

# Predictive Analytics

Predicting Service Life of Aircraft Jet Engines

Part I:

High Pressure Compressors

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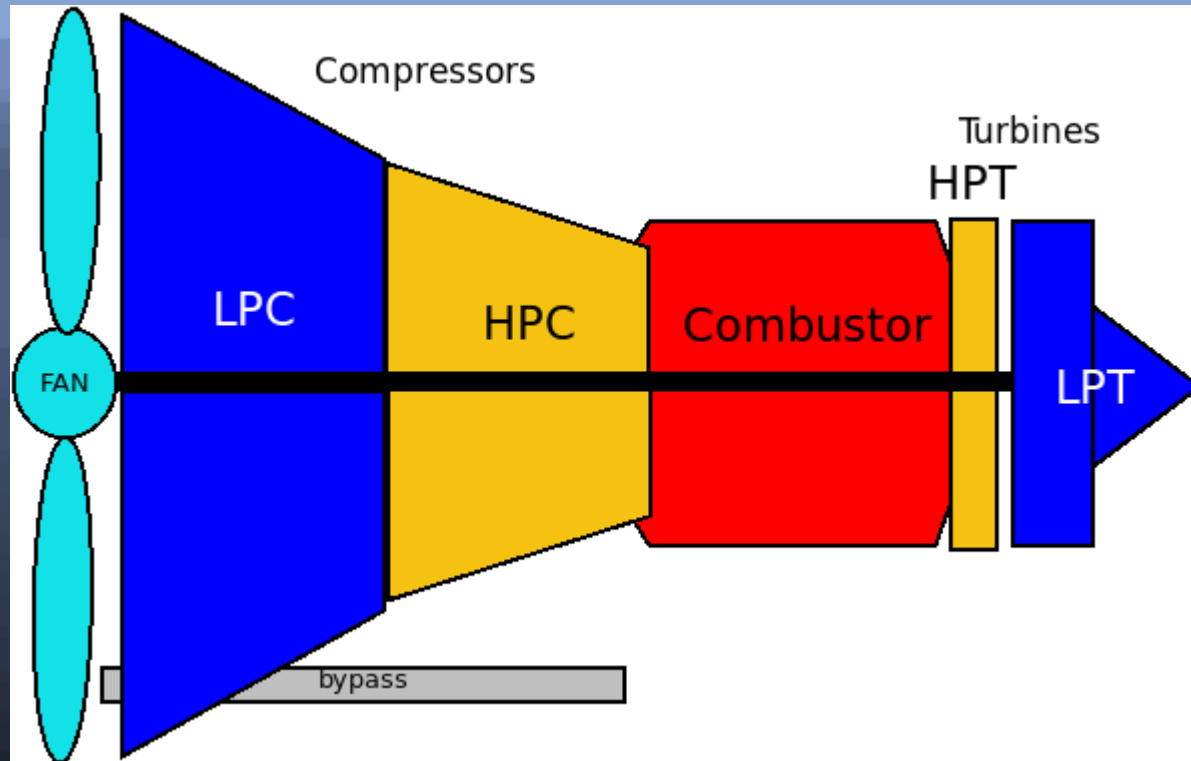
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# Predictive Maintenance

## Demo Example

- Aircraft jet engine run-to-failure data from NASA thermo-dynamical Aero-Propulsion System Simulator
- published experimental data by Saxena et al. (NASA) 2008
- independent analysis by Otmar Mak

# Service Life Prediction



Simplified aircraft jet engine schematic

# Service Life Prediction

## Critical Components

- Fan
- Low pressure compressor (LPC)
- **High pressure compressor (HPC)**
- High pressure turbine (HPT)
- Low pressure turbine (LPT)

Demo: jet engine with 21 sensors

# Service Life Prediction

Jet engine with operational settings op1-op3,  
monitored by 21 sensors:

t2, t24, t30, t50	total temperatures at fan inlet, LPC outlet, HPC outlet, LPT outlet [ $^{\circ}$ R]
p2, p15, p30	pressures at fan inlet, in bypass-duct, at HPC outlet [psia]
nf, nc,nrf, nrc	physical fan and core speeds, corrected fan and core speeds [rpm]
nfdmd,nfcdmd	demanded fan speed, demanded corrected speed [rpm]
epr	engine pressure ratio (p50/p2) [-]
ps	static pressure at HPC outlet [psia]
phi	ratio of fuel flow to ps [pps/psi]
bpr	bypass ratio [-]
farb	burner fuel air ratio [-]
htbleed	bleed enthalpy
w31, w32	HPT and LPT coolant bleed [lbm/s]

# Service Life Prediction

Jet engine operational settings include variation of

- \* *altitudes* from sea level to 40 000 ft
- \* *speeds* at Mach numbers from 0 to 0.9
- \* *sea level temperatures* from -60 to 103°F

Source: **Saxena et al[2008], p. 2**

# HPC Life Predictor

The goal is to *estimate remaining useful component life* in units of time (cycles)

The data available for building an *HPC life predictor* are time series of observables („sensor data“ in cycle time steps) at cruise snapshots that were produced by modifying flow and efficiencies of the HPC module from initial settings (indicating normal deterioration) to values corresponding to failure threshold.

