MTU Aero Engines

Technische Universität München

Analysis of V2500 Engine Deterioration by Operator

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Overview

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2. Preliminary research
3. Datasets
4. Modeling
5. Discussion of Results
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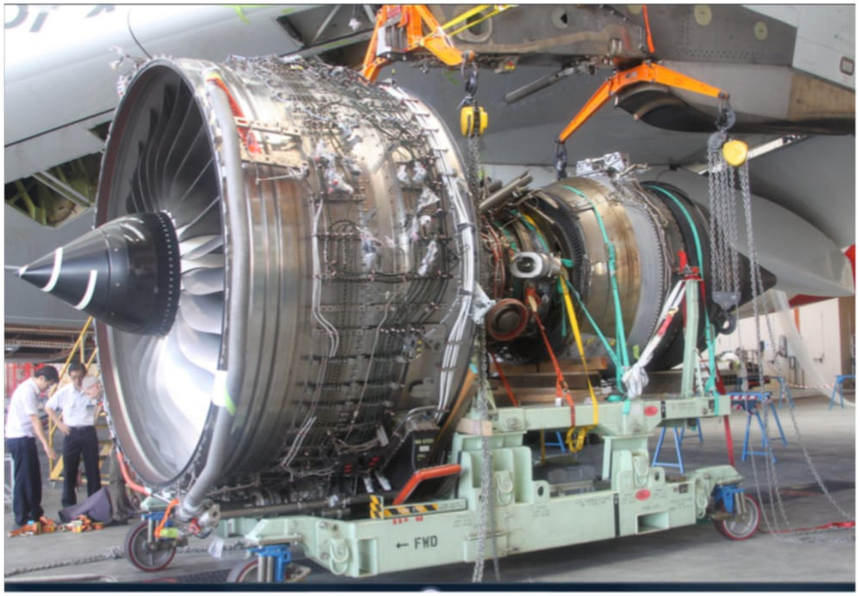

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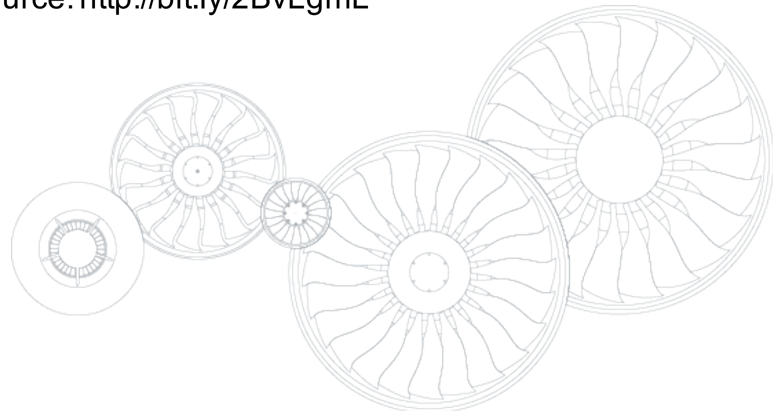

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1. Introduction

Purpose of research

- Better prediction of scrap for airplane components
- Allows sufficient parts to be ready for a shop visit
- Differentiate between operators for cost analysis

Inputs

- Environmental factors
- Flight hours
- Flight cycles

Outputs

- Scrap rates or counts by component

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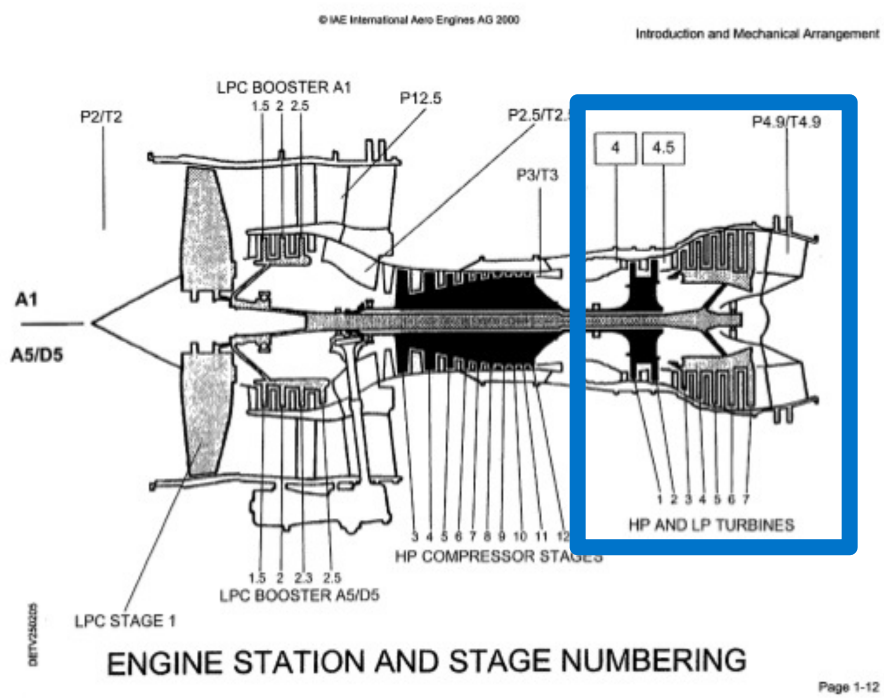
1. Introduction

Terminology and Engine Background



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Airlines are known as **operators**.

