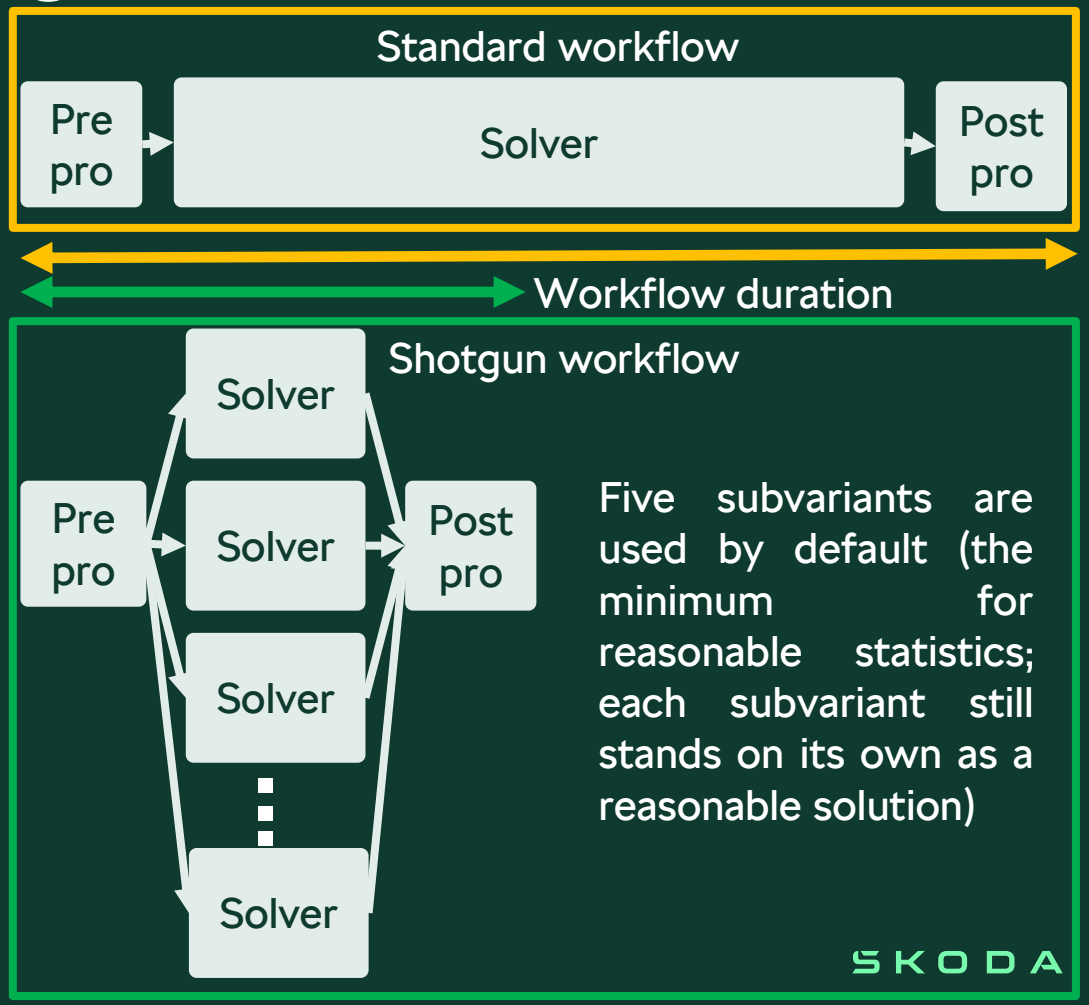
EAM implementation 1/3

- There is no change from the user's perspective
  - One HPC workflow under one ID
  - The workflow shares as many common steps as possible

- Joint preprocessing
- Joint domain flushing
- Joint postprocessing

- The workflow splits at the solver
  - We introduce an infinitesimally small perturbation to the viscosity

- Overnight simulation: 2,100 cores per subvariant (10,500 total)

