Lateral Buckling VAS Model

Prediction by Surrogate Modelling

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Why Surrogate Models?

Engineering Simulations are slow and fragmented, and learnings are lost.

Phase	Category	Challenges	Solutions Using Surrogate Models
Projects	**Time & Resource Constraints**	• Simulations take months to run • Limited ability to iterate quickly • High computational and human effort required • **Bids are lost because we cannot meet schedule**	• Surrogates deliver fast predictions • Support rapid iteration and design validation • Reduce compute and labour overhead • **Completing project ahead of schedule is incentivised**
	Large Design Space & Manual Optimisation	• Too many cases and parameter combinations • Manual optimisation • Time-consuming sensitivity studies • Solver convergence issues	• Use DoE and surrogate models to reduce needed simulations • Enable automated, global optimisation • Instant parametric/sensitivity analysis
	Knowledge Loss	• Engineers rework from scratch for each project • No reuse of past simulation results	• Develop reusable surrogate models from historical data • Enable cross-project learning and adaptation • Run additional simulations off-critical path for model training
Early Stage (Pricing)	**Time & Resource Constraints**	• No time for detailed simulations • Fast cost and solution estimates needed • Reliance on engineering judgment, not data • **Risk of inaccurate early-stage cost predictions**	• Use surrogates for instant predictions based on previously trained models • Support early-stage design without compromising on insight • **Enable reliable and consistent, data-driven predictions**
	Subjectivity & Lack of Analytics	• No structured comparison of options • Decisions made without traceable analytics • No way to quantify risk of design or cost estimates	• Support dashboard-driven FEED analysis • Provide visual insights for trade-off and what-if studies • Use surrogate models with uncertainty quantification (e.g., GP) - Inform prediction bounds and confidence intervals

The inability to reuse knowledge, the reliance on manual processes, and the absence of fast, data-driven predictions expose the company to **delays, cost overruns, and lost bids**.

Lateral Buckling Analysis

Predict pipeline behaviour on the seabed

Analysis Goal

Do we need any external mitigations? If yes, how many and where?

How?

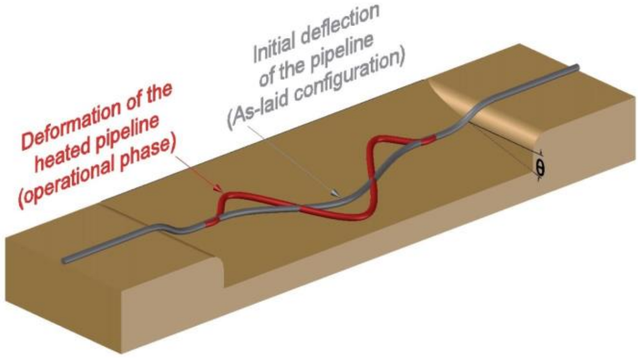
Predict pipeline behaviour through FEA. We check for:

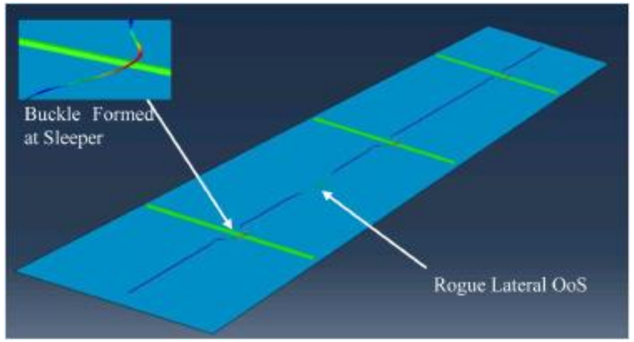
1. Pipeline buckle probability: Is it going to buckle (controlled)?
2. Pipeline Stress (Is it going to break?)
3. Post buckle amplitude (How long the sleeper need to be?)
4. End Loads (Is it safe for the connected structures?)
5. …

Optimisation Criteria

Cost: Lowest number of mitigations (Each mitigation = 2 to 4 million)

Achieved by: Running large case matrix of cases and select least number mitigation configuration that does not break the pipeline.





Analytical Equations?

- Analytical Equations for Lateral Buckling response.
- These equations can be used to estimate buckle mitigations solutions without doing FEA.
- Required Abaqus cases (4.2 million)
  - Single sleeper
  - Full factorial approach
  - 3 cases per variable
- Uncertain efficiency of equations.
  - Non-linearity may not be sufficiently captured
  - More simulations may be required to improve equations.
  - Difficult to ascertain which cases to run to improve equation's reliability.

Time Consuming | Low Reliability (?)