Component **sets** of interest

- High Pressure Turbine (HPT)
  - Blades 1 and 2 (HPTB1/2)
  - Vanes 1 and 2 (HPTV1/2)
- Low Pressure Turbine (LPT)
  - Blades 3 through 7 (LPTB3-7)

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2. Preliminary research

- Failure Classification
- Damage Mechanisms
- Flight Segments
- Airport Connection
- Environmental Factors

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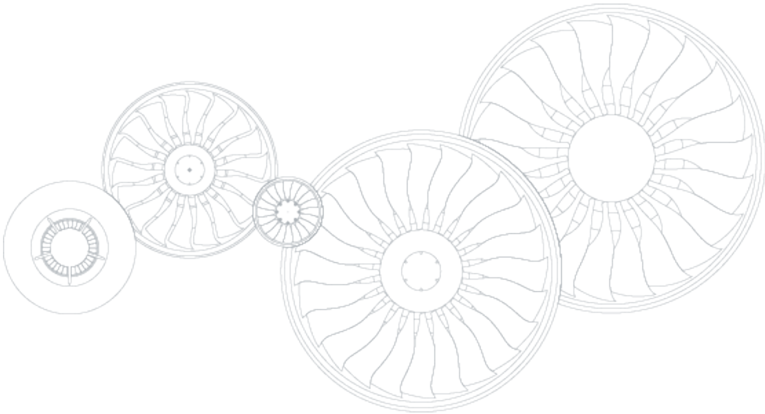

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2. Background Information

Failure Classification

- Serviceable
- Repair
- Scrap

Damage Mechanisms

- Environment-linked (oxidation, corrosion, erosion)
- Non-environment-linked (creep, fretting, abrasion)

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2. Background Information

Flight Segments

- Flight cycle – Gate departure until landing
- Taxiing, take-off, ascent, derate
- Cruise, descent

Airport Connection

- Concentration near airports is practical
- Observations linked through
  - City serviced
  - Latitude and Longitude

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2. Background Information

Environmental Factors

- Temperature
- Particulate matter
  - Measured at 2.5 µm and 10 µm (10^{-6} m)
- SO_2 and other sulphurous oxides
- NO_2 and other nitrous oxides

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3. Datasets

- Shop Visit Results
- Flightradar24
  - Balance Measure
- Engine Trend Monitoring (ETM)
- Environmental Data

Source: http://bit.ly/2GehL8a

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3. Datasets
Shop Visit Results

- Internal maintenance records for 26 operators
- Engine-specific
  - Scrap rates and counts by component
  - Flight hours, cycles and their ratio
  - Operator
- Serialized HPTB1/2
- Missing value problem

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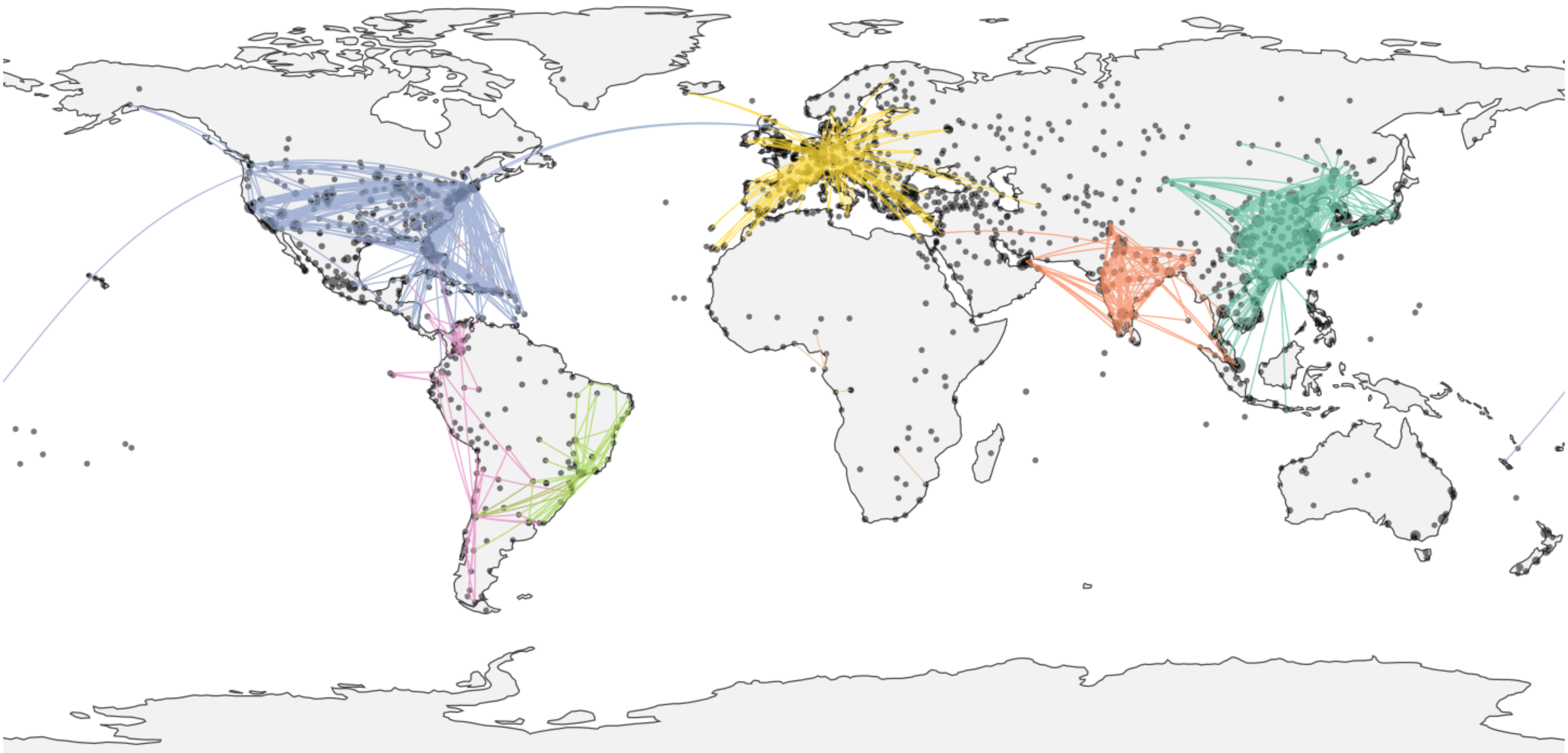
3. Datasets
Flightradar24



