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Evaluation of PHEVs Fuel Efficiency and Cost Using MonteCarlo Analysis

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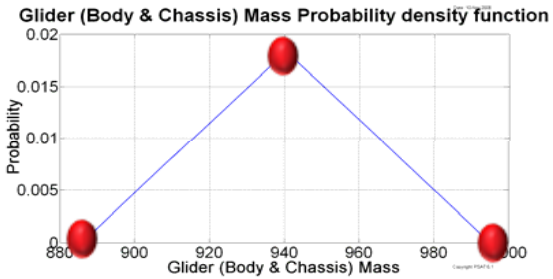
Study Objectives

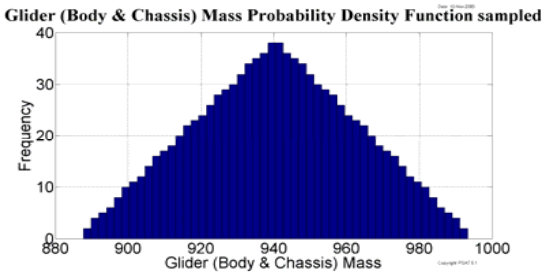
How does Monte Carlo compare with 3 points analysis (low, medium, high)?

Current Methodology



Three vehicles defined

MonteCarlo

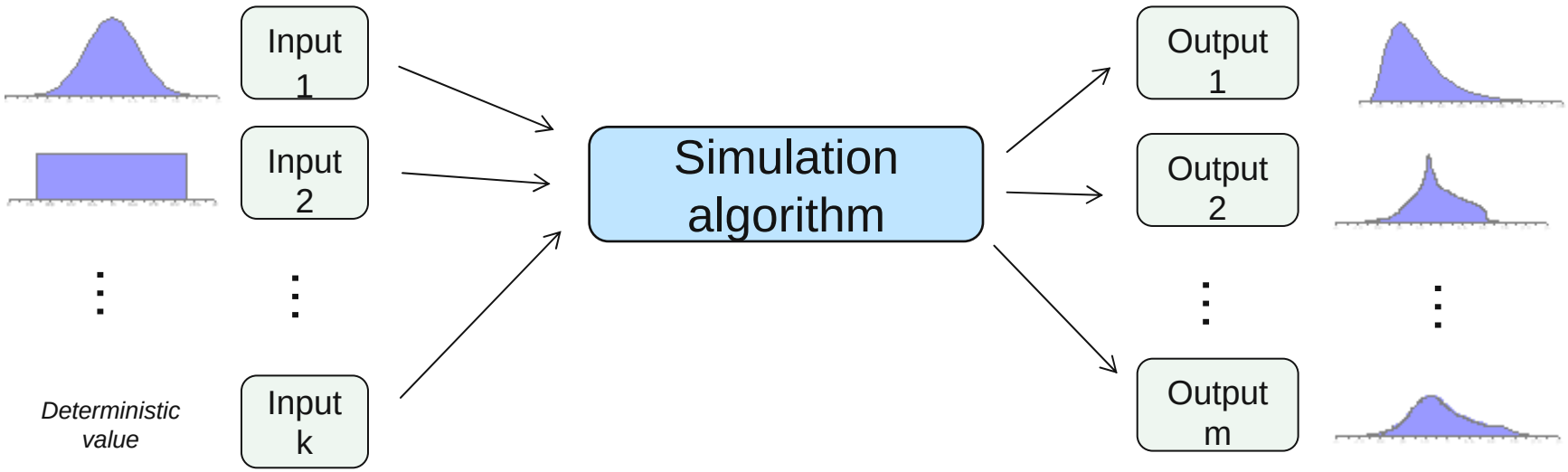


Hundreds of vehicles defined

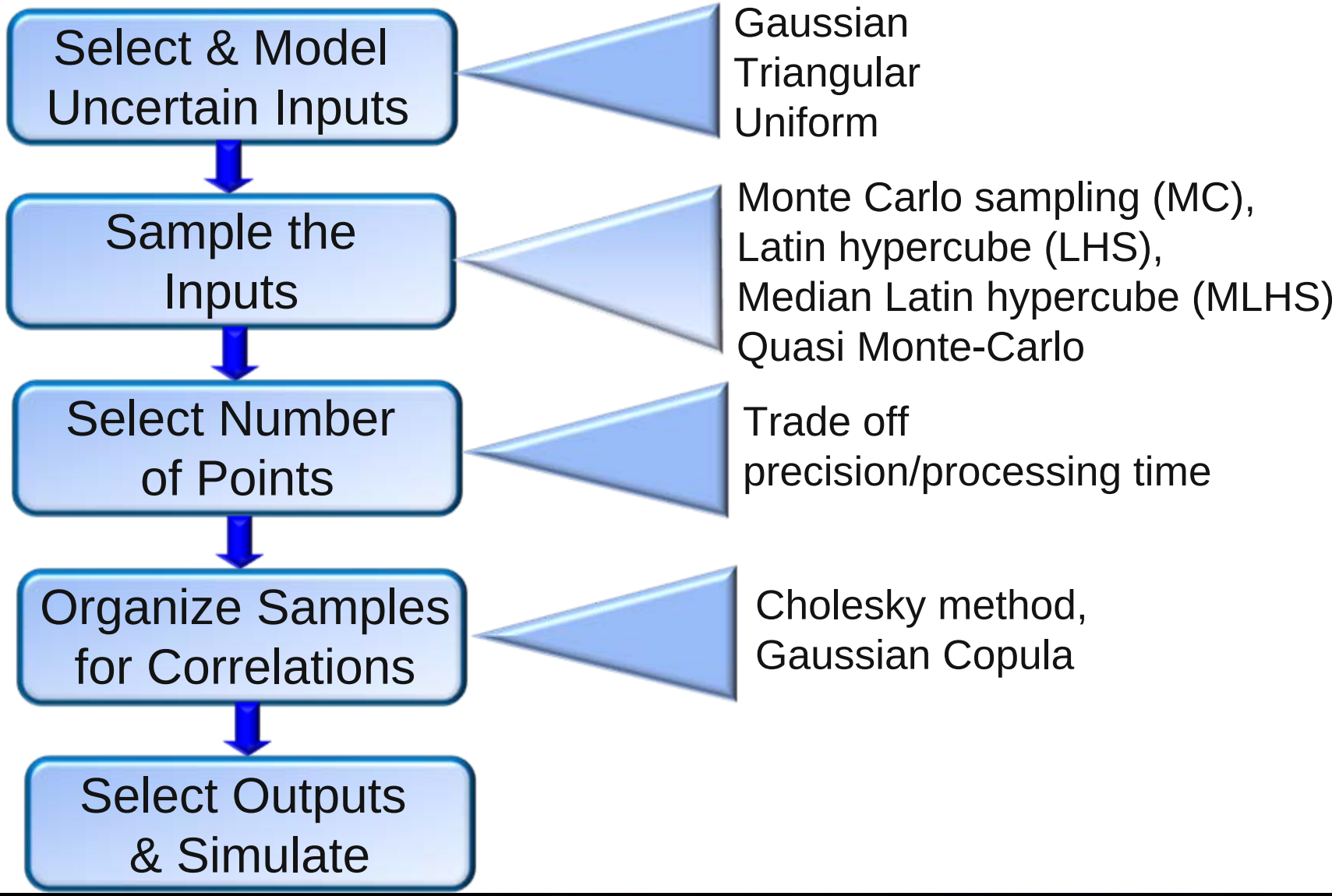
- Process:
  - Implement Monte Carlo methodology in PSAT
  - Validate the process
  - Select most appropriate options for PSAT
  - Compare results with existing 3 points study