Input	Range	Output
Pipe OD	[6” – 14”]	Buckle Initiation Force
Pipe WT	[0.375” – 1.5”]	Post Buckle EAF
External coating	[0” – 3”]	Max Longitudinal Stress
Temperature	[0 - 350°F]	Max Longitudinal Strain
Pressure	[4 – 15ksi]	Buckle Amplitude
Axial pipe/soil friction	[0.2 – 0.8]	Axial Stress Range
Lateral pipe/soil friction	[0.5 – 1.3]	
Sleeper height	[2 – 4ft]	
Sleeper friction	[0.05 – 0.6]	
Contents Density	[20 – 65 pcf]	
Mode shapes	2 Modes	
…		

Proposed Solution

Machine Learning Based Prediction

Low Data Requirement:

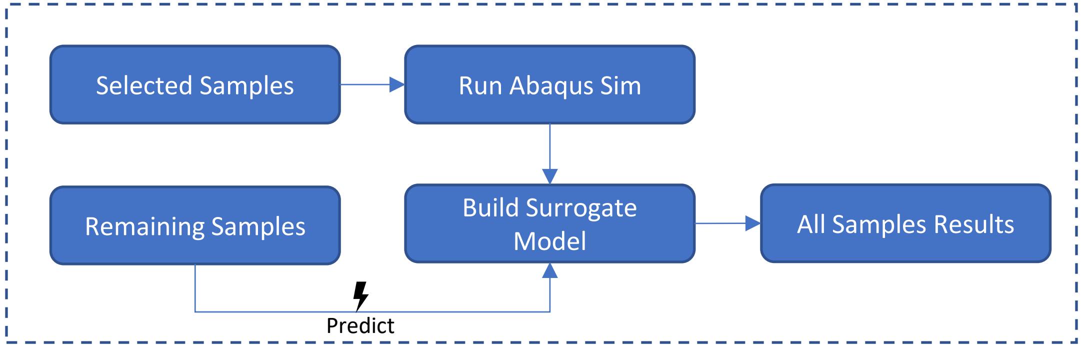
- Identifies data points that exhibit non-linearity.
- Informative data points.
- Better mapping of input-output space.

Mapping Complex Relationships

- Automatic learning (Input – output relationship)
- Wide range of off the shelf algorithms available.
- Predictions are quick and can be integrated with Excel/Mathcad based tools.

Faster Development | High Reliability

Workflow



Input	Range	Output
Pipe OD	[6” – 14”]	Buckle Initiation Force
Pipe WT	[0.375” – 1.5”]	Post Buckle EAF
External coating	[0” – 3”]	Max Longitudinal Stress
Temperature	[0 - 350°F]	Max Longitudinal Strain
Pressure	[4 – 15ksi]	Buckle Amplitude
Axial pipe/soil friction	[0.2 – 0.8]	Axial Stress Range
Lateral pipe/soil friction	[0.5 – 1.3]	
Sleeper height	[2 – 4ft]	
Sleeper friction	[0.05 – 0.6]	
Contents Density	[20 – 65 pcf]	
Mode shapes	2 Modes	
…		

Proof-of-Concept

Objective

- Identify a dummy case
- Small subset of variables.
- Other parameters are kept constant.
- Comprehensive testing of predictions.
- ML model with low complexity.
- Evaluate errors and validate the approach

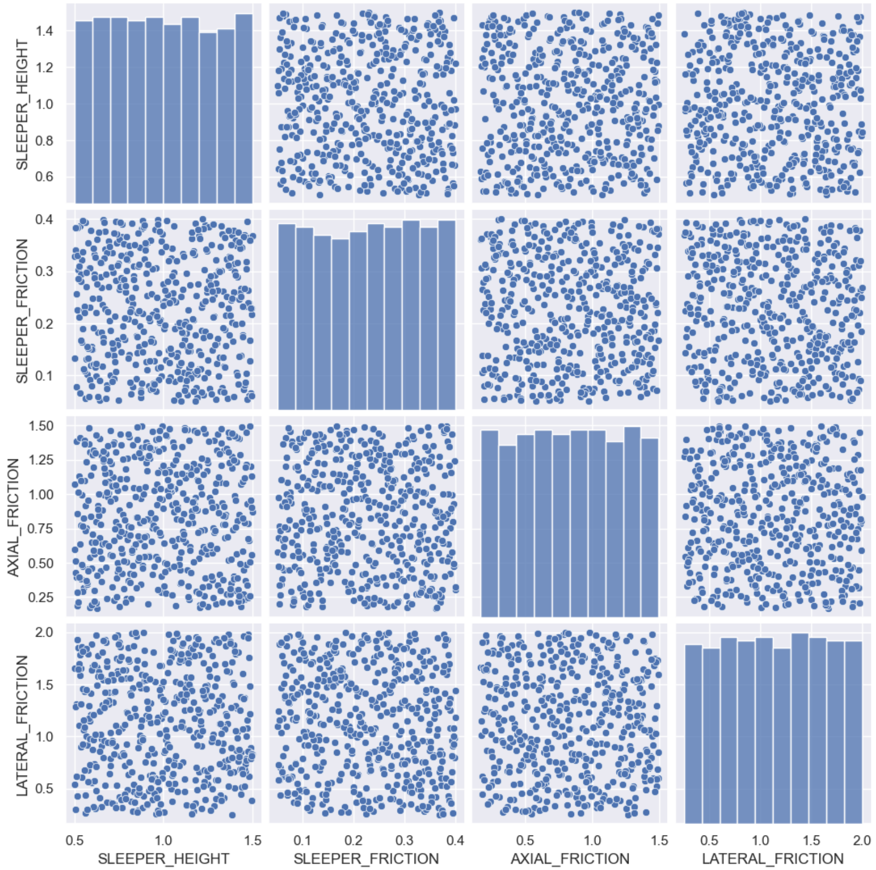
Subsequent Objective

- Identify real cases to start the model building
- Incremental expansion of the variables
- Add models with higher complexity