Source: **Saxena et al[2008], p. 6**

# HPC Life Predictor

Modified definition of objective *in this study* as compared to Saxena et al. [2008]:

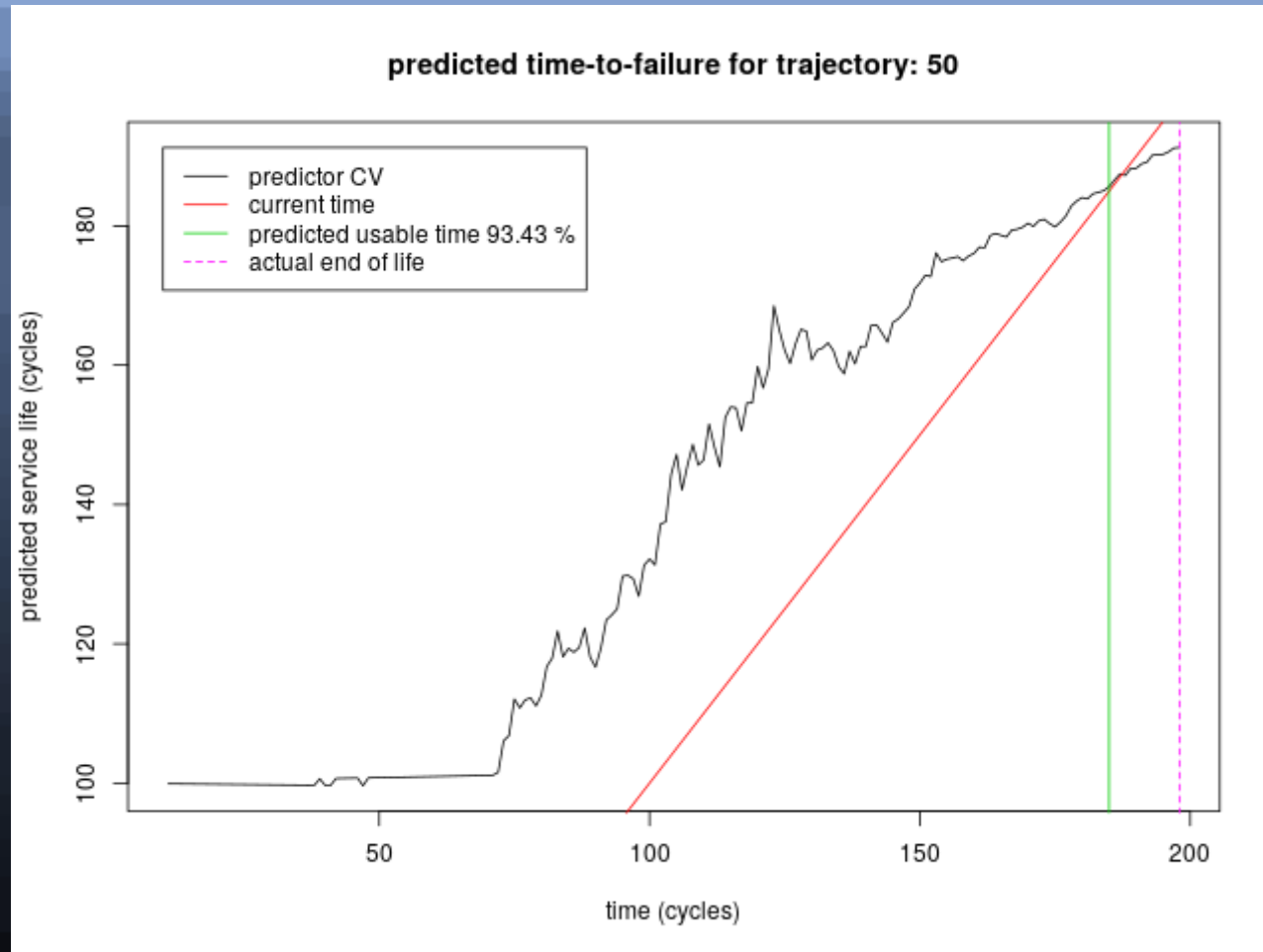
The **objective of the HPC life predictor** is to *estimate total time until failure* with highest possible accuracy while minimizing the risk of overestimating *time until failure*