Monte Carlo Definition
Uncertain Inputs

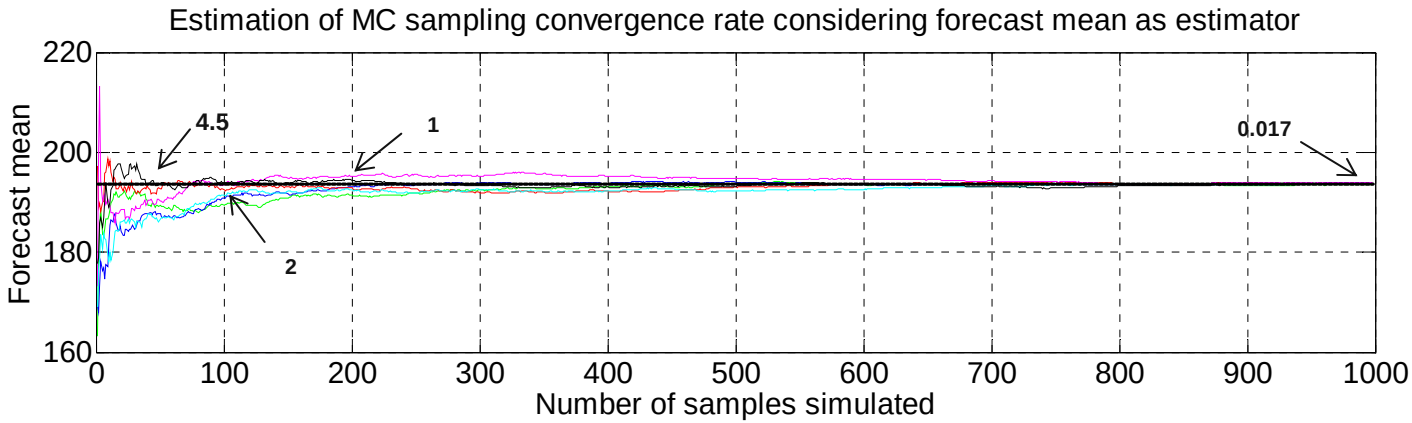
- Uncertainty is modeled by a probability density function (pdf)
- How is the uncertainty **propagating** into the algorithm?
- Complex algorithm: knowing the input pdf we cannot directly compute/derive the outputs!



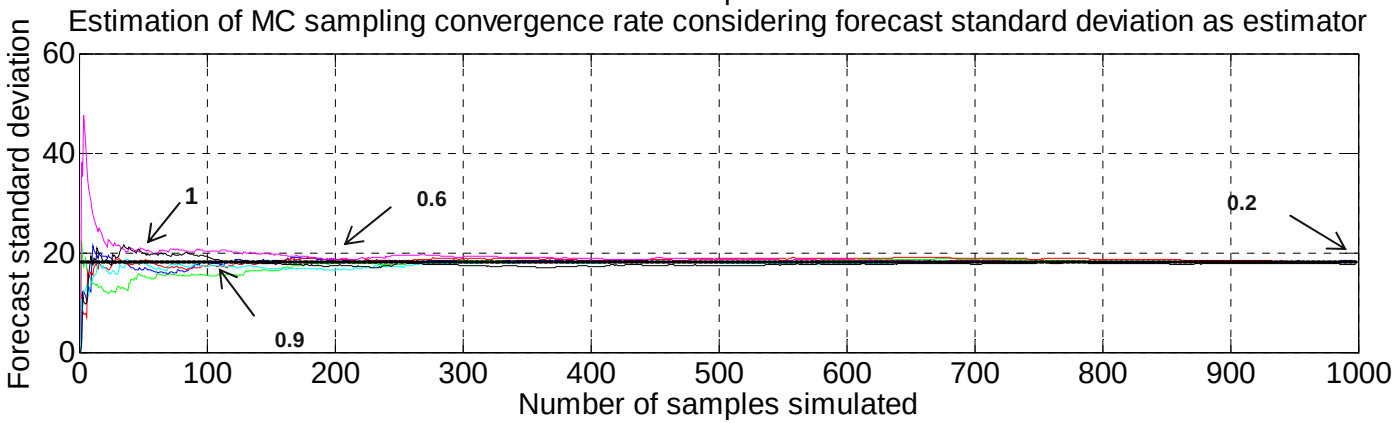
Monte Carlo Implementation Process



Input Sampling Methodology Selection
Monte Carlo (MC) Sampling



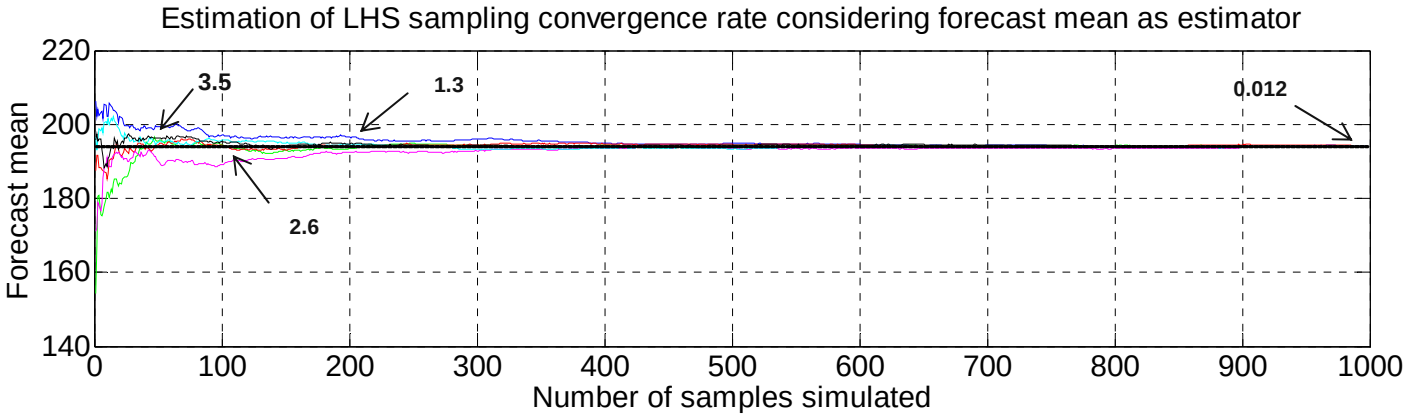
- Means converge to 193.9 Wh/mile



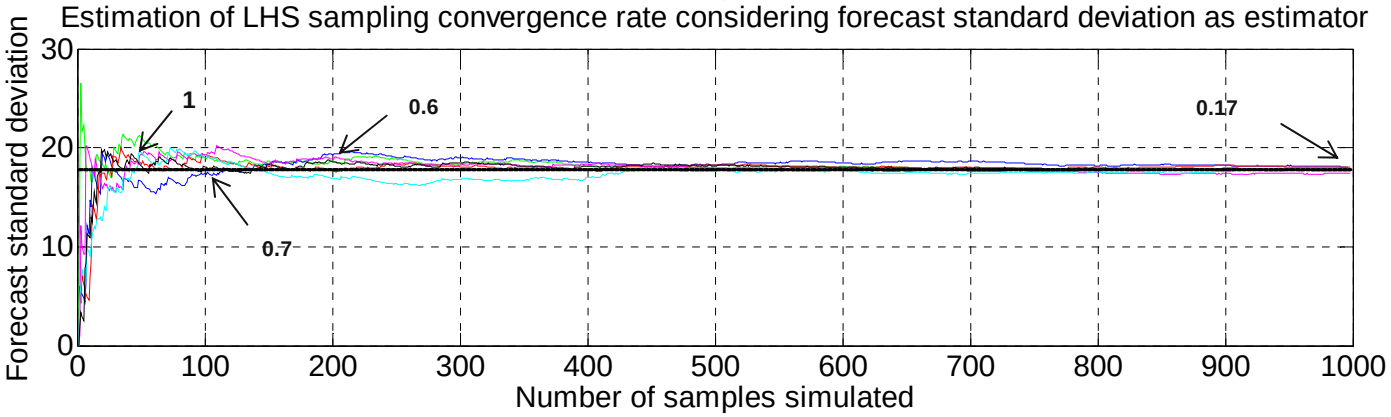
- Standard deviations converge to 18.1

Assumptions: 5 uncertain inputs, Monte Carlo sampling, fuel consumption simulation.