Input	Range	Output
Pipe OD	273.1mm	Buckle Initiation Force
Pipe WT	22.2mm	Post Buckle EAF
External coating	3.2mm	Max Longitudinal Stress
Temperature	60°C	Max Longitudinal Strain
Pressure	22 MPa	Buckle Amplitude
Axial pipe/soil friction	**[0.2 – 1.5]**	Axial Stress Range
Lateral pipe/soil friction	**[0.5 – 1.5]**	
Sleeper height	**[0.17 – 1.5m]**	
Sleeper friction	**[0.05 – 0.6]**	
Contents Density	650 kg/m^3	
Mode shapes	1 Mode	
…		

Data Generation

- 1000 data points generated (For Training and Testing)
- Sampling using Latin Hypercube Sampling (LHS)
- Abaqus simulations on Rescale (8 x 4 cores)
- FastFEA used for postprocessing
- Total Simulation time: 24 hours



Data Snapshot (1000 Rows)

SLEEPER_HEIGHT	SLEEPER_FRICTION	AXIAL_FRICTION	LATERAL_FRICTION	ESF1	AMP_Y	AMP_Z	SM2	SM3	EE11	BIF	S11
1.383	0.3688	1.2726	0.2517	-126327	1.37912	1.20117	162916	29.8416	-6.01983e-05	-126327	-1.23726e+07
0.801	0.2079	0.7698	0.6367	-80851.3	0.797122	5.30714	124253	81.653	-0.00118891	-133029	-2.41507e+08
1.089	0.1924	1.089	1.5188	-95804.5	1.08512	5.19107	144619	93.4727	-0.00141417	-131241	-2.87266e+08
1.059	0.2968	0.8736	0.7732	-89953.1	1.05512	5.23108	142467	99.1745	-0.00116227	-155988	-2.36095e+08
1.435	0.266	1.0731	0.8502	-94054.5	1.43112	4.31907	165569	96.9502	-0.000942134	-143827	-1.92065e+08
0.847	0.1764	0.8337	1.6552	-101457	0.843122	5.31337	127969	79.3145	-0.00159016	-134527	-3.23015e+08
0.893	0.3234	0.6262	1.5328	-110042	0.889122	5.40639	131365	85.5863	-0.00156445	-169952	-3.17791e+08