# HPC Life Predictor

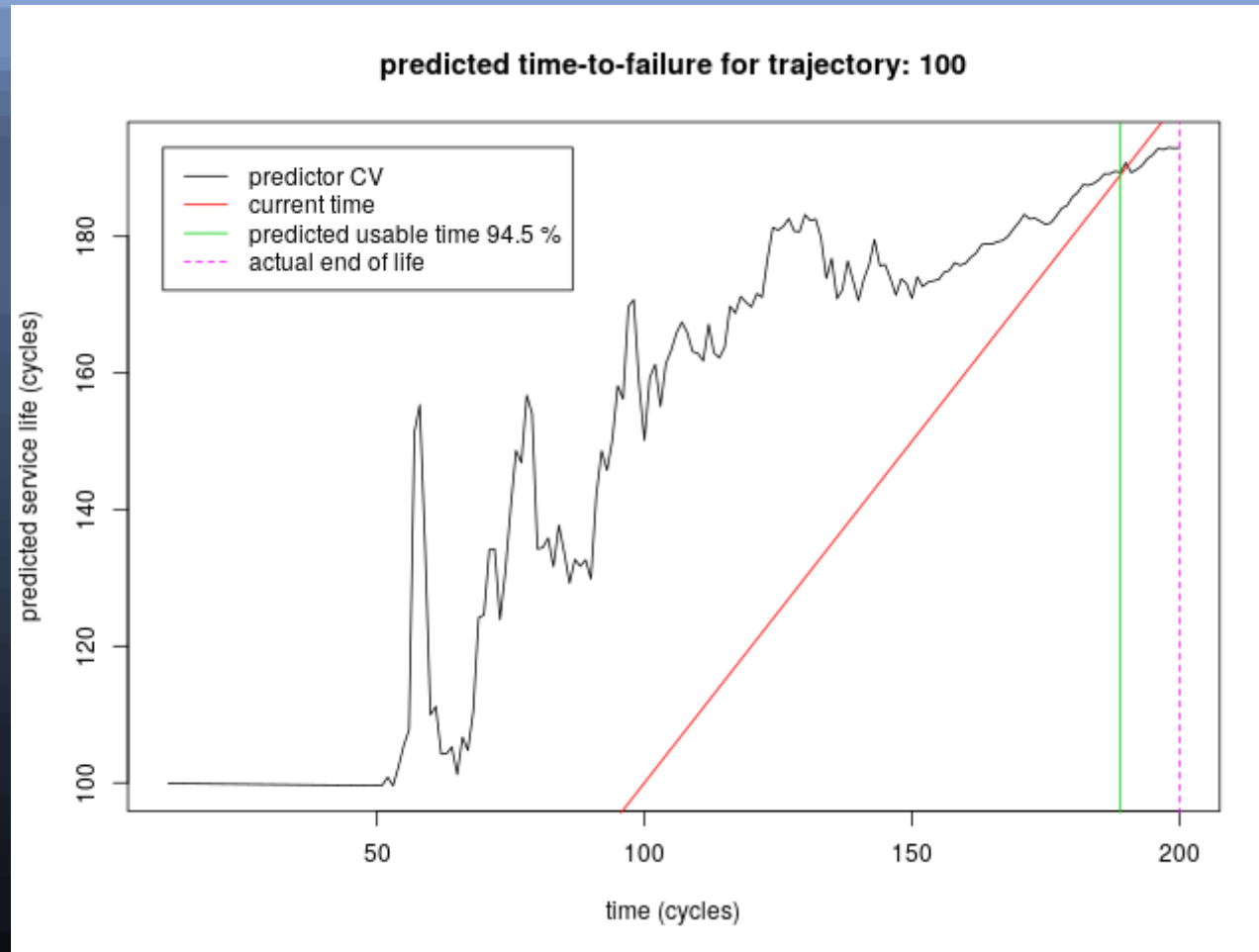
Relevant features are derived from following sensor data:

<b>t24, t30, t50</b>	total temperatures at LPC outlet, HPC outlet, LPT outlet [ $^{\circ}\text{R}$ ]
<b>p30</b>	pressures at HPC outlet [psia]
<b>ps</b>	static pressure at HPC outlet [psia]
<b>phi</b>	ratio of fuel flow to ps (pps/psi)
<b>bpr</b>	bypass ratio [-]
<b>htbleed</b>	bleed enthalpy
<b>w31, w32</b>	HPT and LPT coolant bleed [lbm/s]