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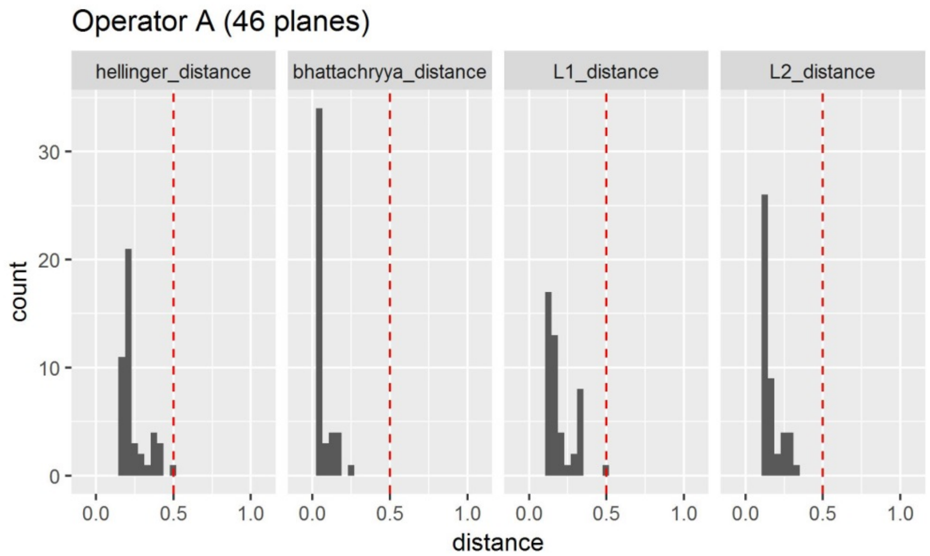
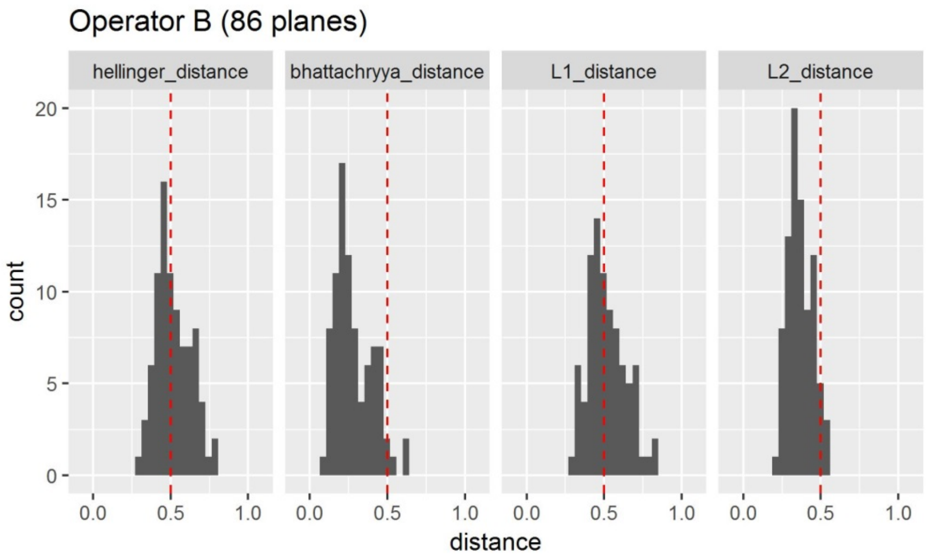
3. Datasets

Flightradar24 – Balance Measure

- Flight distribution
  - by operator
  - by plane
- Distance between distributions
  - 0 implies perfect balance
  - 1 implies perfect disagreement





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3. Datasets

Engine Trend Monitoring

- Operator owning the engine
- Engine readings while in-flight
- Links individual engines to the aircraft they are attached to
- Ultimately could not be used

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3. Datasets
Environment Data

- Connected each of the environmental factors to airports
- Reduced number of airports to 80% of most traveled
- Focus on globally comparable data
- Focus on trusted data sources
- Aggregate on an annual basis

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3. Datasets

Environment Data – Temperature

- Source: Current Weather Results, Weather Base
- Method of measurement: Self-reporting stations globally
- Frequency: Monthly highs and lows
- Units: Degrees Celsius
- Time period: average from 1990 until 2015
- Connection to airports: Match by city name

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3. Datasets

Environment Data – Particulate Matter (PM2.5 & PM10)

- Source: World Bank compilation of government measures
- Method of measurement: Self-reporting stations globally
- Frequency: Varies, aggregated to annual
- Units: Micrograms per cubic metre (µg / m^3)
- Time period: Between 2012 and 2015, depending on country
- Connection to airports: Match by city name
- Supplemental data: WHO Satellite readings

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3. Datasets

Environment Data – SO_2

- Source: Socioeconomic Data and Applications Center
- Method of measurement: Estimations of anthropogenic emissions
- Frequency: Annual
- Units: kg / person
- Time period: 2005
- Connection to airports: By country

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3. Datasets

Environment Data – NO_2

- Source: Tropospheric Emission Monitoring Internet Service (ESA)
- Method of measurement: Satellite observation, slant method
- Frequency: Monthly averages aggregated annually
- Units: 10^{15} molecules per cm^2
- Time period: December 2016 to November 2017
- Connection to airports: By latitude and longitude