Input

Output

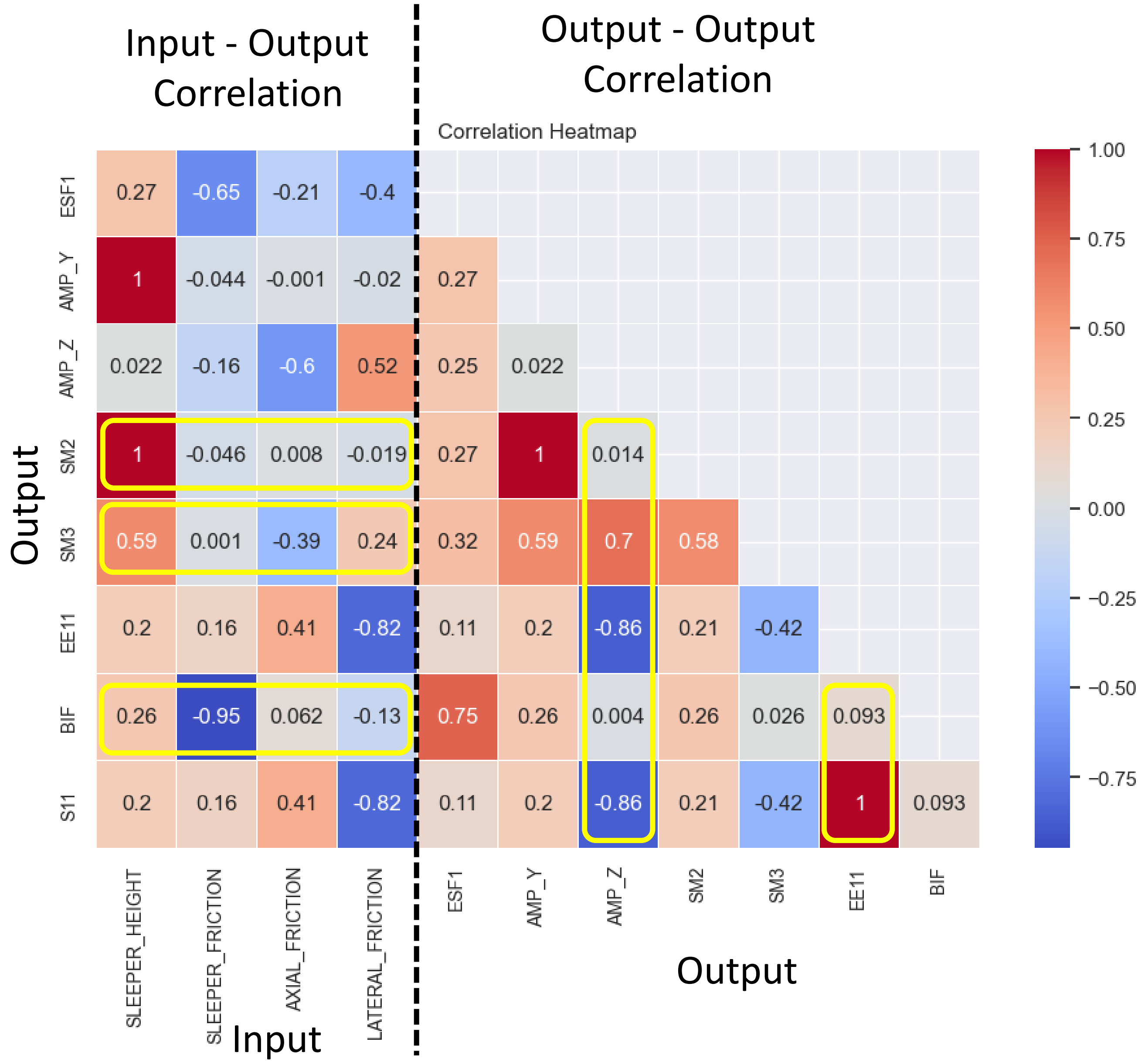
Correlation Plots

A measure of dependency

Types of Correlation:

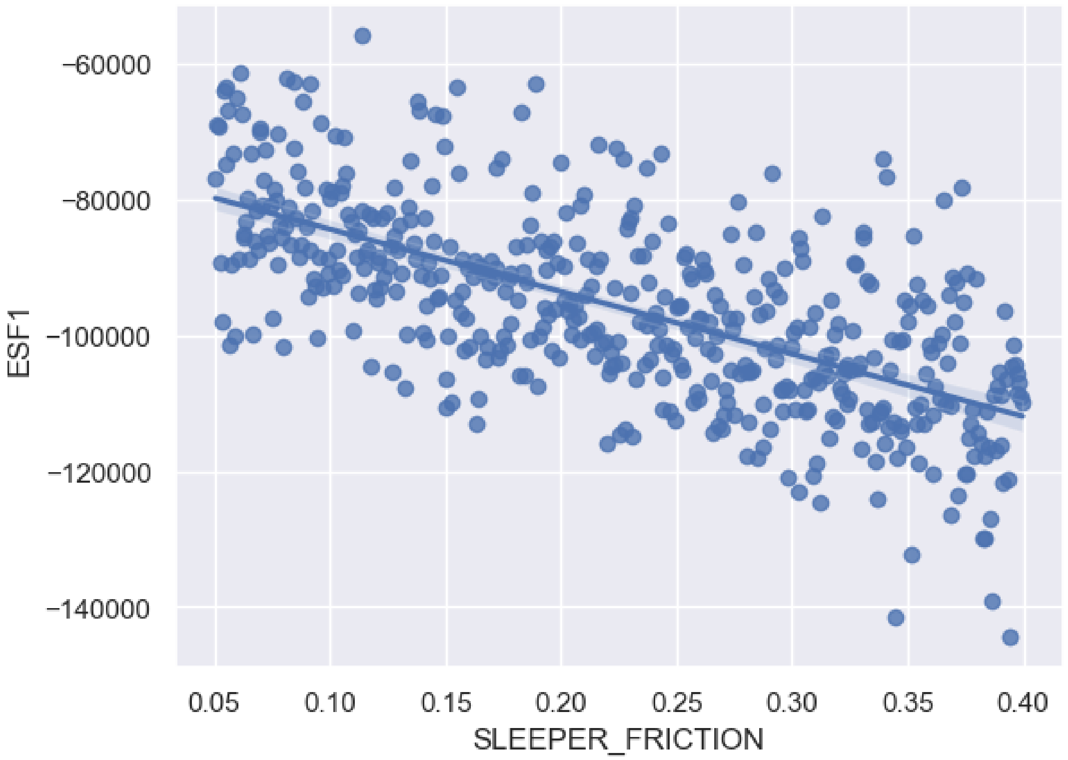
- **Positive (Red Colour)**
  - Strong (Dark Colours, Value close to 1)
  - Weak (Light Colours, Value close to 0)
- **Negative (Blue Colour)**
  - Strong (Dark Colours, Value close to -1)
  - Weak (Light Colours, Value close to 0)