Input Sampling Methodology Selection
Latin Hypercube Sampling (LHS)



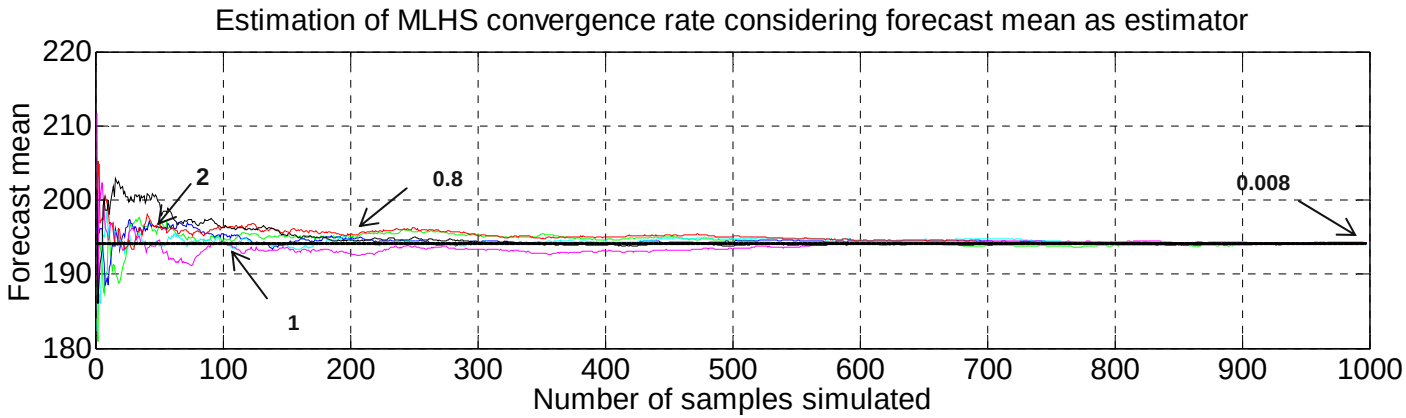
- Means converge to 194.1 Wh/mile



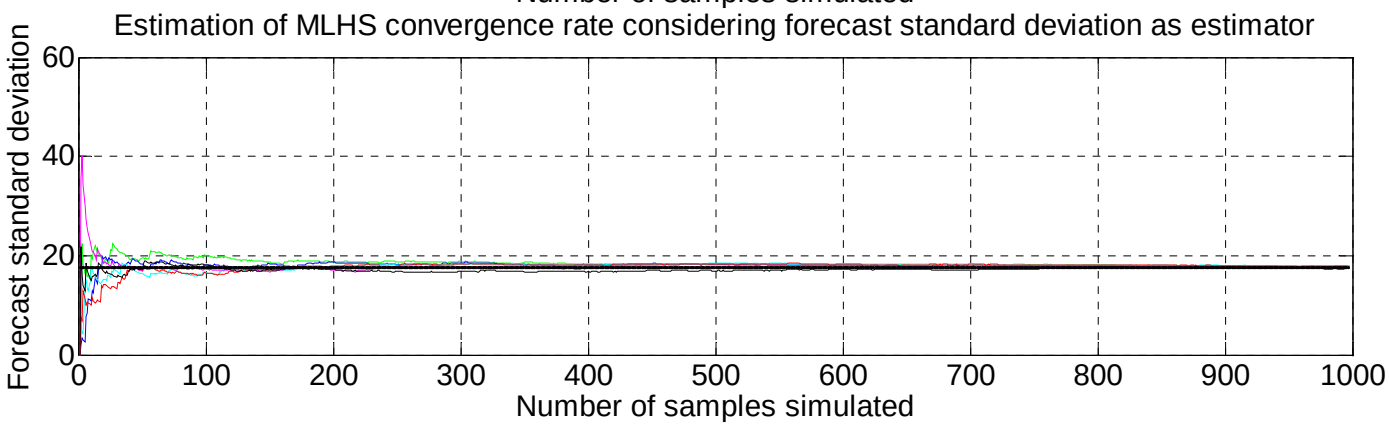
- Standard deviations converge to 17.9 Wh/mile

Assumptions: 5 uncertain inputs, Latin hypercube sampling, fuel consumption simulation

Input Sampling Methodology Selection
Median Latin Hypercube Sampling (MLHS)