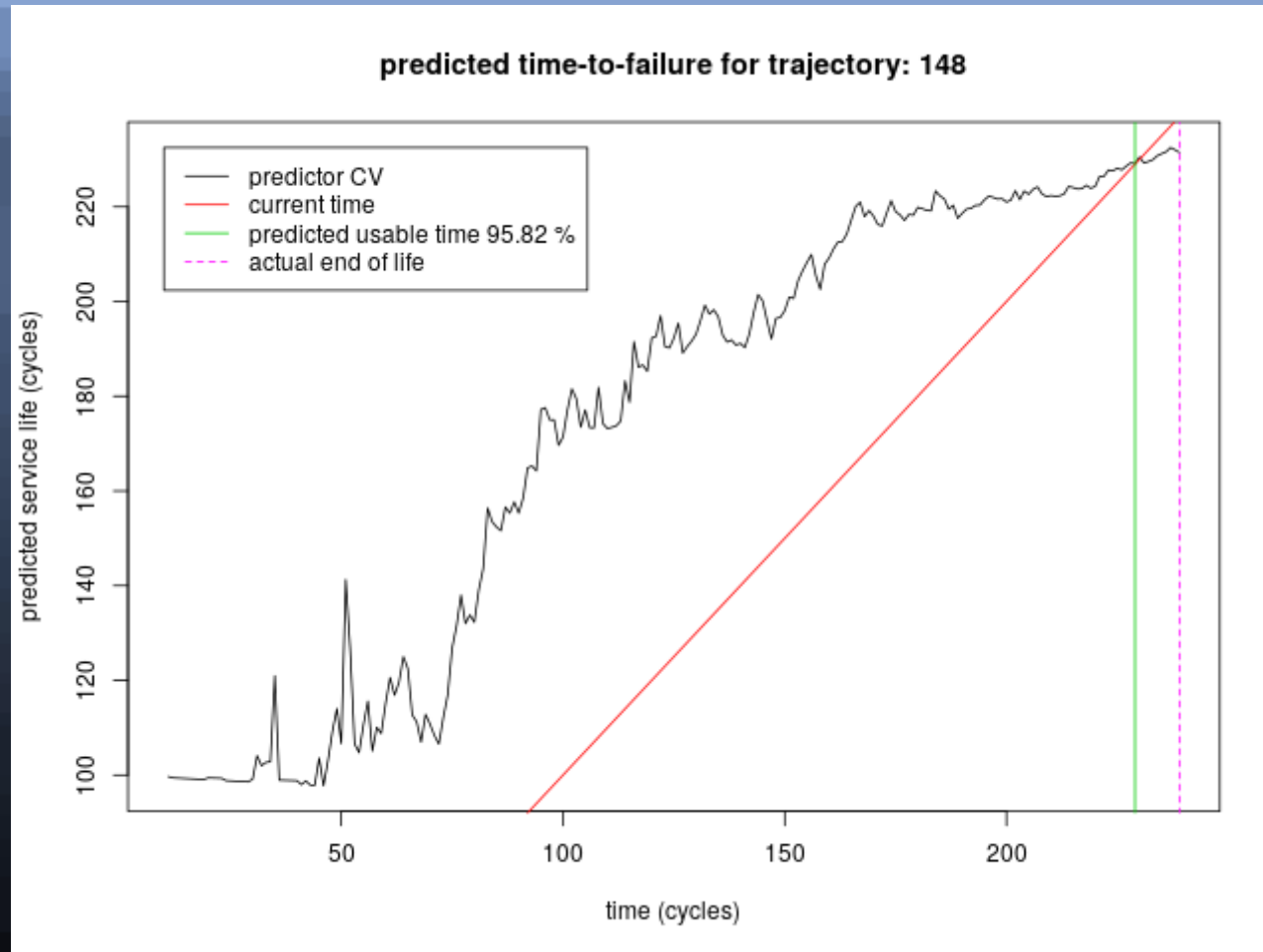
# HPC Life Prediction Examples



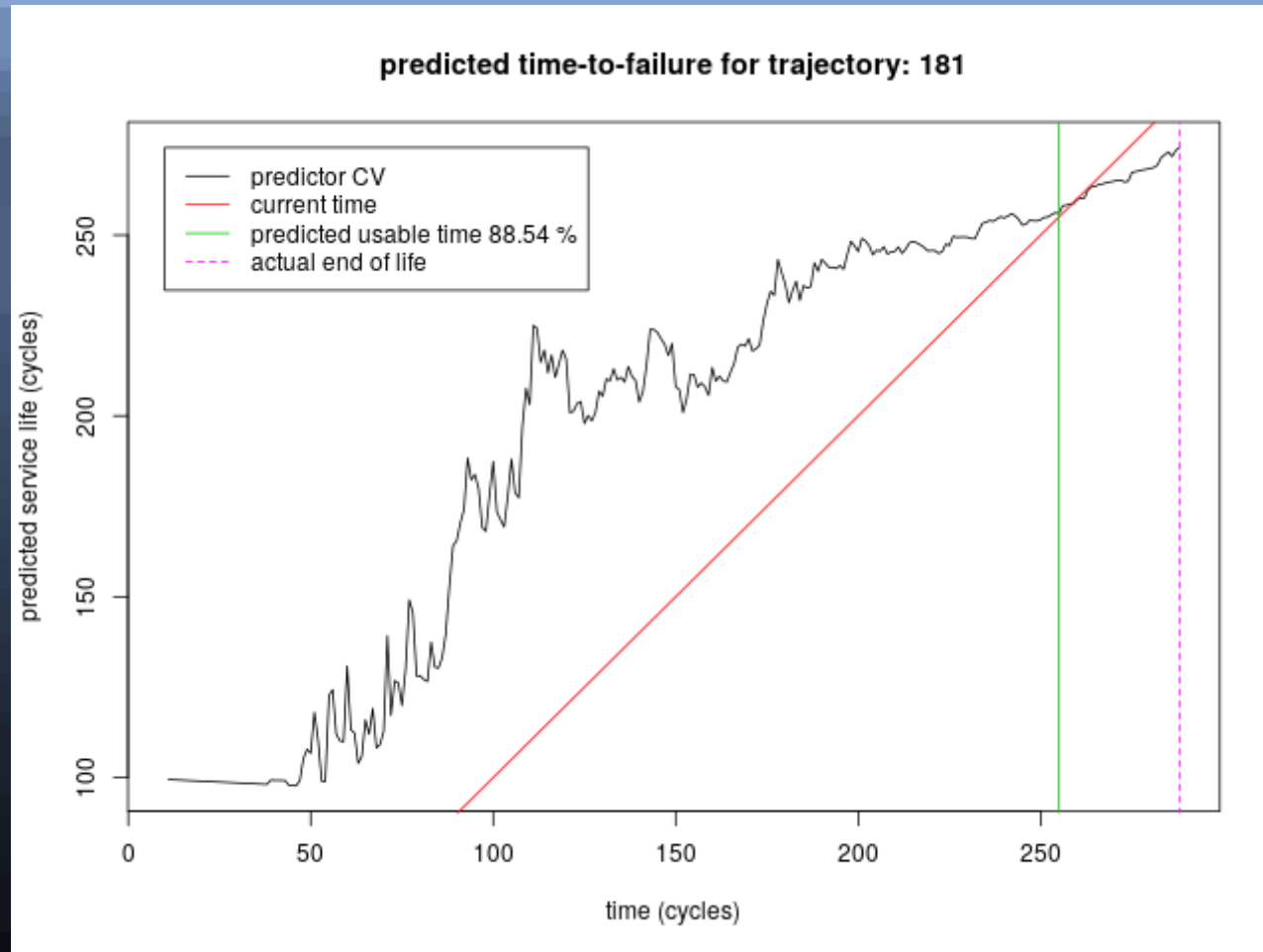
# HPC Life Prediction Examples



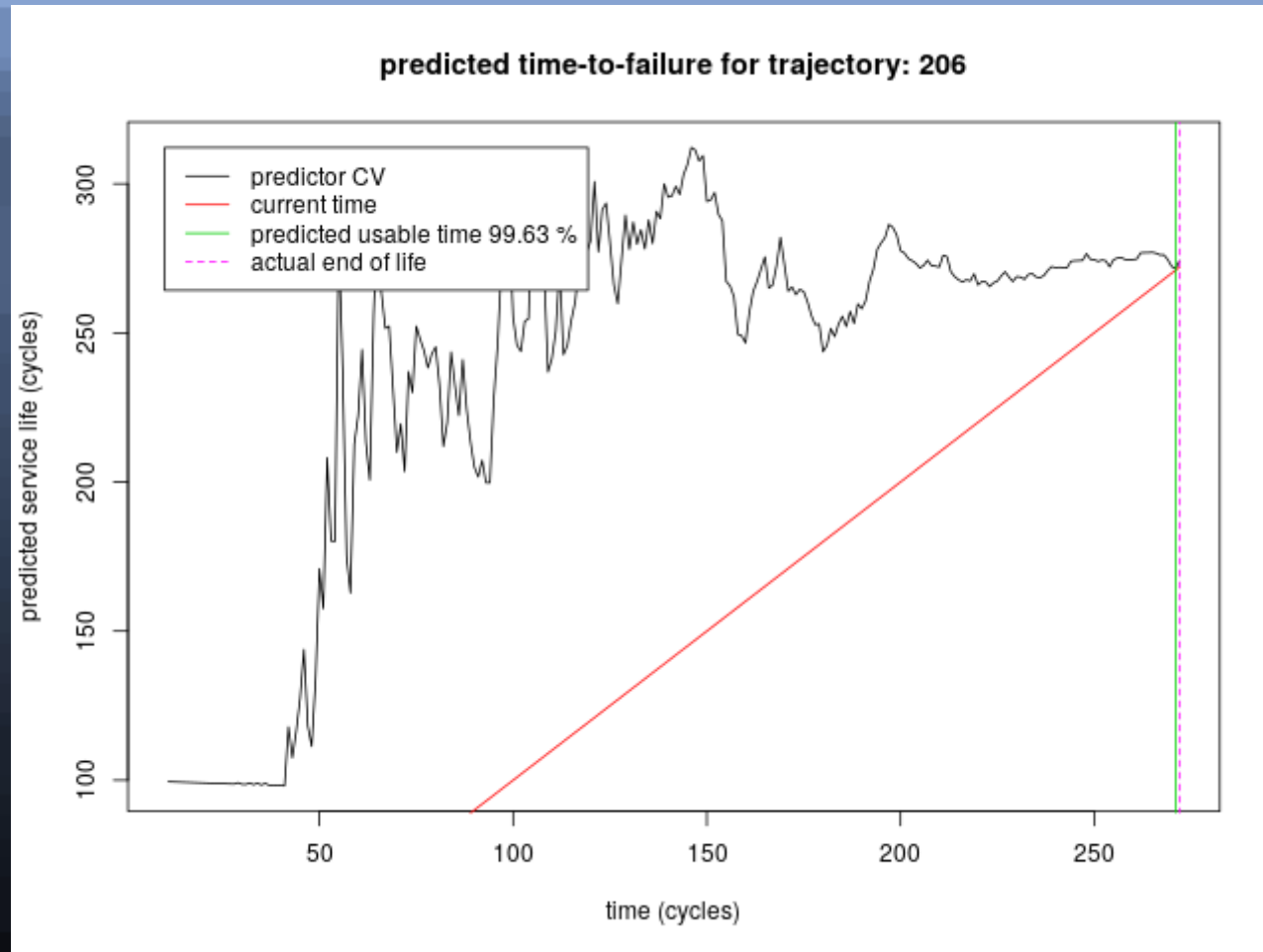
# HPC Life Prediction Examples



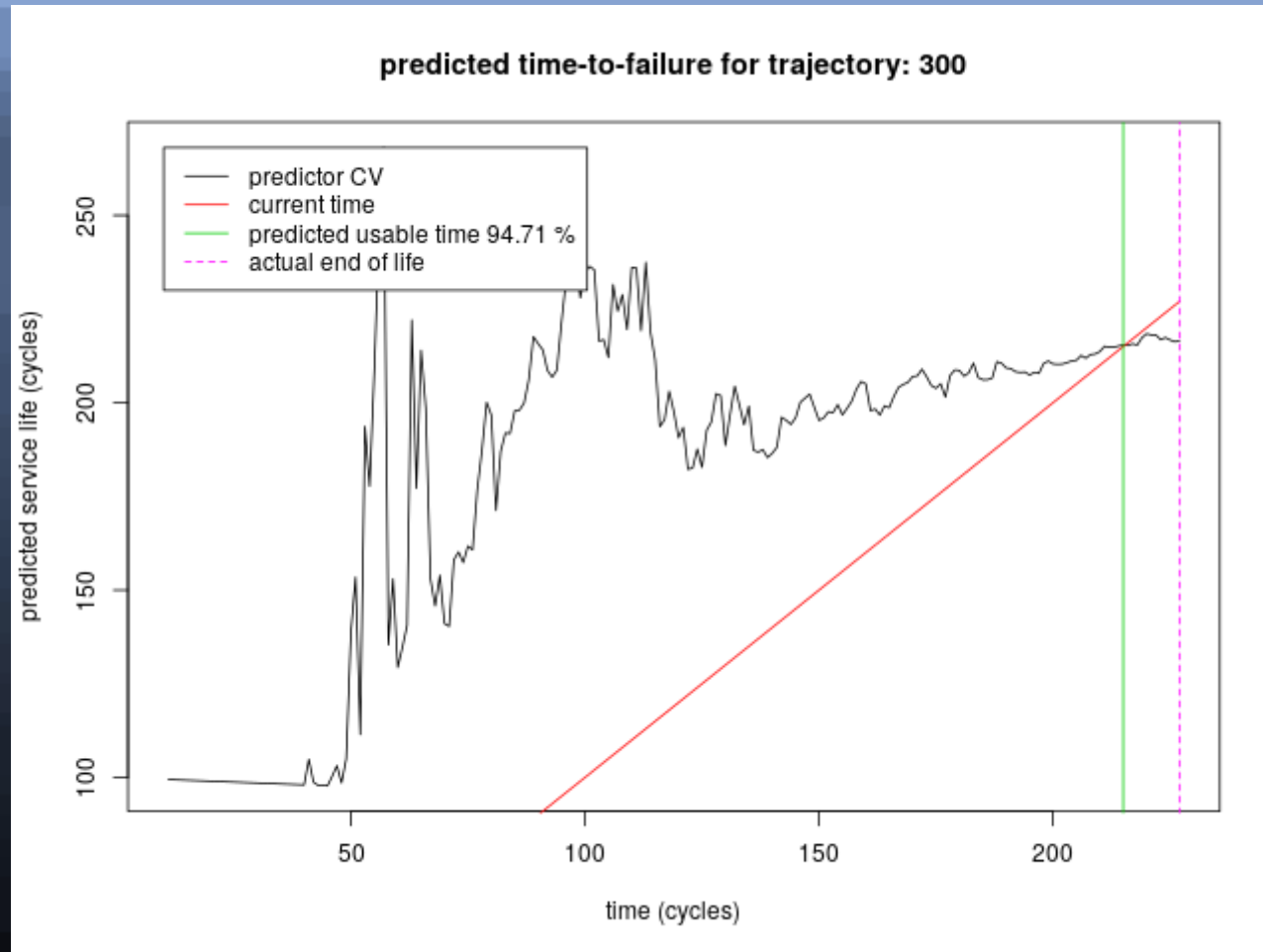