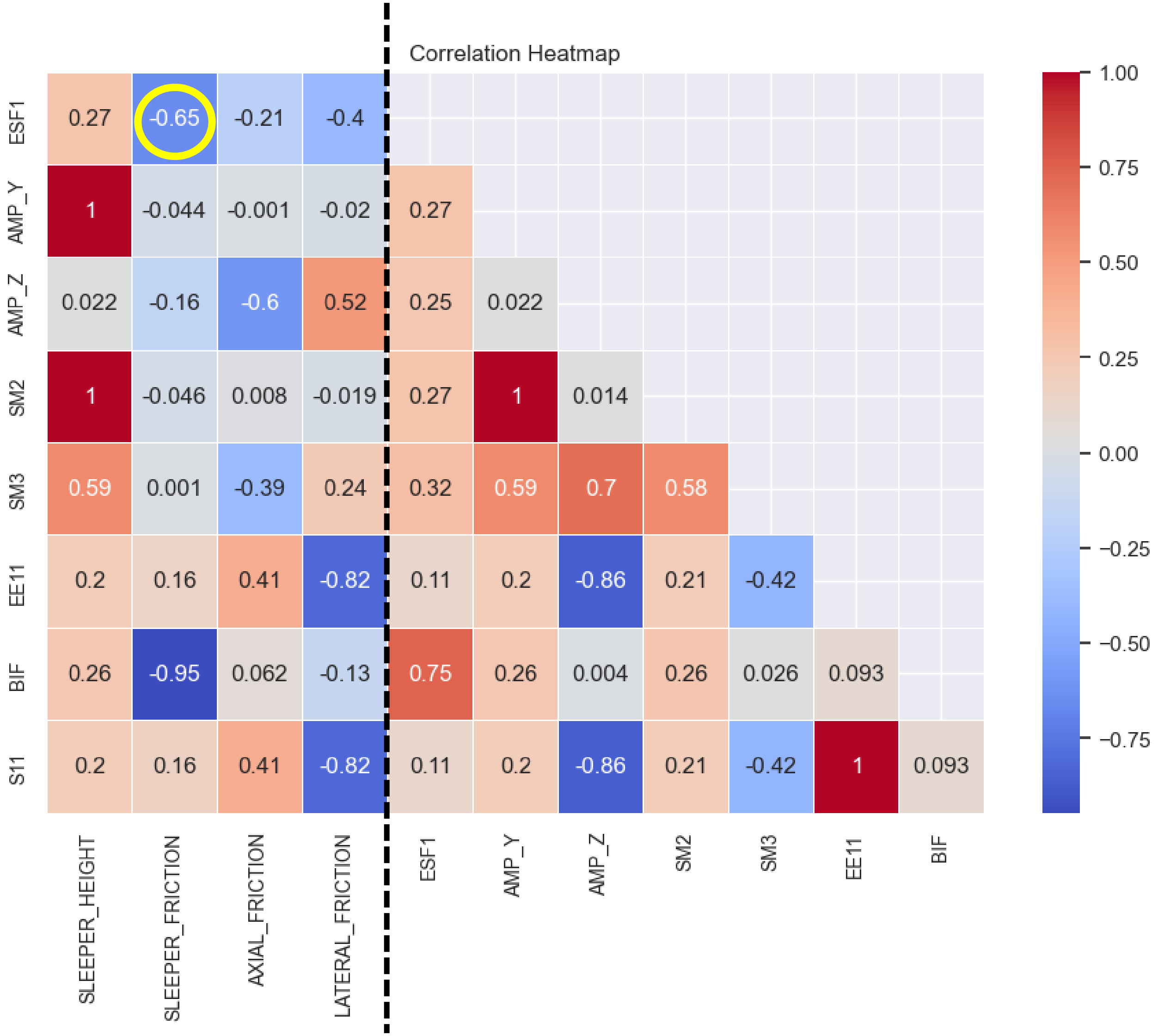
** No plastic strain (PE11) observed in the data points*