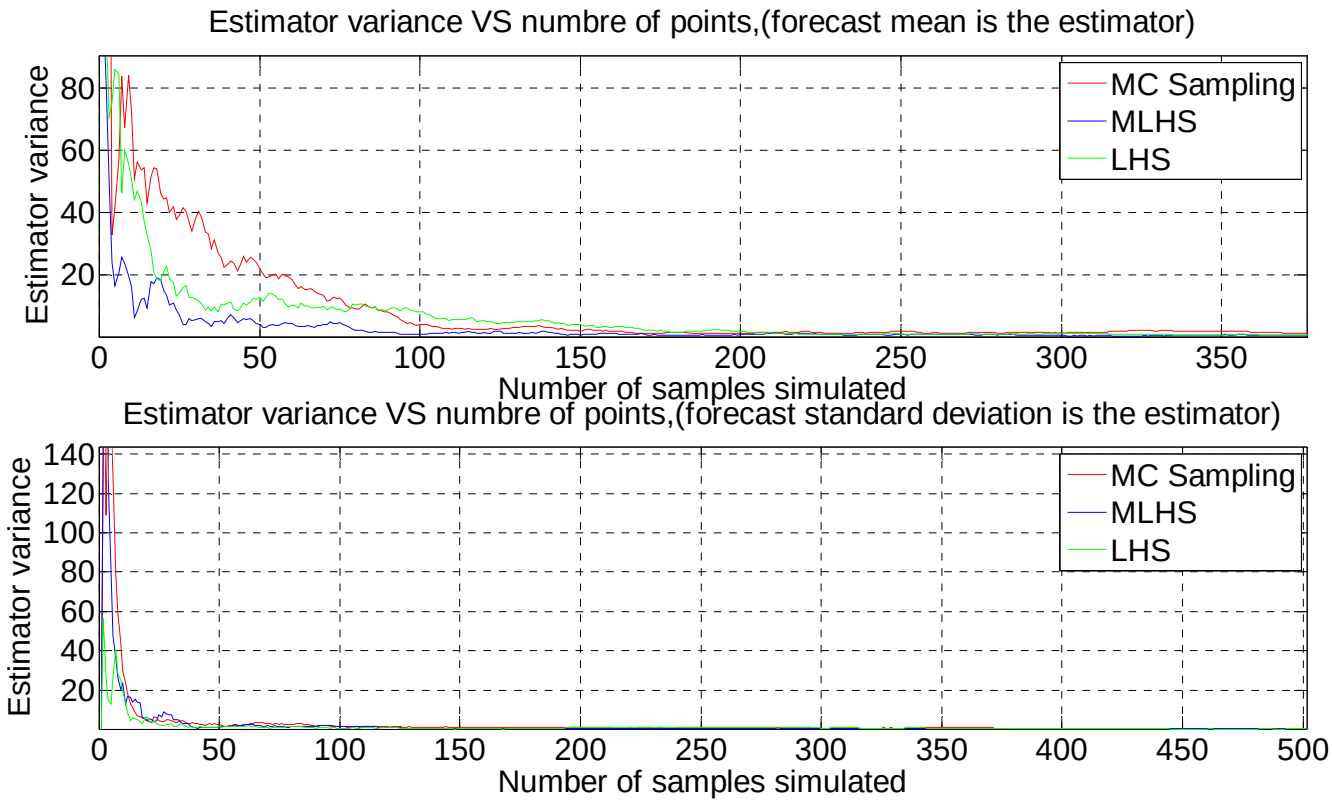
- Means converge to 194.1 Wh/mile



- Standard deviations converge to 17.7 Wh/mile

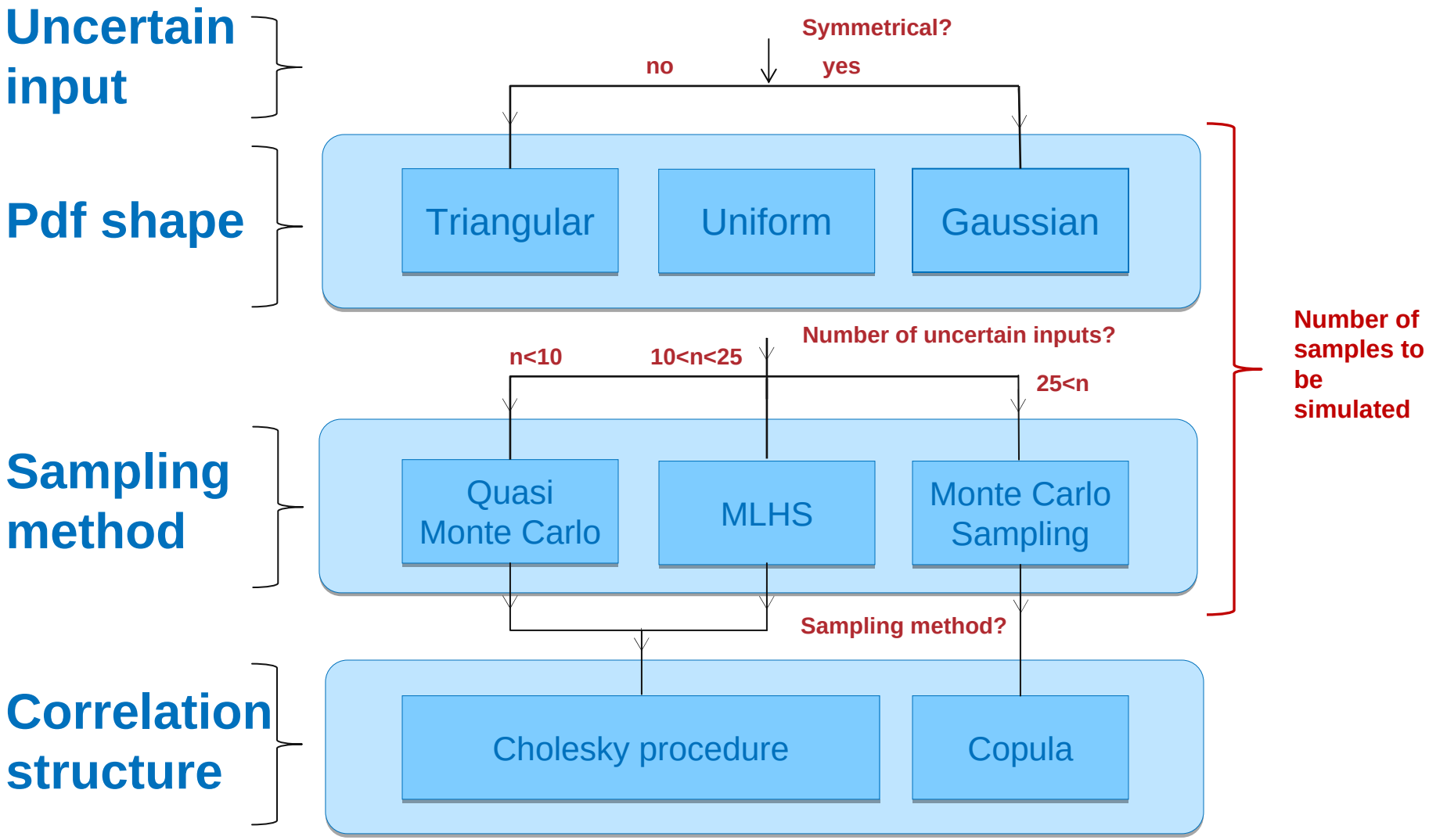
Assumptions: 5 uncertain inputs, Latin hypercube sampling, fuel consumption simulation

Input Sampling Methodology Selection
Methodologies Comparison



- All the methods converge to the same values
- MLHS performs better than the other methods
- Quasi Monte Carlo performs even better
- No real impact of the method on the convergence rate for variance

Process Used for the Study

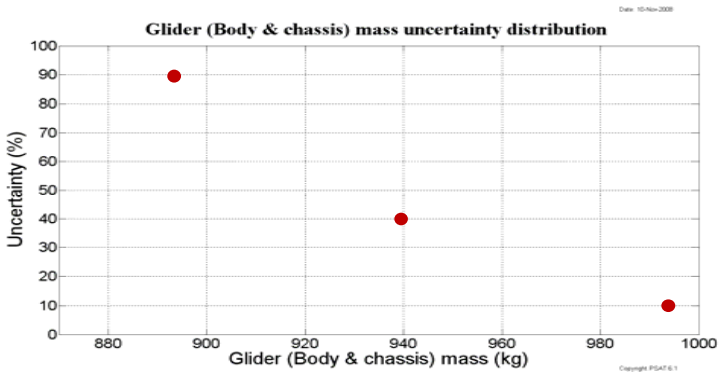


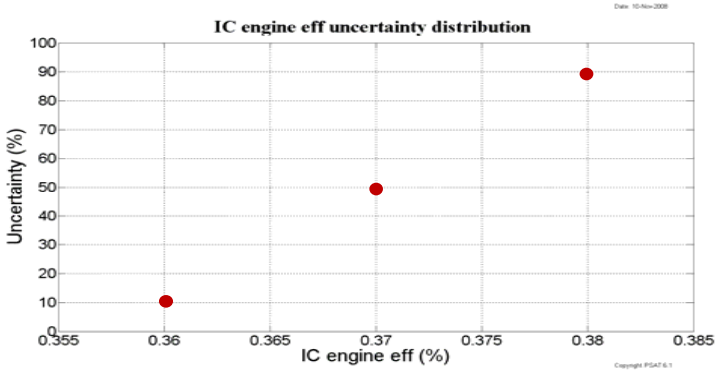
Reference Vehicle
Main Assumptions

Vehicle: Midsize Power Split PHEV 10AER

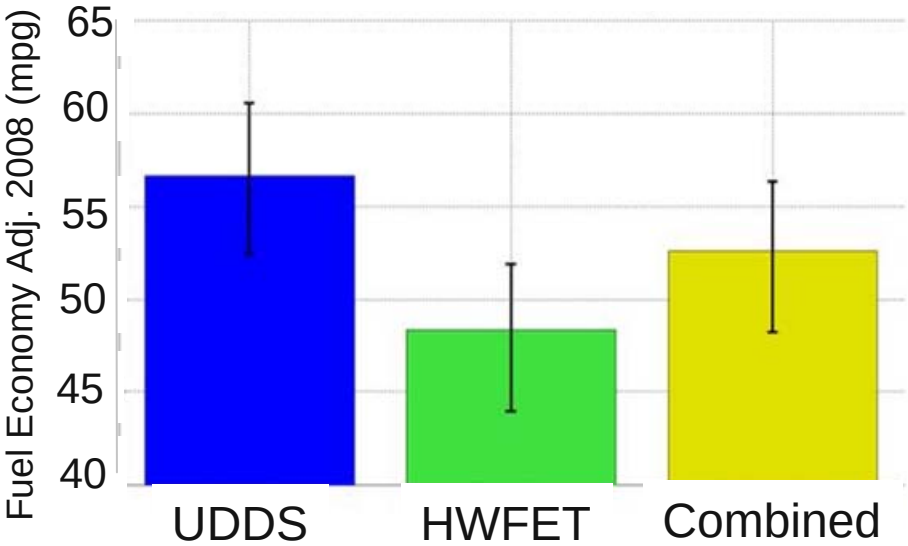
Uncertain inputs	Low uncertainly	Medium uncertainty	High uncertainty
Glider (Body & Chassis) mass (kg)	995	940	886
Motor Controller #1 power density (kg)	4900	6000	12600
Electric Motor #1 power density (W/kg)	1085	1255	1300
Motor Controller #2 power density (W/kg)	4900	6000	12600
Electric Motor #2 power density (W/kg)	1085	1255	1300
Frontal Area (m2)	2.244	2.222	2.2
Coefficient Drag	0.24	0.27	0.31
Rolling Resistance	0.0072	0.0078	0.01
IC Engine eff (%)	0.36	0.37	0.38
Electric Drive #1 eff (%)	0.95	0.955	0.97
Electric Drive #2 eff (%)	0.93	0.955	0.96
Electrical Power (W)	220	210	200