# HPC Life Prediction Examples



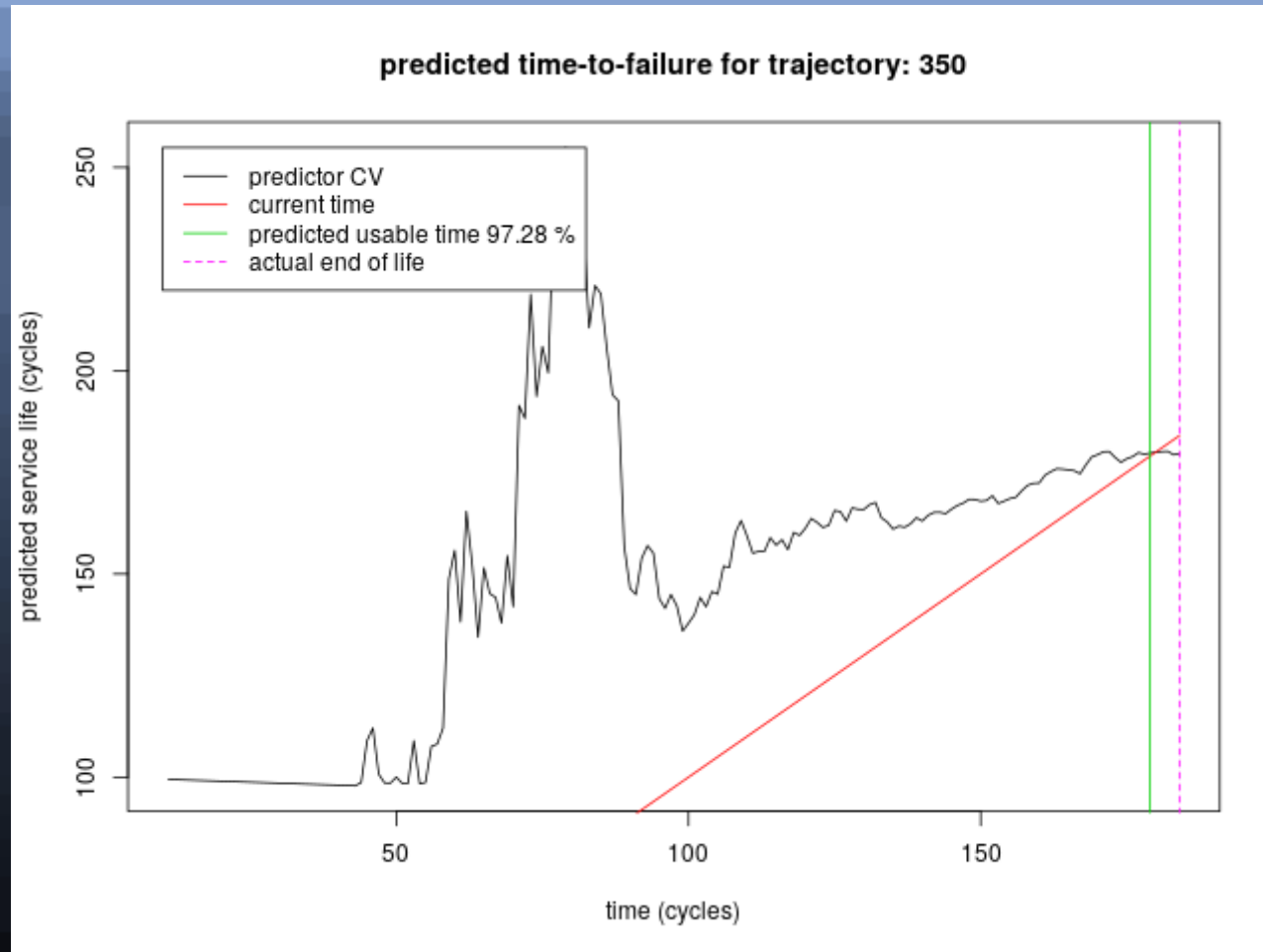
# HPC Life Prediction Examples



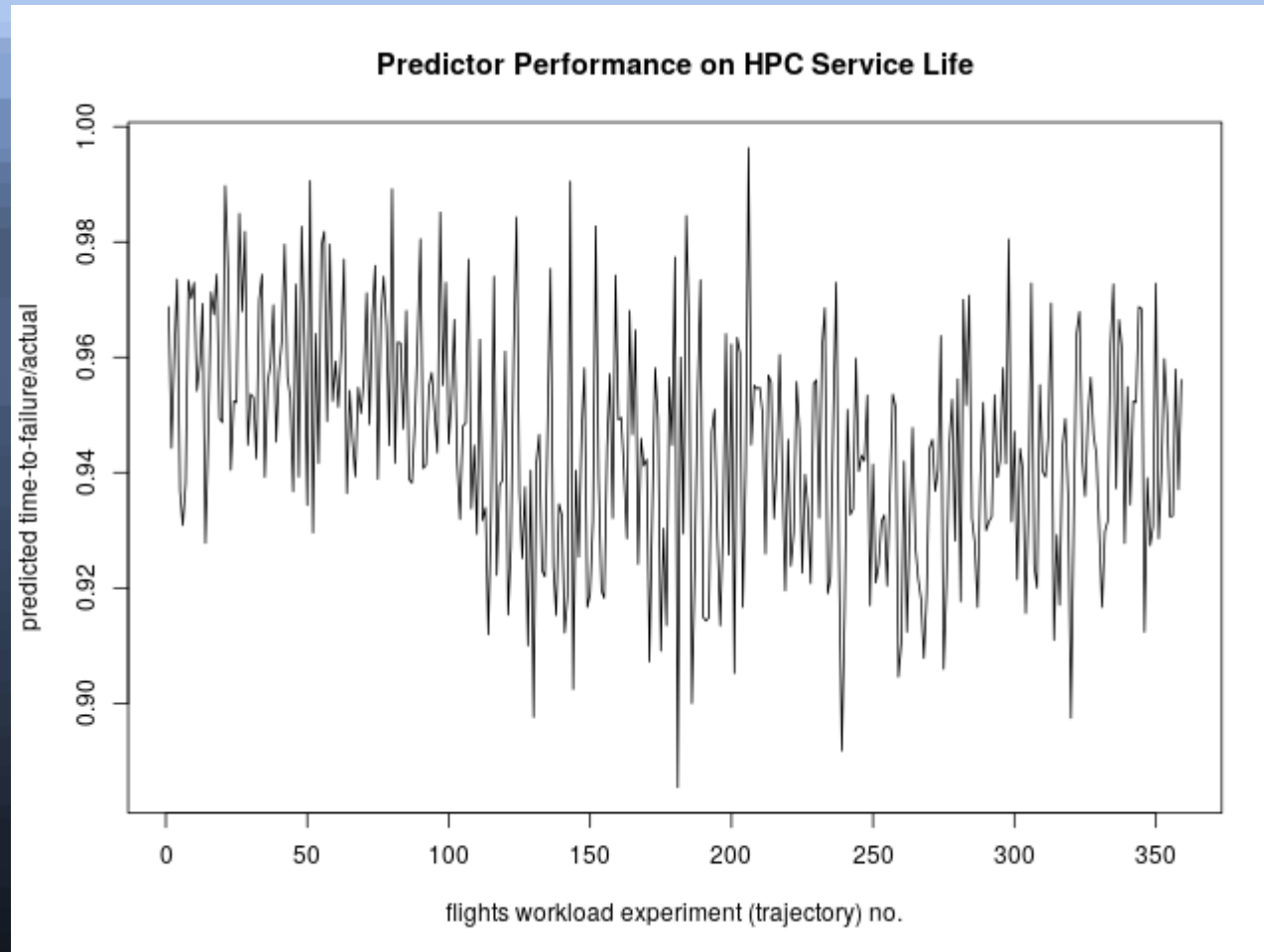
# HPC Life Prediction Examples



# HPC Life Prediction