Correlation Plots

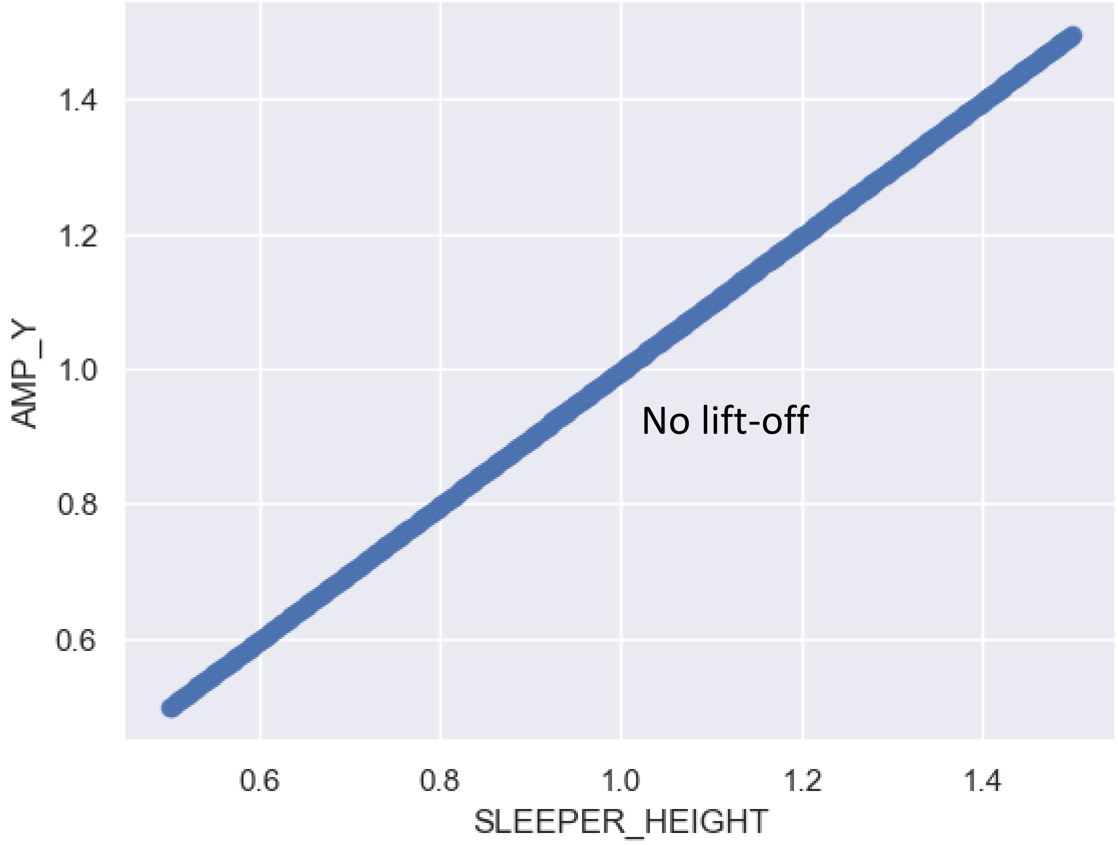
Effective Axial Force

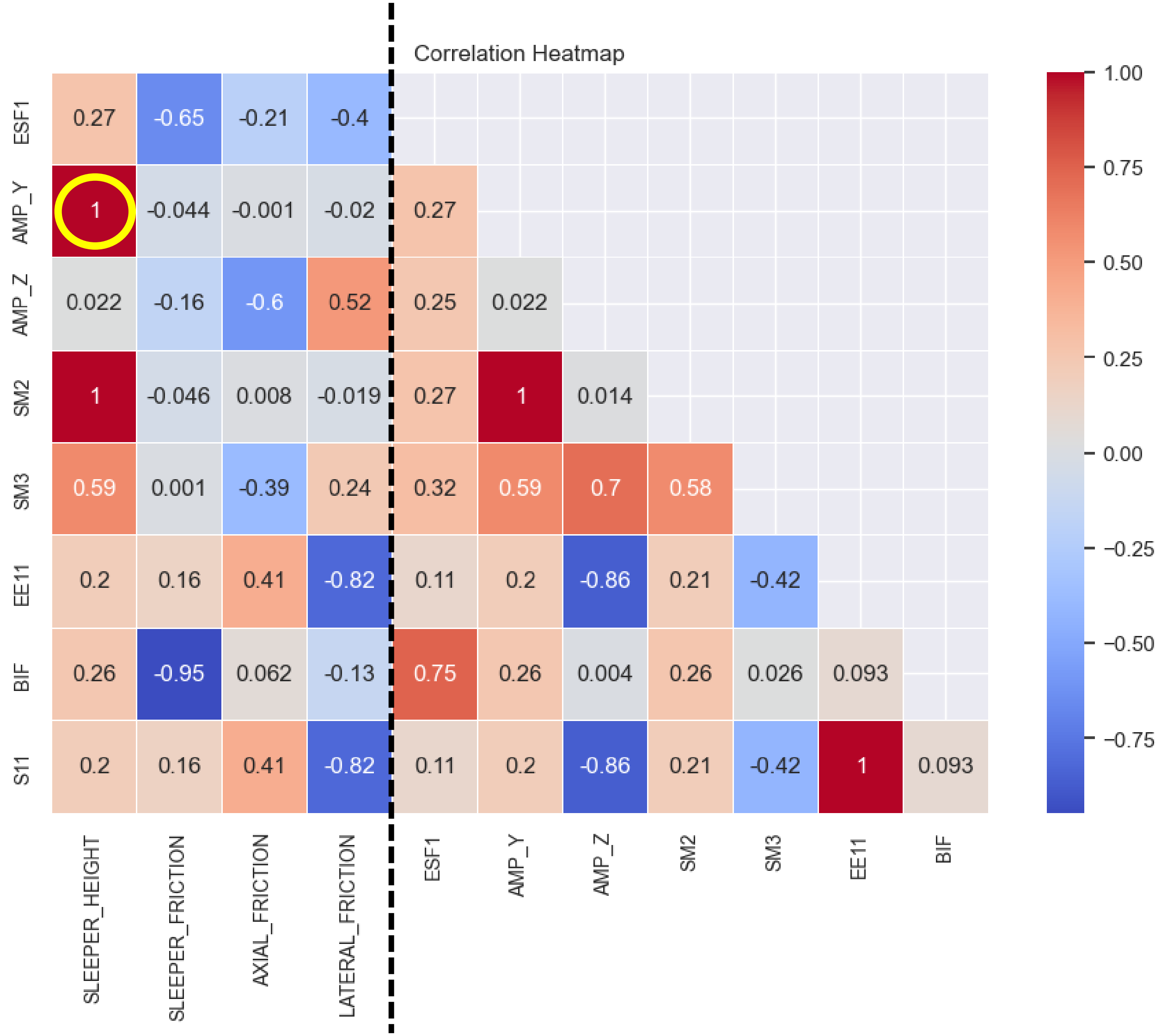