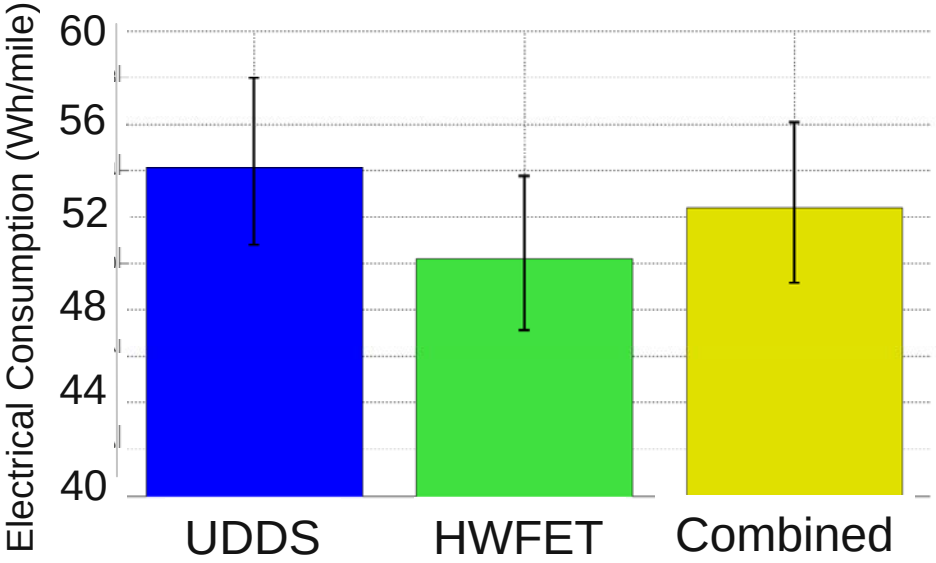
Graphical representation:

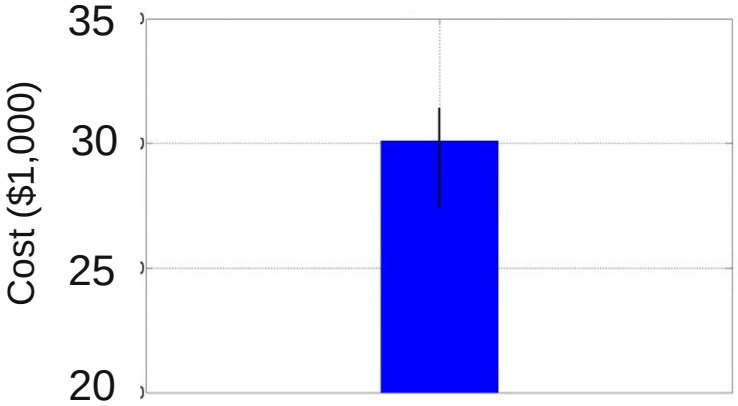




Reference Vehicle
Fuel Efficiency & Cost Results

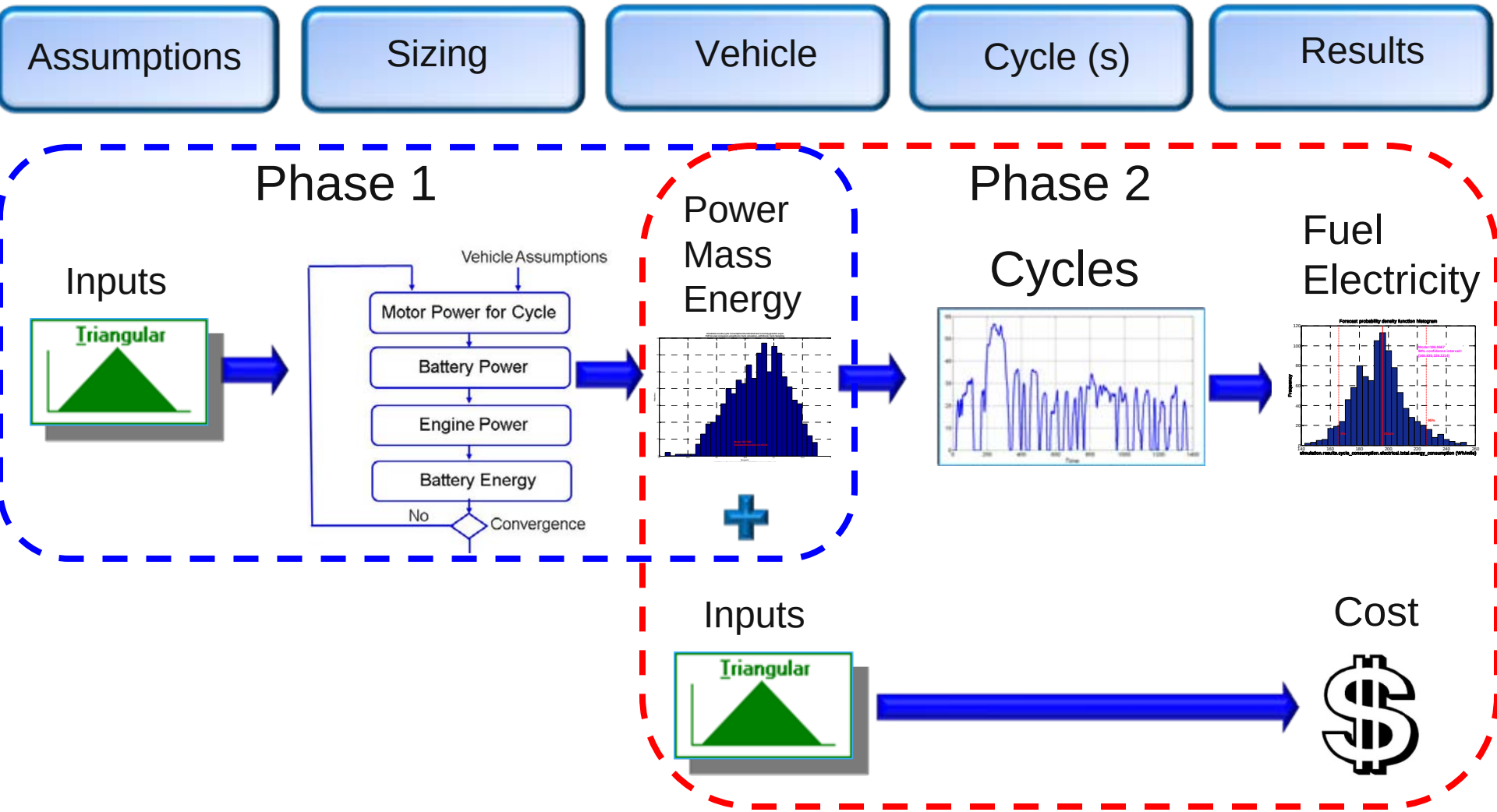






3 values per forecast. However, no quantifiable confidence interval!

Process to Simulate Single Vehicle



Monte Carlo Analysis
Assumptions

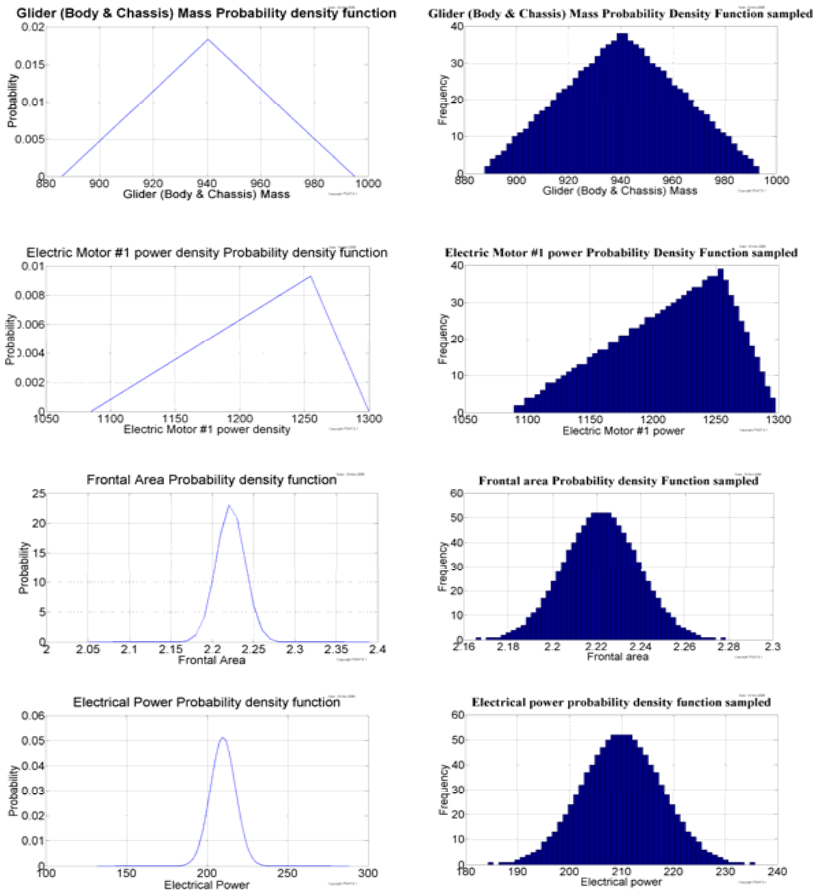
Vehicle: midsize PHEV 10AER used for GPRA/PDS 2009