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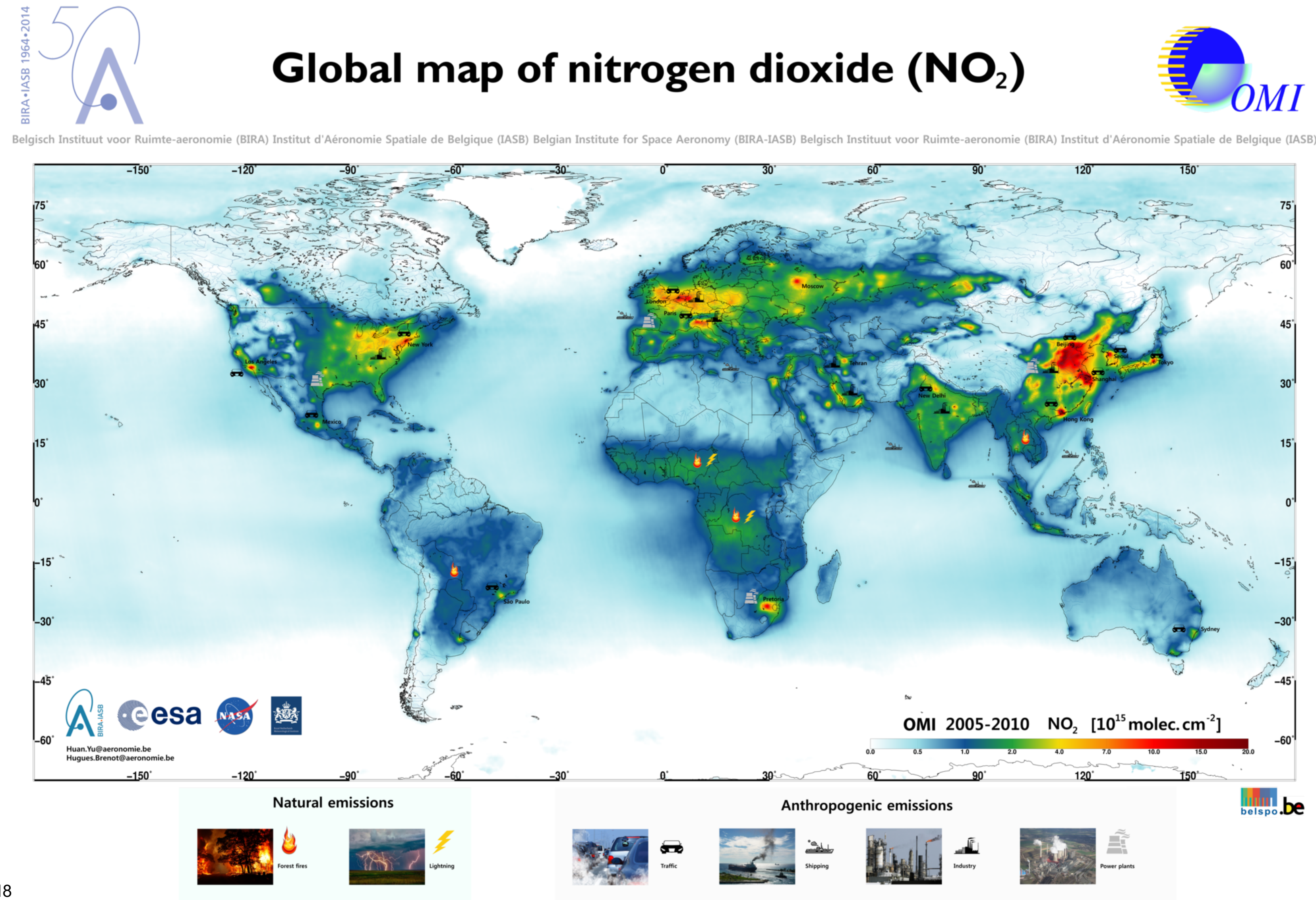
3. Datasets



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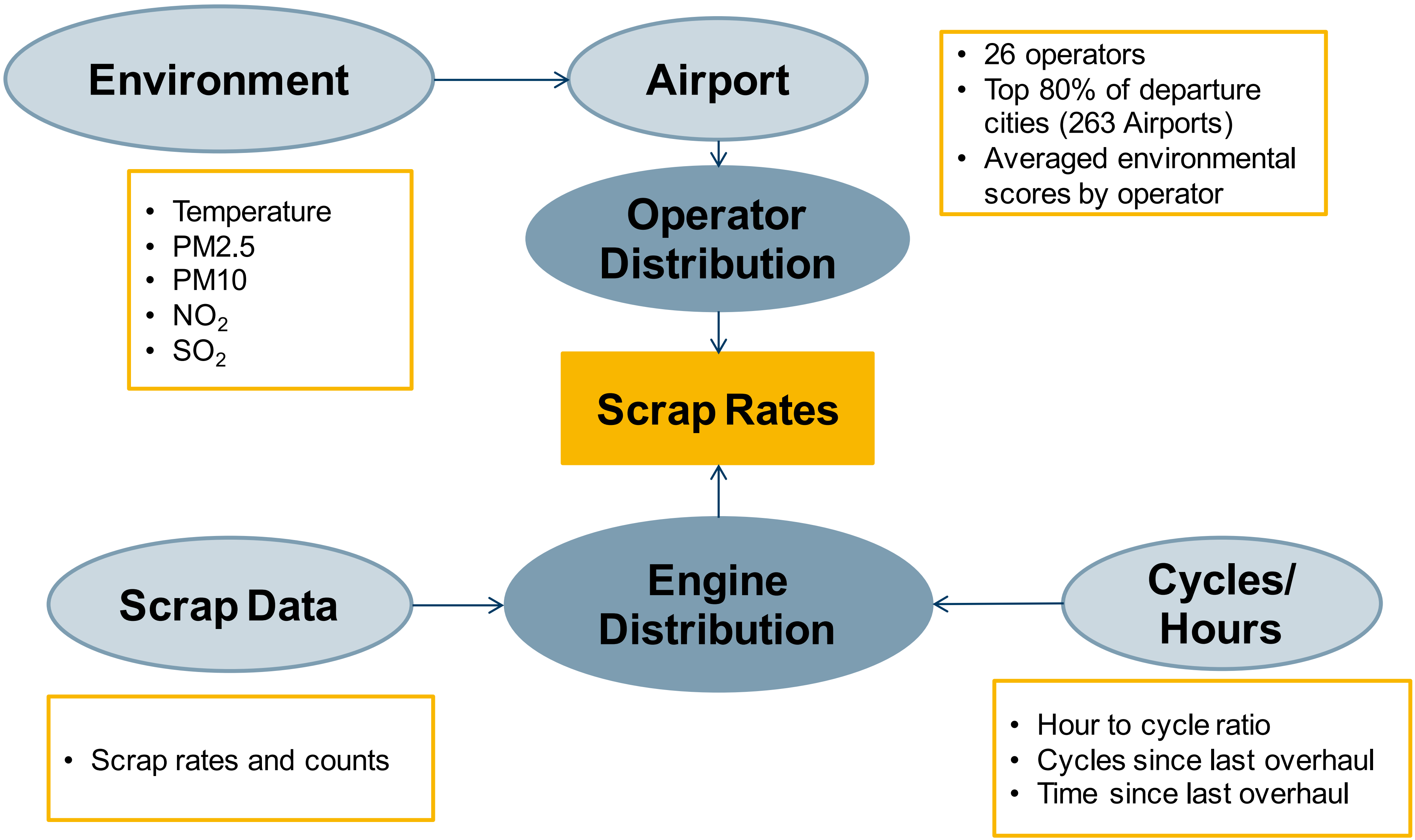
3. Datasets