Correlation Plots

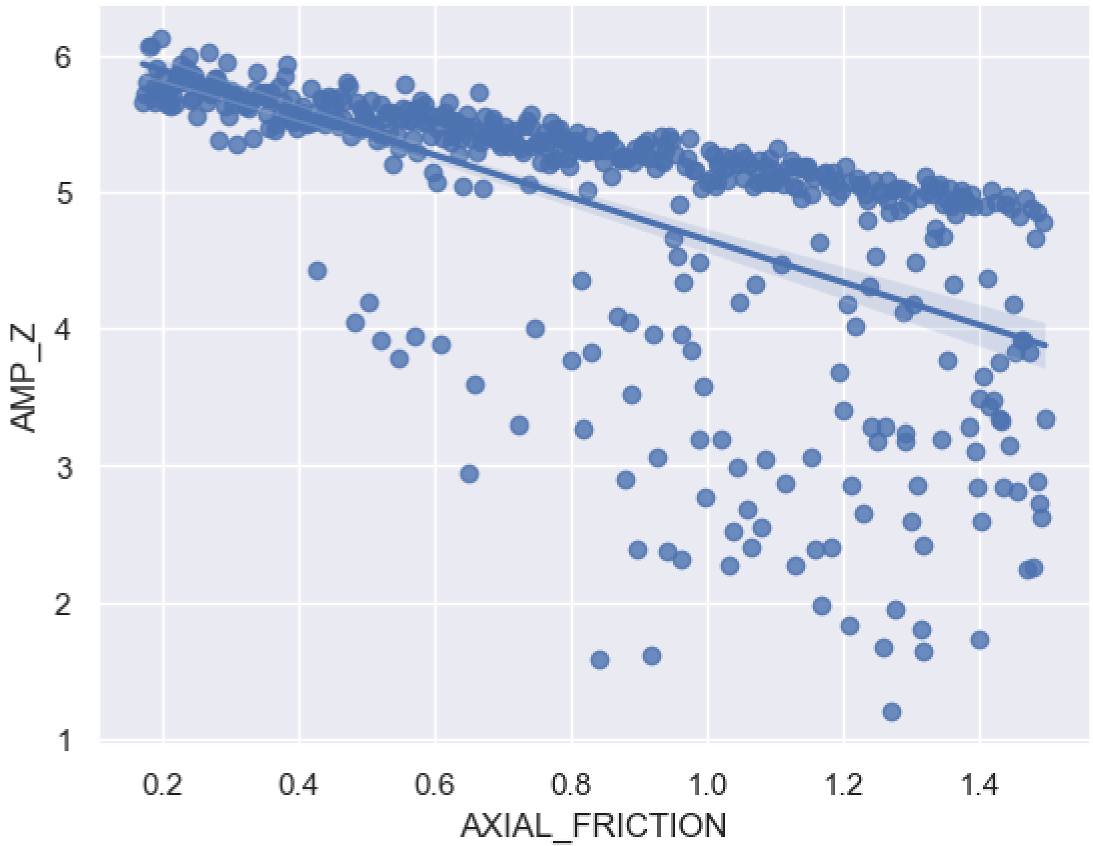
Buckle Amplitude (Vertical)