Monte Carlo: 1000 points-MLHS-no correlations

Uncertain inputs considered:

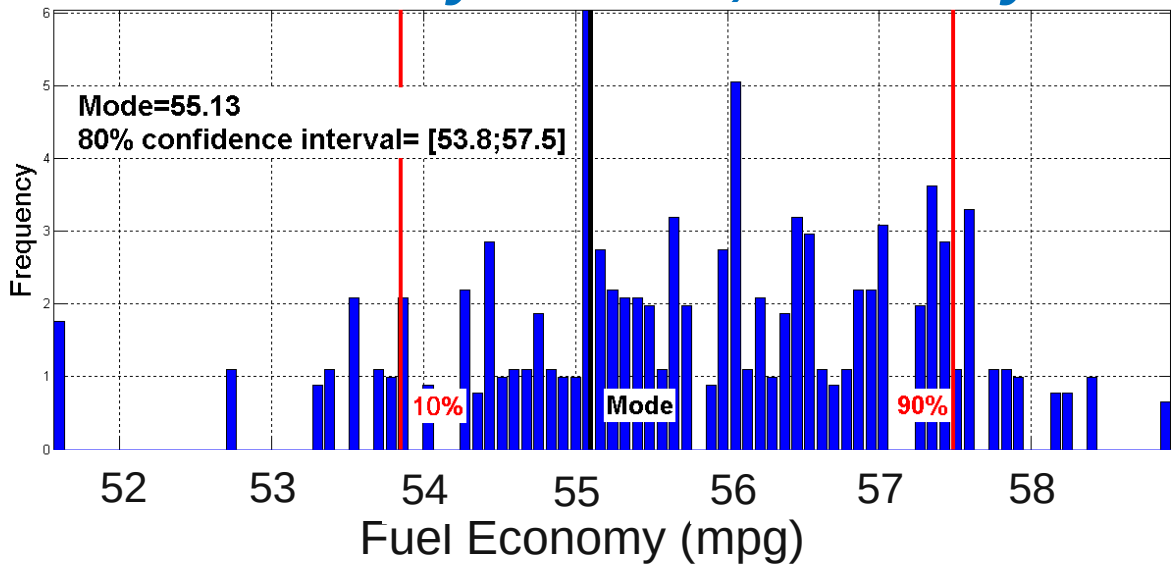
- Glider (Body & Chassis) Mass
- Motor Controller #1 power density
- Electric Motor #1 power density
- Motor Controller #2 power density
- Electric Motor #2 power density
- Frontal Area
- Coefficient Drag
- Rolling Resistance
- IC Engine eff
- Electric Drive #1 eff
- Electric Drive #2 eff
- Electrical Power

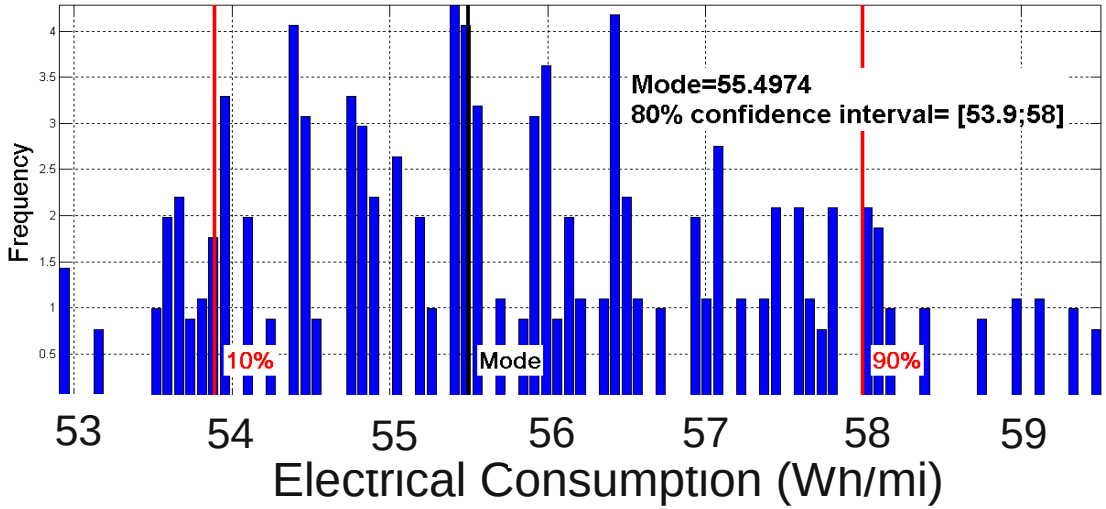
Examples:



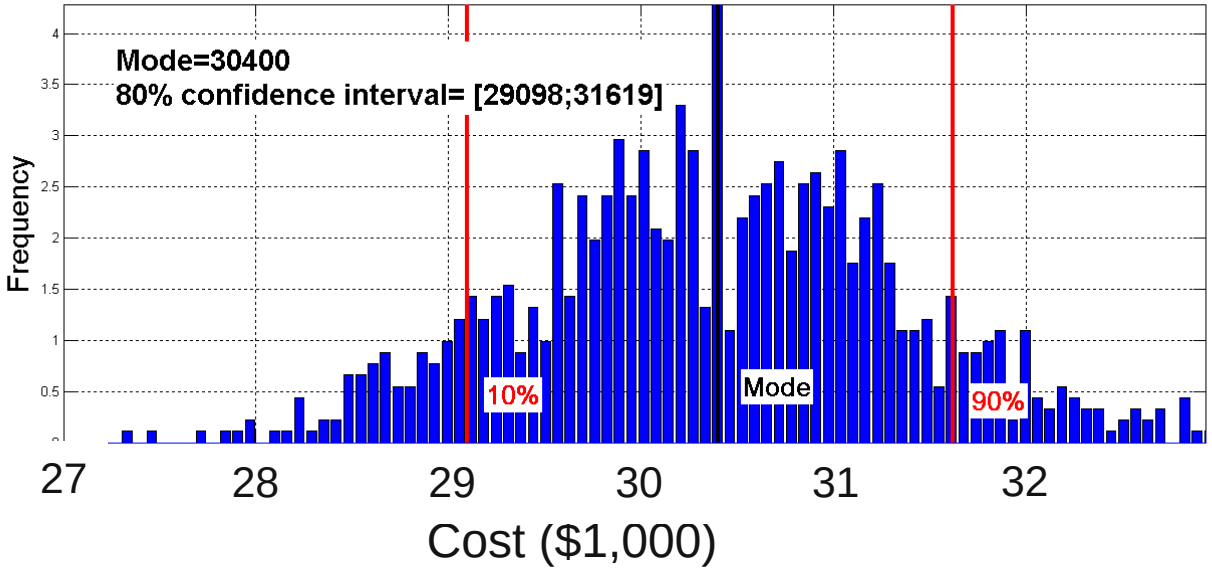
Monte Carlo Analysis

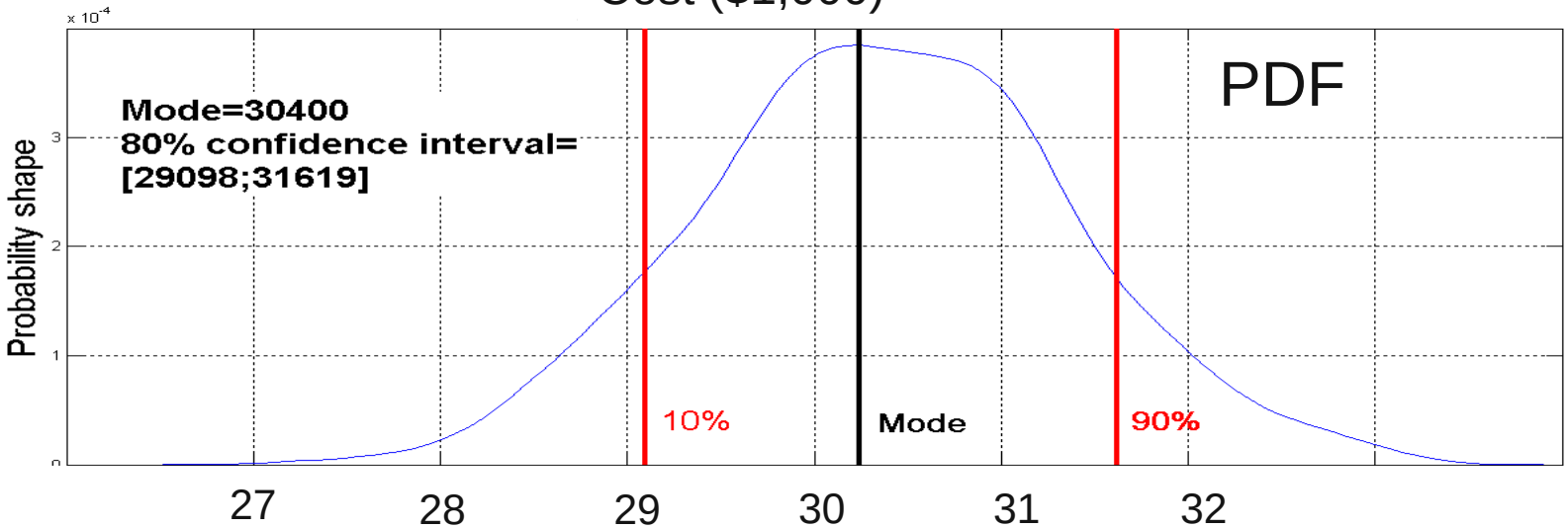
Fuel Efficiency Results, UDDS cycle





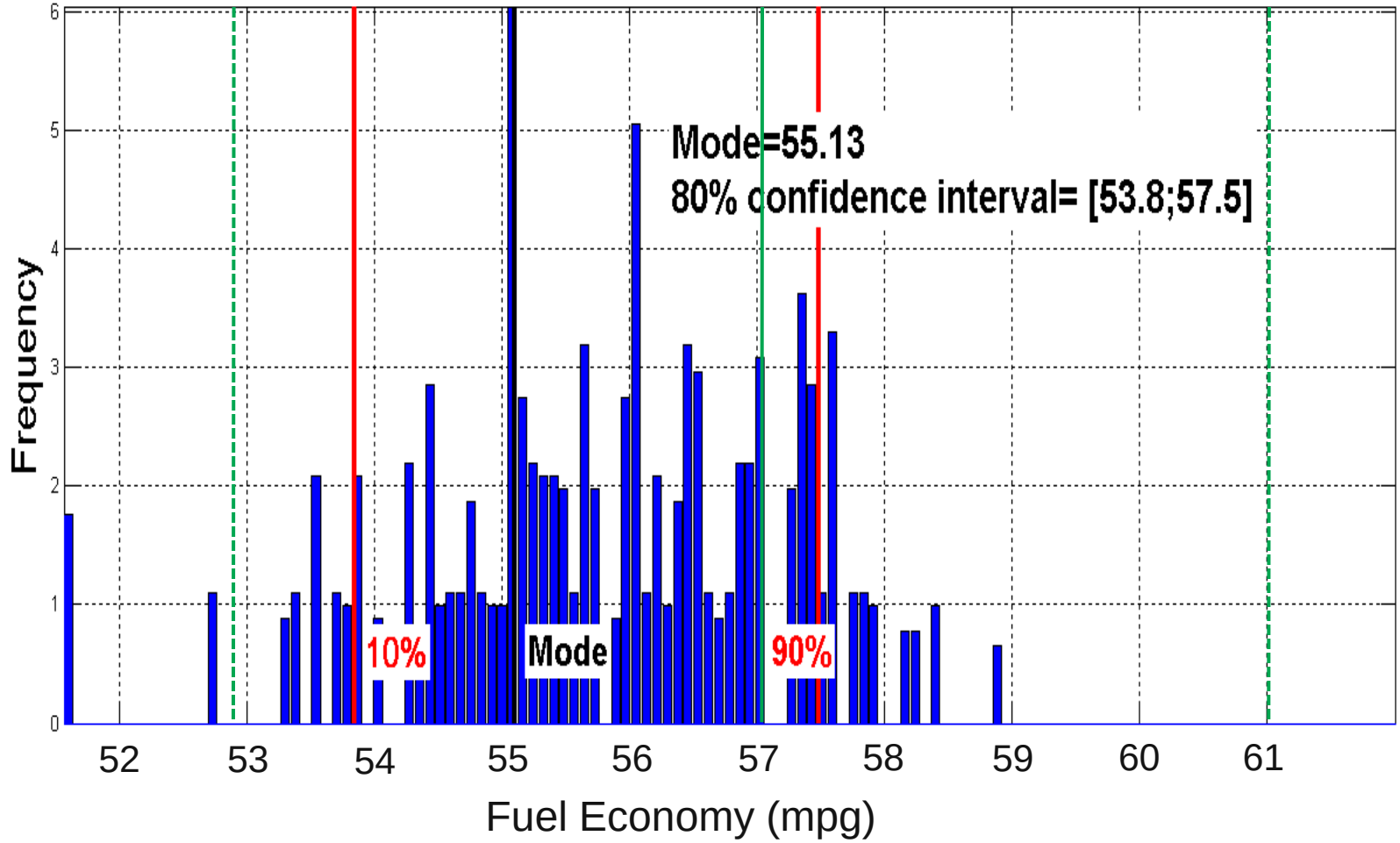
Monte Carlo Analysis
Cost Results





Comparison Between Methodologies

Fuel Economy, UDDS cycle



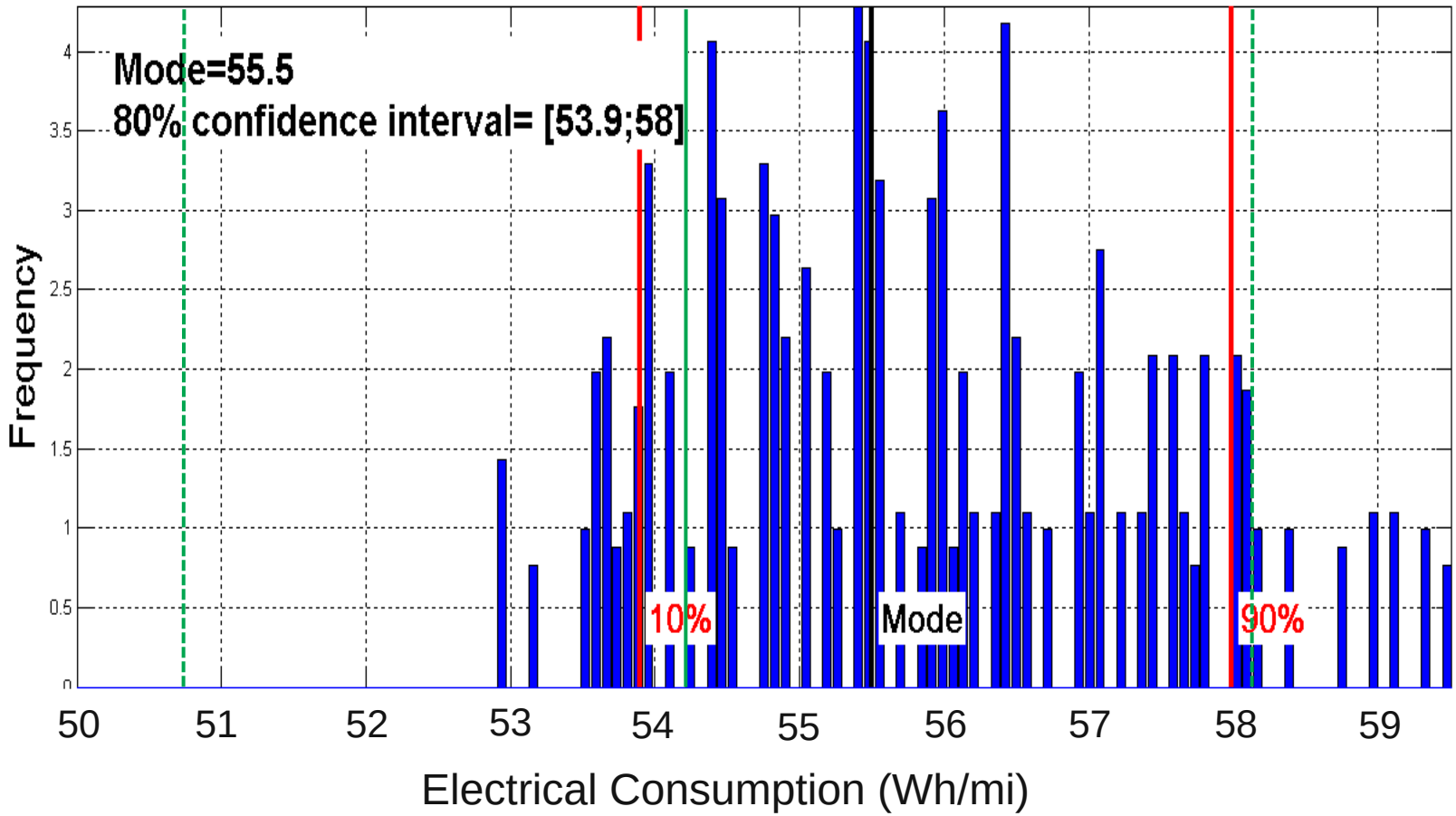
Percentiles, 3 points study

Mode, 3 points study

Percentiles, Monte Carlo

Mode, Monte Carlo

Comparison Between Methodologies
Electrical Consumption, UDDS cycle



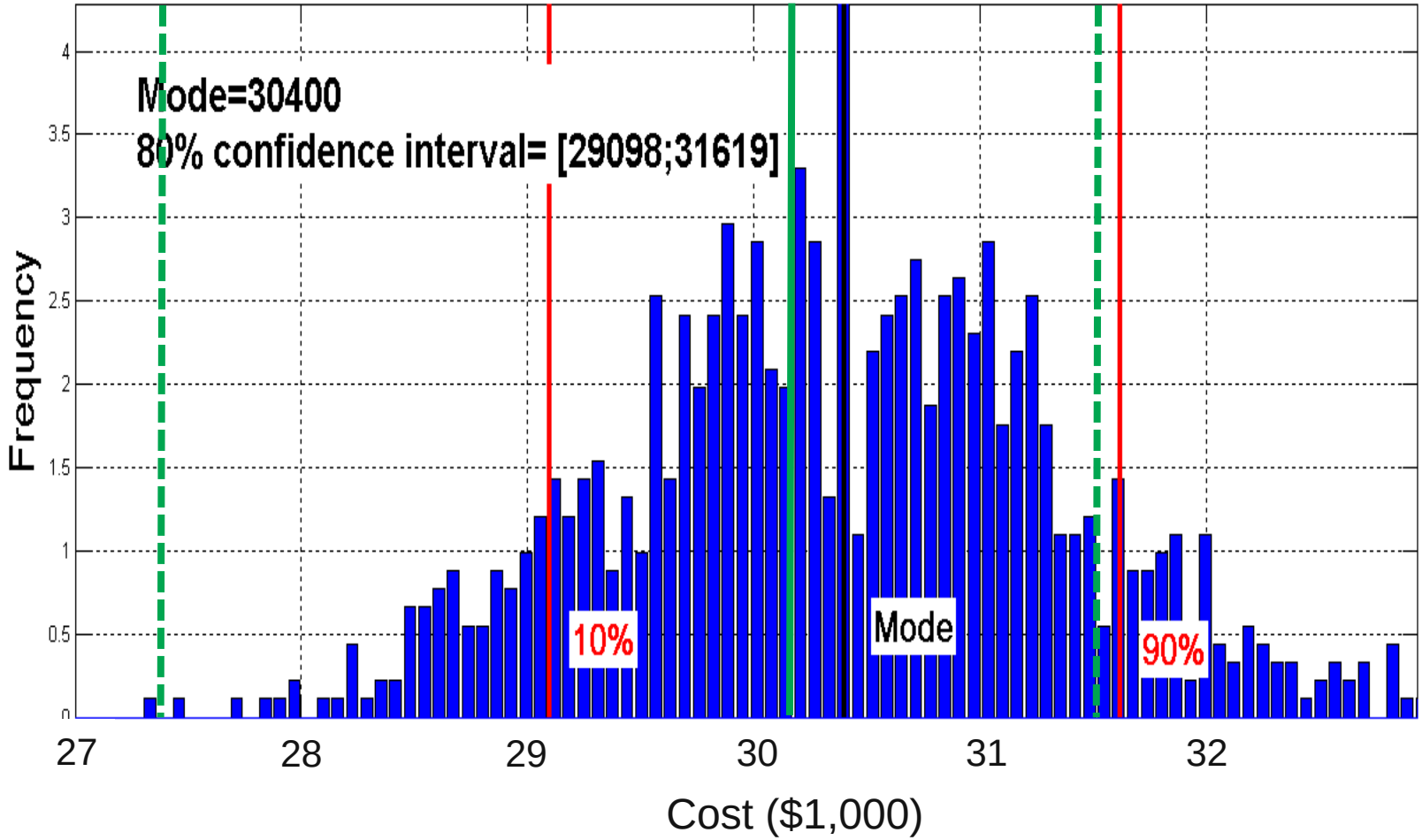
Percentiles, 3 points study

Mode, 3 points study

Percentiles, Monte Carlo

Mode, Monte Carlo

Comparison Between Methodologies
Cost



Percentiles, 3 points study

Mode, 3 points study

Percentiles, Monte Carlo

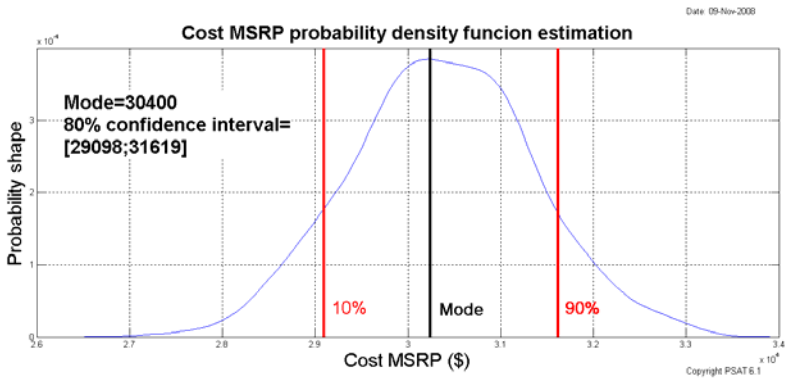
Mode, Monte Carlo

Conclusions

- A Monte Carlo library containing all the essential features required to carry out accurate studies of the uncertainty propagation has been implemented into PSAT and validated.