Goal Overview



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4. Modeling

- Fleet Approach
- Single Engine Approach
  - Scrap Rate Modeling
  - Scrap Count Modeling

Source: http://bit.ly/2iXufbo

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4. Modeling

Fleet Approach

Volume of dataset

- Each operator was a data point, ranging from 17 to 25 data points

Features

- Averaged hours and cycles flown of whole operator’s fleet
- Environmental scores of operator

Predicted Values

- Average scrap rate of operator

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4. Modeling

Fleet Approach

- Minor manual feature selection due to very high correlations

VCSN – cycles since new

VCSO1 – cycles since last overhaul

VTSN – times since new

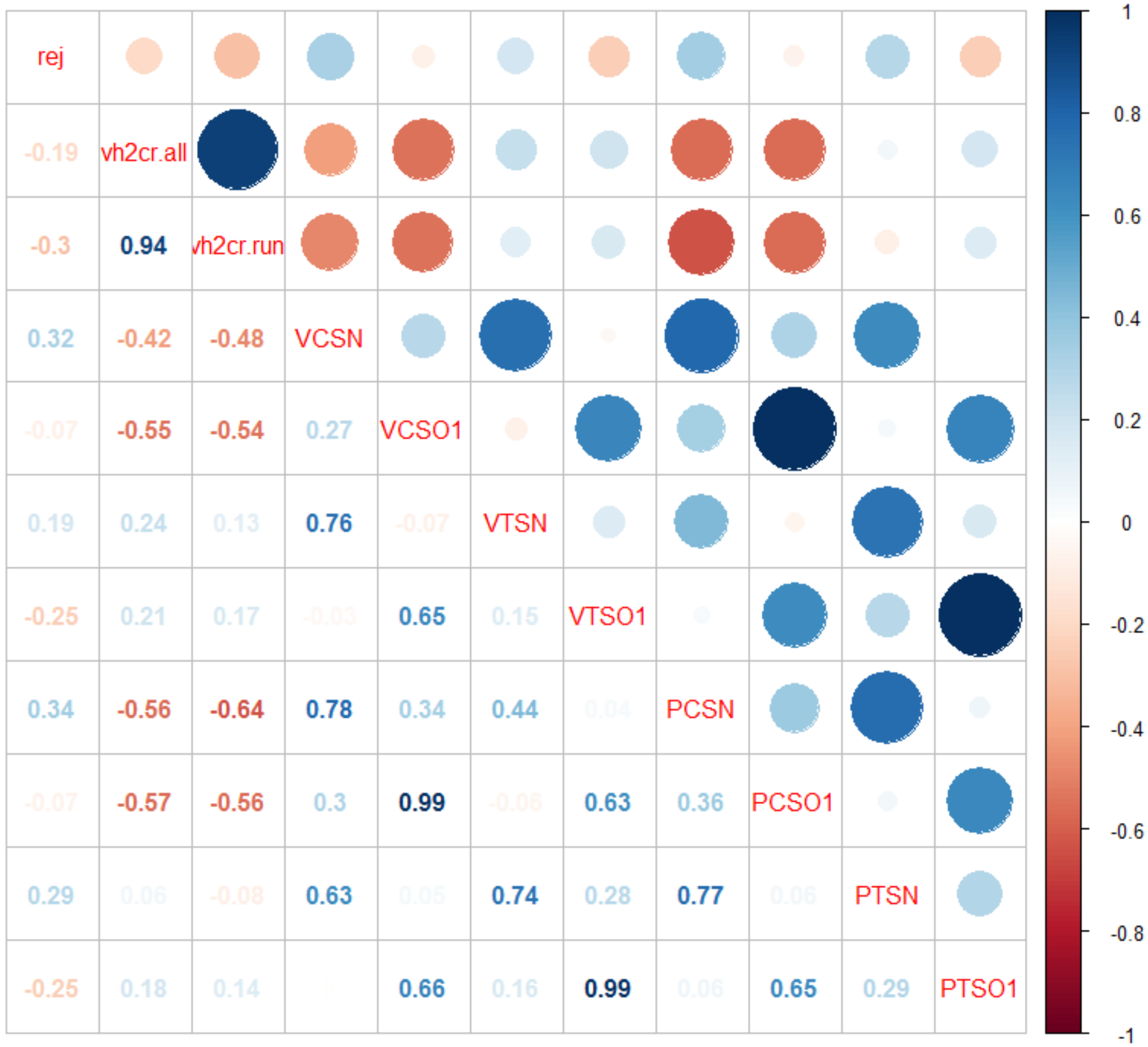
VTSO1 – times since last overhaul

vh2cr.all – hours to cycles ratio

vh2cr.run – hours to cycles ratio since last overhaul

V* – engine

P* – part



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4. Modeling
Fleet Approach

- Omitting 100% scrap rates in average calculation
- Simple linear regression used due to limited number of data points
- AIC (Akaike Information Criterion) was used for feature selection
- Model performance measured with leave one out cross validation (LOOCV)

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4. Modeling

Single Engine Approach

Volume of dataset

- Individual engines were data points, ranging from 300 to 900 data points

Features

- Hours and cycles flown by engine
- Environmental score for engine by operator not unique
- Interaction between environment and flight cycles