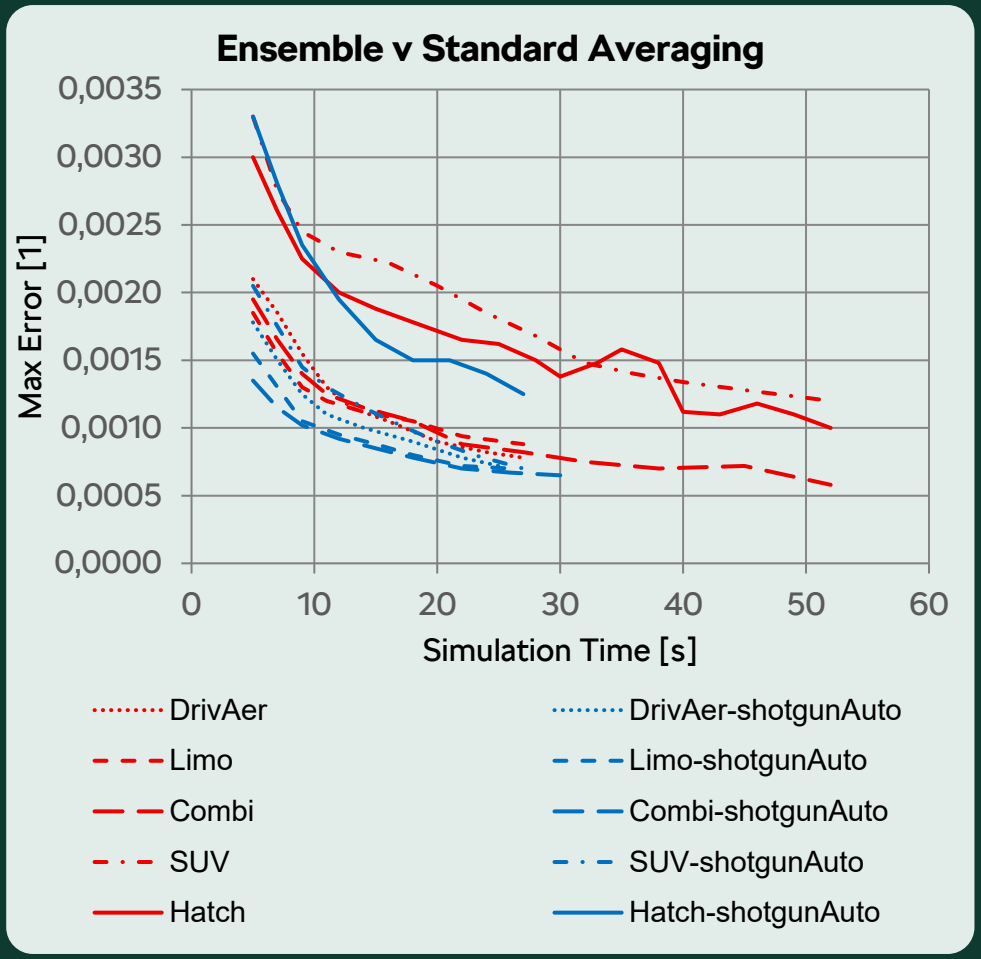


EAM implementation 2/3

- Domain flushing
  - We tested the length of the flushing time against the error-versus-averaging-window curve
  - Total flushing time combines a shared variable-Δt stage with a per-subvariant decorrelation stage

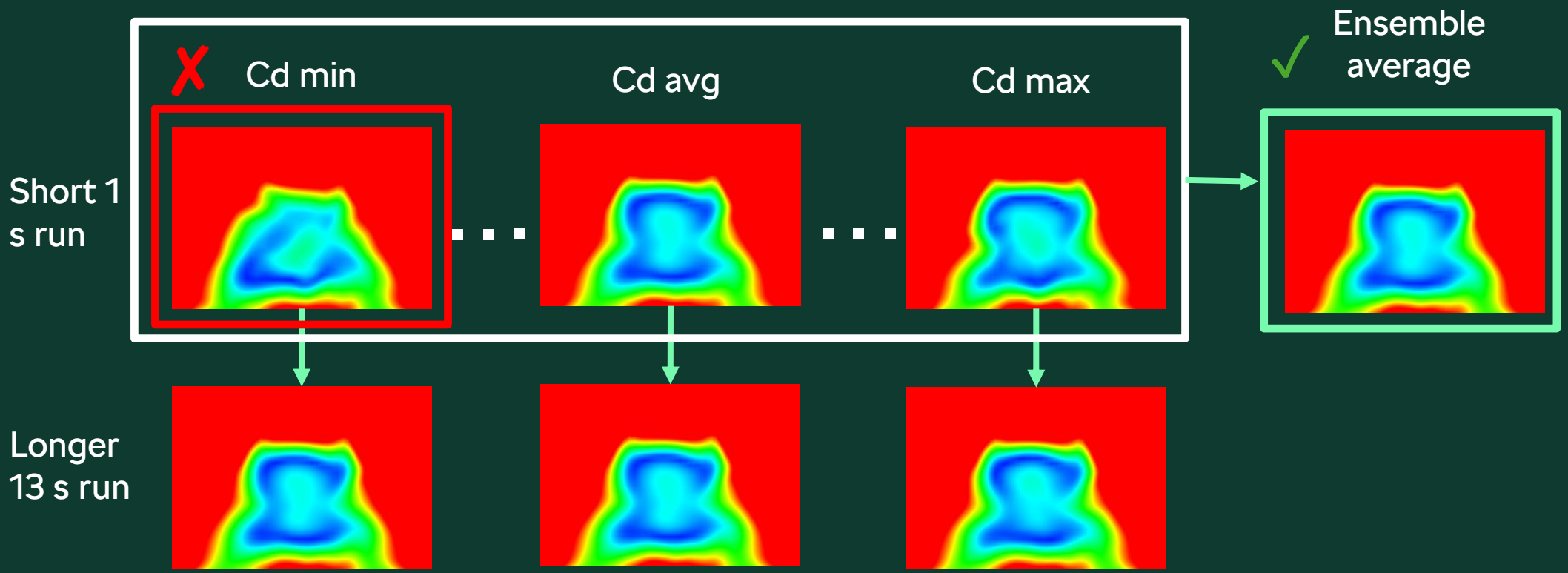
- Decorrelation time (overhead)
  - Investigation of the effect of decorrelation time on the error-versus-averaging-window curve and visual checks confirmed that less than 0.5 s is sufficient