- Different sampling methods were compared for several powertrain configurations. For each option, the most appropriate number of samples was defined.
- The results from Monte Carlo based on a midsize PHEV were defined and compared with the existing 3 points option, demonstrating that Monte Carlo provided a narrower range.
- With a number of points ranging from 100 to 200, uncertainties have a computational cost.
- While providing useful insight for the uncertainty of specific technologies, this method is currently only applicable to studies with limited number of vehicles or powertrain configurations.

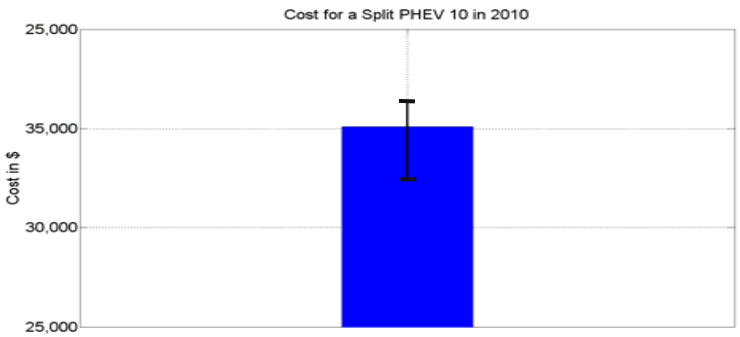
Comparison Between Methodologies
Simulation Results

Monte Carlo simulation:



- Most likely value and confidence interval
- Full description of the output forecast
- Theoretical justifications
- Precision and reliability
- Correlations

3 points simulation:



- Most likely value
- Side values are not representatives
- No theoretical justification
- No correlations
- Cannot characterize the uncertainty on the output