Predicted Values

- Scrap rate of single engine
- Scrap count of single engine

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4. Modeling
Scrap rate modeling

Binomial Regression

- Logit and C-Log-Log links used
- Fits for the scrap rates

Regression Trees

- Pruning in order to minimize cross-validated error

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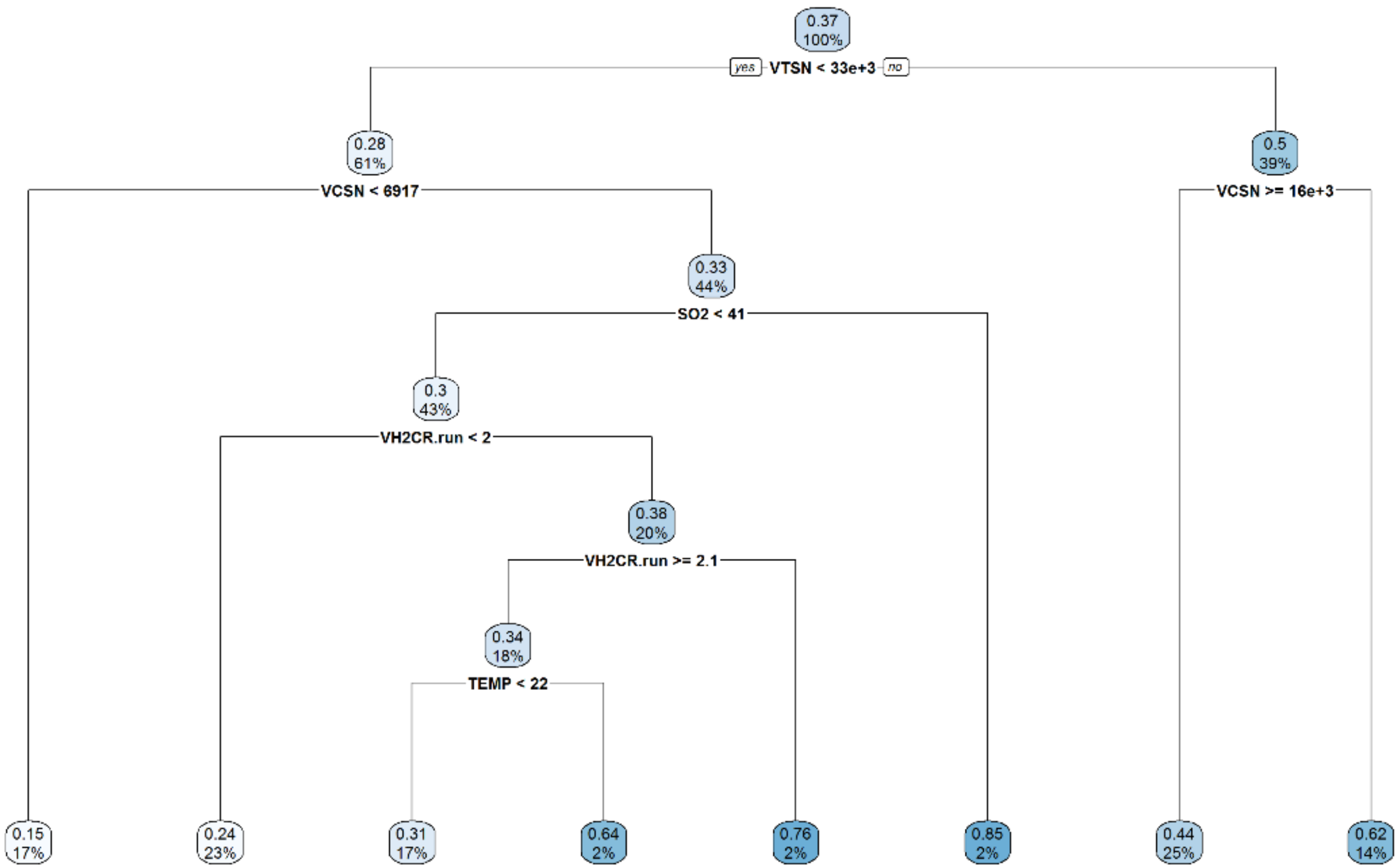
4. Modeling

Example Regression Tree (HPTB2)



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4. Modeling

Scrap Count Modeling

Poisson Regression

- Extension to counting distributions to check predictions for scrap counts
- Each component set has differing numbers of blades and vanes

Negative Binomial Regression

- Relaxes restriction on mean and variance from Poisson distribution

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5. Discussion of Results

- Environmental Factors
- Fleet Approach
- Single Engine Approach
  - Scrap Rate Modeling
  - Scrap Count Modeling

Source: http://bit.ly/2Bt27H2

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5. Discussion of Results
Environment Data

	TEMP	PM2.5	PM10	NO2	SO2
Min.	9.6	8.3	12.4	11.8	6.2
1st Qu.	15.9	14.9	23.3	16.7	20.0
Median	18.4	23.3	31.0	38.7	24.9
3rd Qu.	21.8	45.3	70.3	63.7	38.5
Max.	27.5	82.2	128.4	182.2	58.2
Range	17.8	73.9	116.0	170.3	52.0
Mean	18.8	32.2	49.7	48.4	27.4

- Each factor has a different range
- Normalization would impact interpretation
- Direct connections can be drawn

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5. Discussion of Results

Fleet Approach

- Different stages have different factors affecting damage mechanisms
- Limited number of data points

	High Pressure Turbine				Low Pressure Turbine				
Feature	**Blade 1**	**Blade 2**	**Vane 1**	**Vane 2**	**Blade 3**	**Blade 4**	**Blade 5**	**Blade 6**	**Blade 7**
VCSN	✓				✓		✓	✓	✓
vh2cr.all					✓		✓		
VTSN		✓	✓	✓	✓				
VCSO1									
PM2.5	✓	✓						✓	✓
PM10			✓	✓				✓	✓
SO2				✓			✓		✓
NO2				✓					
TEMP						✓	✓		✓

	statistically significant
✓	feature selected

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5. Discussion of Results
Fleet Approach