- Automatic termination
  - Each subvariant stops once Cd has stabilized



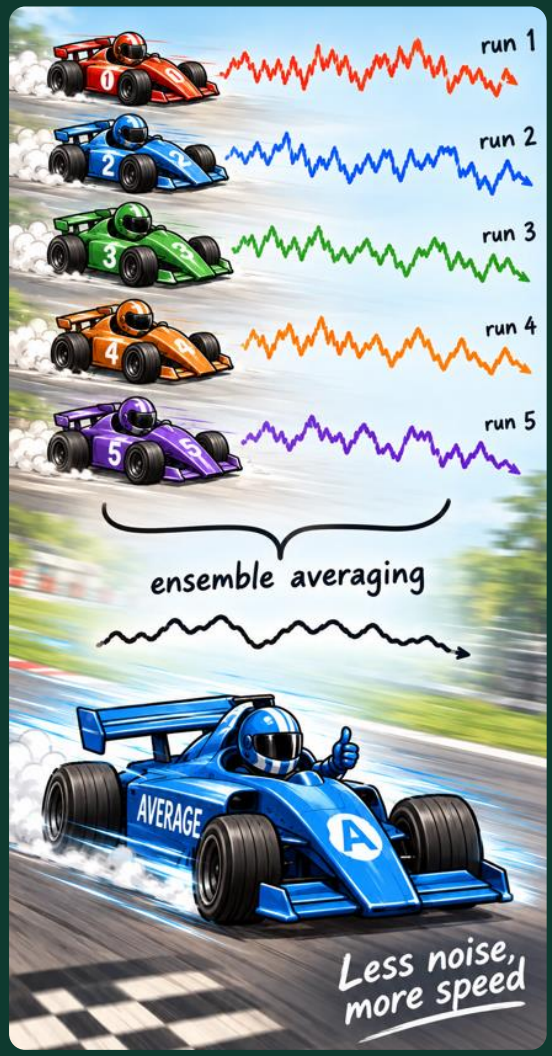
EAM implementation 3/3

- We need to average the flow fields across all ensemble subvariants
- We also export selected variables from the Cd-max and Cd-min subvariants, along with their differences



Advantages of the EAM

- **EAM shorten wall-clock time if sufficient resources are available**
  - It is not necessary to increase the number of CPUs for individual runs — the problem of scalability is minimized
  - **With respect to result uncertainty, an overnight simulation covers the same duration as the WT measurement**
- **Multiple independent solutions provide an uncertainty estimate**
- For favorable geometries, EAM substantially reduces the total simulation time required to reach low uncertainty
- The ensemble also reduces the risk that a single hardware failure invalidates the result



BACKUP

Abstract

Accurate prediction of external automotive aerodynamics requires nonstationary (transient) flow simulations that capture the temporal fluctuations of the surrounding air. However, these simulations are computationally expensive and often require days of wall-clock time on large high-performance computing (HPC) clusters, making them impractical for iterative engineering development cycles. This paper presents a parallel ensemble averaging method that replaces a single long transient simulation with multiple shorter simulations that run concurrently. Artificial, infinitesimal perturbations—implemented as minute changes in dynamic viscosity on the order of 0.0001×10^{-5} kg/(m·s)—are introduced into each sub-simulation to decorrelate the flow fields after a short transient period. The resulting ensemble of signals is then treated as statistically independent samples, enabling both rapid convergence of mean aerodynamic coefficients and quantified uncertainty estimation. The method was developed using hundreds of wind-tunnel drag coefficient (Cd) measurements and validated against extensive CFD datasets covering multiple vehicle configurations, simulation durations of 4–60 s, and two major commercial solvers. Results confirm that the ensemble approach achieves uncertainty levels equivalent to a single long simulation at a fraction of the elapsed wall-clock time, enabling overnight simulations that previously required multiple days.

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Error vs averaging window

Hypothesis: The Cd (noise) error is decreasing nonlinearly with increasing length of averaging window (starting at high value at time 0 and approaching 0 value at infinite time)