Examples



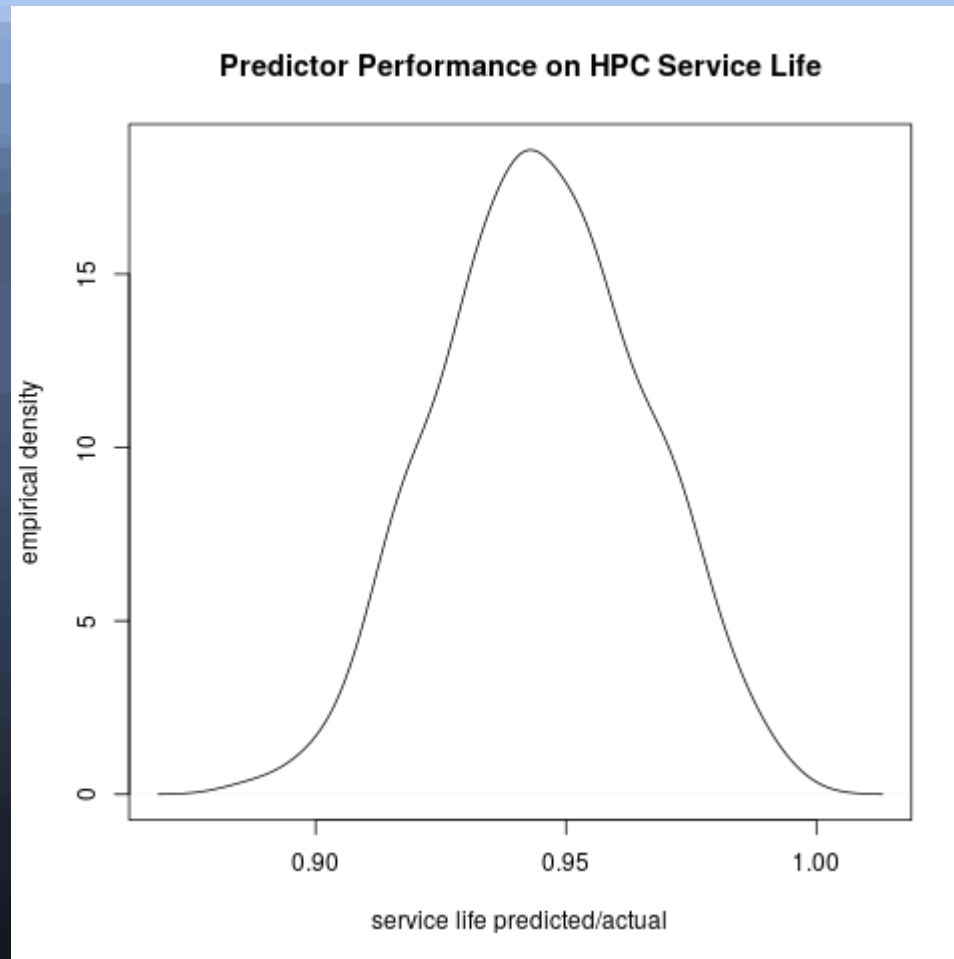
# HPC Life Predictor Performance



10-fold cross-validation results

# HPC Life Predictor Performance

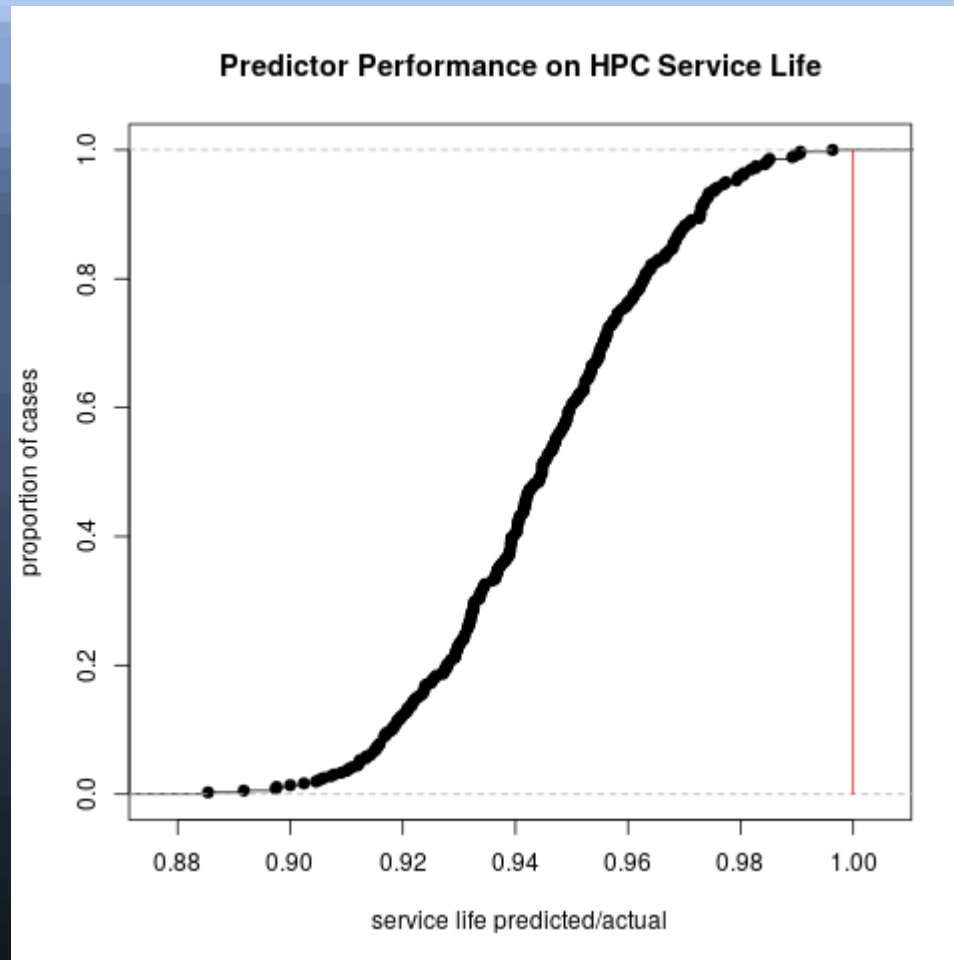
mean= 94.5%  
min = 88.5%  
max = 99.6%



10-fold cross-validation results

# HPC Life Predictor Performance

mean= 94.5%  
min = 88.5%  
max = 99.6%



10-fold cross-validation results

# HPC Life Prediction

## References

Saxena et al[2008]:

Abhinav Saxena, Kai Goebel, Don Simon, Neil Eklund:  
Damage Propagation Modeling for Aircraft Engine Run-to-Failure Simulation

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# Demo: Predictive Analytics

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