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5. Discussion of Results

Single Engine Approach – Overview

Model Type \ Part	High Pressure Turbine				Low Pressure Turbine				
	HPTB1	HPTB2	HPTV1	HPTV2	LPTB3	LPTB4	LPTB5	LPTB6	LPTB7
Binomial	351.60	358.49	23.86	36.08	310.89	371.05	41.53	5.07	18.49
Poisson	299.22	534.54	19.16	17.72	498.02	386.51	176706.59	4.73	53.27
Negative Binomial	290.32	1637.92	44.85	16.92	578.16	388.86	125.83	6.62	216.80
Regression Tree	430.77	372.30	71.16	14.13	540.52	769.34	283.61	295.75	207.00

- Mean Squared Error (MSE) of count prediction for 15-fold cross-validation
- Different model types perform better for different components
- Certain parts had consistently low scrap rates
- Use MSE only within a component, not between components

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5. Discussion of Results

Single Engine Approach – HPT Models

Negative Binomial

HPTB1	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	7.599	5.25E-01	14.462	< 2e-16
TEMP	-0.182	1.98E-02	-9.200	< 2e-16
NO2	-0.033	6.85E-03	-4.827	1.4E-06
PM2.5	9.91E-04	8.77E-03	0.113	0.910
SO2	-0.026	7.68E-03	-3.394	0.001
VCSN	-3.59E-04	3.00E-05	-11.937	< 2e-16
VTSN	2.18E-05	3.81E-06	5.740	0.000
VH2CR_Total	-0.109	5.98E-02	-1.819	0.069
NO2:PM2.5	6.87E-04	2.31E-04	2.968	0.003
TEMP:VCSN	1.33E-05	1.15E-06	11.607	< 2e-16
NO2:VCSN	2.48E-06	4.05E-07	6.125	0.000
PM2.5:VCSN	8.48E-07	5.34E-07	1.588	0.112
SO2:VCSN	1.30E-06	4.65E-07	2.792	0.005
NO2:PM2.5:VCSN	-5.01E-08	1.35E-08	-3.710	0.000
Theta estimated at 1.418				

Binomial

HPTB2	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-3.448	4.323	-0.8	0.4251
PM2.5	0.021	0.022	0.936	0.3492
SO2	-0.098	0.129	-0.76	0.4476
VCSN	-1.60E-04	1.83E-04	-0.87	0.3830
SO2:VCSN	9.91E-06	5.79E-06	1.713	0.0866

Negative Binomial

HPTV2	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-8.698	1.07E+00	-8.12	0.000
NO2	0.020	4.05E-03	4.94	0.000
TEMP	0.204	4.66E-02	4.389	0.000
VCSN	3.54E-05	1.96E-05	1.802	0.072
VTSN	1.10E-04	1.23E-05	8.986	< 2e-16
Theta estimated at 0.3579				

Poisson

HPTV1	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-3.384	5.43E+00	-0.623	0.533
NO2	0.008	3.88E-03	2.056	0.040
PM2.5	-0.030	1.16E-02	-2.562	0.010
PM10	-0.480	9.11E-02	-5.266	0.000
SO2	-0.437	1.92E-01	-2.272	0.023
TEMP	0.534	2.59E-01	2.064	0.039
VCSN	-1.99E-04	3.10E-04	-0.641	0.521
VH2CR_Total	0.528	1.07E-01	4.941	0.000
PM10:SO2	0.023	3.14E-03	7.238	0.000
PM10:TEMP	0.013	3.32E-03	3.802	0.000
SO2:TEMP	0.011	1.05E-02	1.041	0.298
NO2:VCSN	4.32E-07	1.91E-07	2.257	0.024
PM10:VCSN	2.94E-05	7.42E-06	3.966	0.000
SO2:VCSN	2.80E-05	1.03E-05	2.708	0.007
TEMP:VCSN	-1.45E-05	1.46E-05	-0.998	0.318
PM10:SO2:TEMP	-7.77E-04	1.14E-04	-6.798	0.000
PM10:SO2:VCSN	-1.31E-06	2.78E-07	-4.703	0.000
PM10:TEMP:VCSN	-7.69E-07	2.60E-07	-2.953	0.003
SO2:TEMP:VCSN	-7.63E-07	5.47E-07	-1.394	0.163
PM10:SO2:TEMP:VCSN	4.57E-08	1.03E-08	4.443	0.000

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5. Discussion of Results

Single Engine Approach – Regression HPT

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5. Discussion of Results

Single Engine Approach – LPT Models

Binomial

LPTB3 cloglog	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-6.455	2.230	-2.894	0.0038
NO2	-0.043	0.042	-1.014	0.3108
VCSN	9.12E-05	6.88E-05	1.326	0.185
VH2CR_Total	0.982	0.466	2.107	0.0351
NO2:VCSN	2.81E-06	1.97E-06	1.431	0.1525

Binomial

LPTB4 cloglog	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-2.18847	0.324	-6.747	1.51E-11
PM10	0.0108	0.007	1.552	0.121

Binomial

LPTB5 logit	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-1.022	2.731	-0.374	0.7083
PM10	0.037	0.018	2.04	0.0414
SO2	-0.114	0.065	-1.764	0.0777
VCSN	-4.54E-04	2.24E-04	-2.026	0.0428
VTSN	1.72E-04	9.70E-05	1.776	0.0758

Poisson

LPTB6	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	2.799	1.62E+00	1.732	0.083
PM10	-0.146	4.35E-02	-3.348	0.001
PM2.5	0.302	7.72E-02	3.908	0.000
SO2	-0.096	2.09E-02	-4.595	0.000
NO2	-0.113	2.67E-02	-4.224	0.000
TEMP	-0.177	6.45E-02	-2.738	0.006
VCSN	1.40E-04	4.04E-05	3.472	0.001
VH2CR_Total	0.595	2.04E-01	2.919	0.004
PM2.5:SO2	0.002	5.14E-04	3.579	0.000
NO2:TEMP	6.84E-03	1.59E-03	4.303	0.000
PM10:VCSN	1.16E-05	2.99E-06	3.88	0.000
PM2.5:VCSN	-2.77E-05	5.77E-06	-4.79	0.000

Binomial

LPTB7 cloglog	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-8.0076	2.773	-2.887	0.00389
PM10	0.0220	0.013	1.709	0.08753
VH2CR_Total	1.4564	1.091	1.335	0.18186

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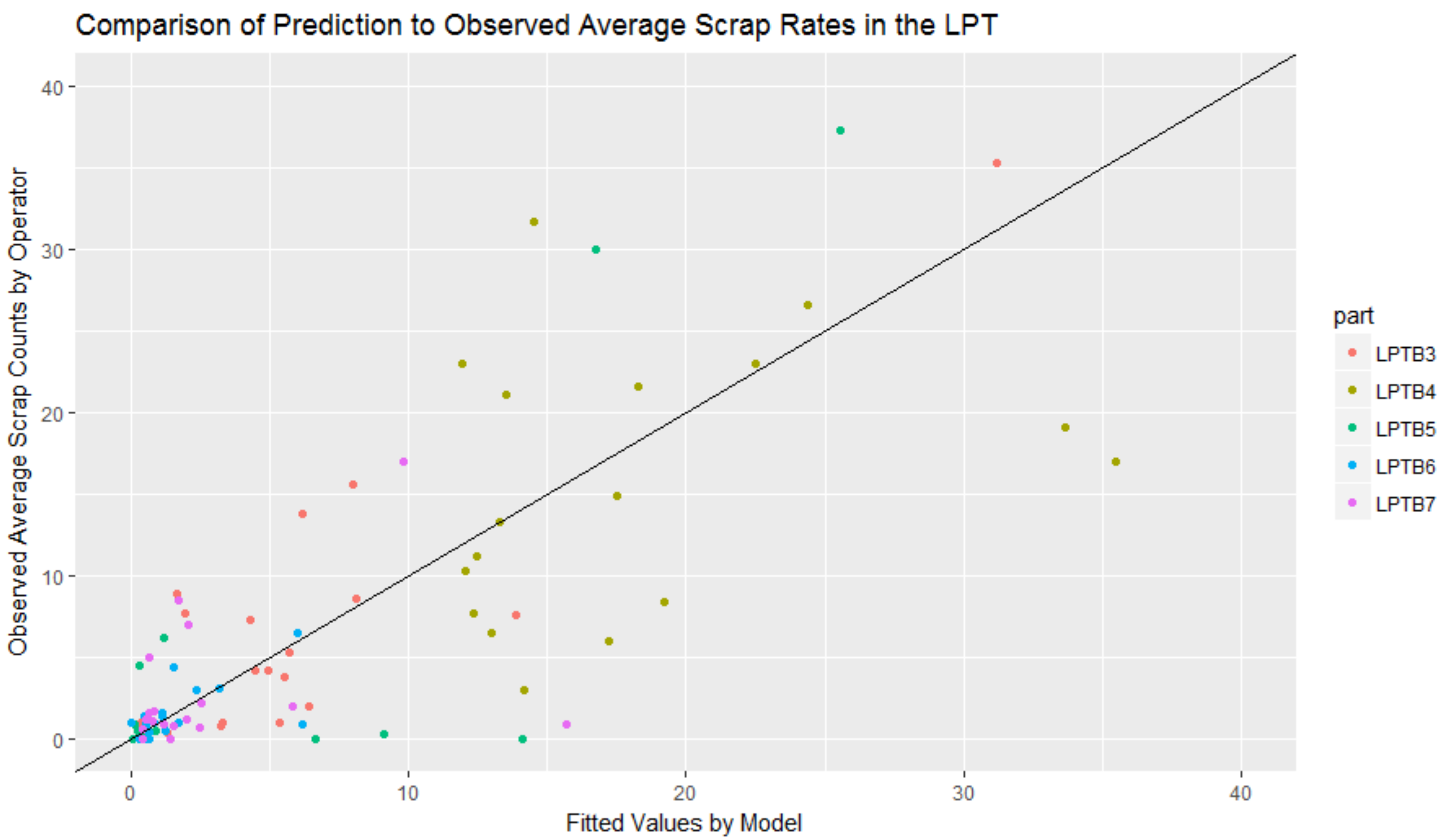
5. Discussion of Results

Single Engine Approach – Regression LPT



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5. Discussion of Results

Single Engine Approach – Decision Trees

- VTSN and VCSN were considered the most important features
- Occasionally trees were almost entirely pruned
- Lack of stability

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5. Discussion of Results

Model Assessment

Fleet Approach

- ✓ Simple, interpretable model
- – Few data points
- – Does not take into account fleet size

Single Engine Approach

- ✓ Increased the number of data points
- ✓ Uses individual engine measures
- – Environmental scores by operator

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6. Recommendations

- New Data Connections
- New Data Sources

Source: http://bit.ly/2EtDYmk

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6. Recommendations

New Data Connections

- **ETM** datasets from more operators
- Incorporating a **derate** factor in modeling
- **Temporal consistency** across datasets
- Standarization of **removal reason** of engine

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6. Recommendations

New Data Sources

- More **recent** environmental data with better **granularity**
- **Policy-specific** knowledge of MTU customers
- Include new features:
  - airport size
  - altitude of airport

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Future Outlook

Environment

- Temperature
- PM2.5
- PM10
- NO_2
- SO_2 accuracy
- Environmental agency data
- Exact location matching

Airport

- 26 operators
- Top 80% of departure cities (263 Airports)
- Airport size, number of passengers
- More operators
- ETM data to match exact engine path

Operator Distribution

Operator Characteristics

- Customer specific policies regarding scrap rates
- Budget classification
- Derate calculation

Scrap Rates

Scrap Data

- Scrap Rate and Scrap Count
- Removal reason standardization
- ‘Repair Scrap’ vs ‘Scrap’

Engine Distribution

Cycles/ Hours

- Hour to cycle ratio
- Time since last overhaul
- Cycles since last overhaul

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