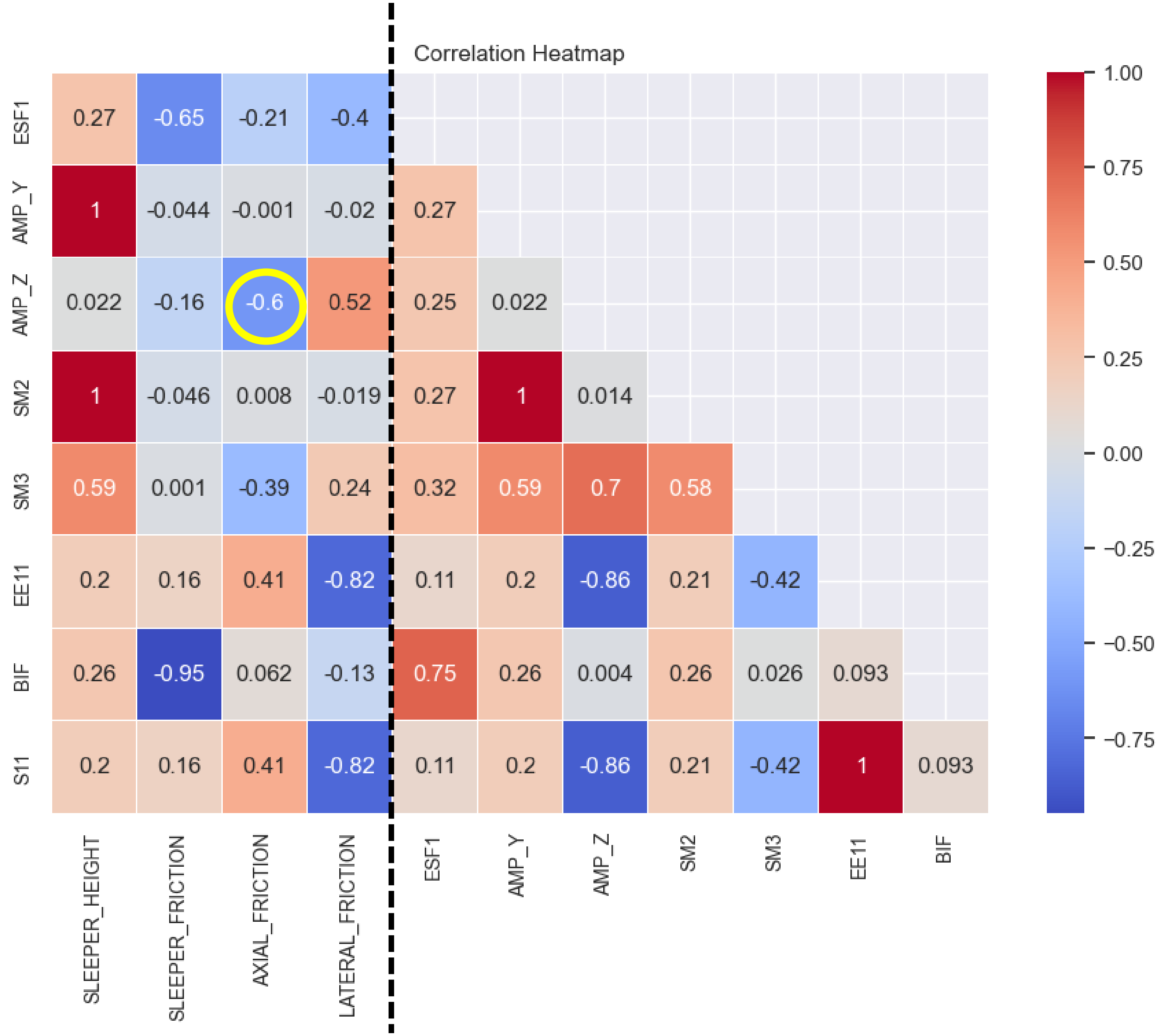




Correlation Plots

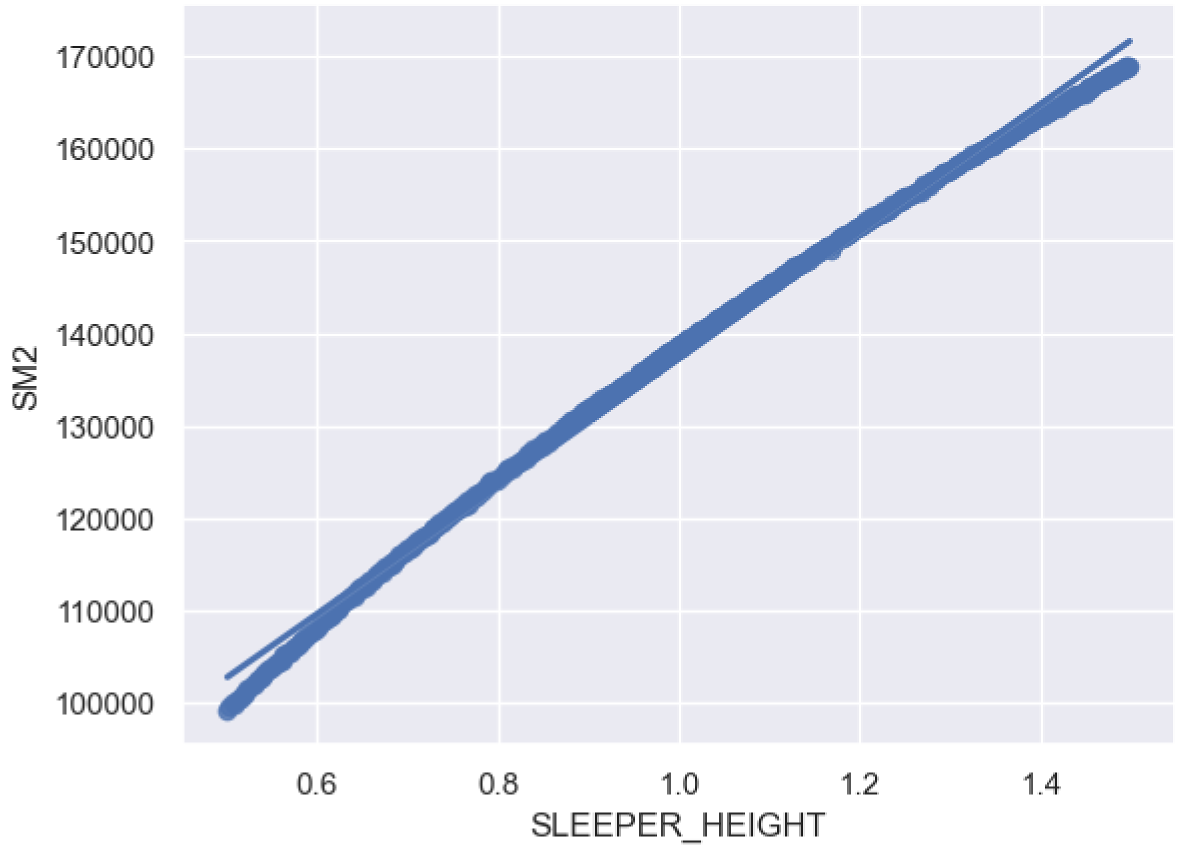
Buckle Amplitude (Lateral)

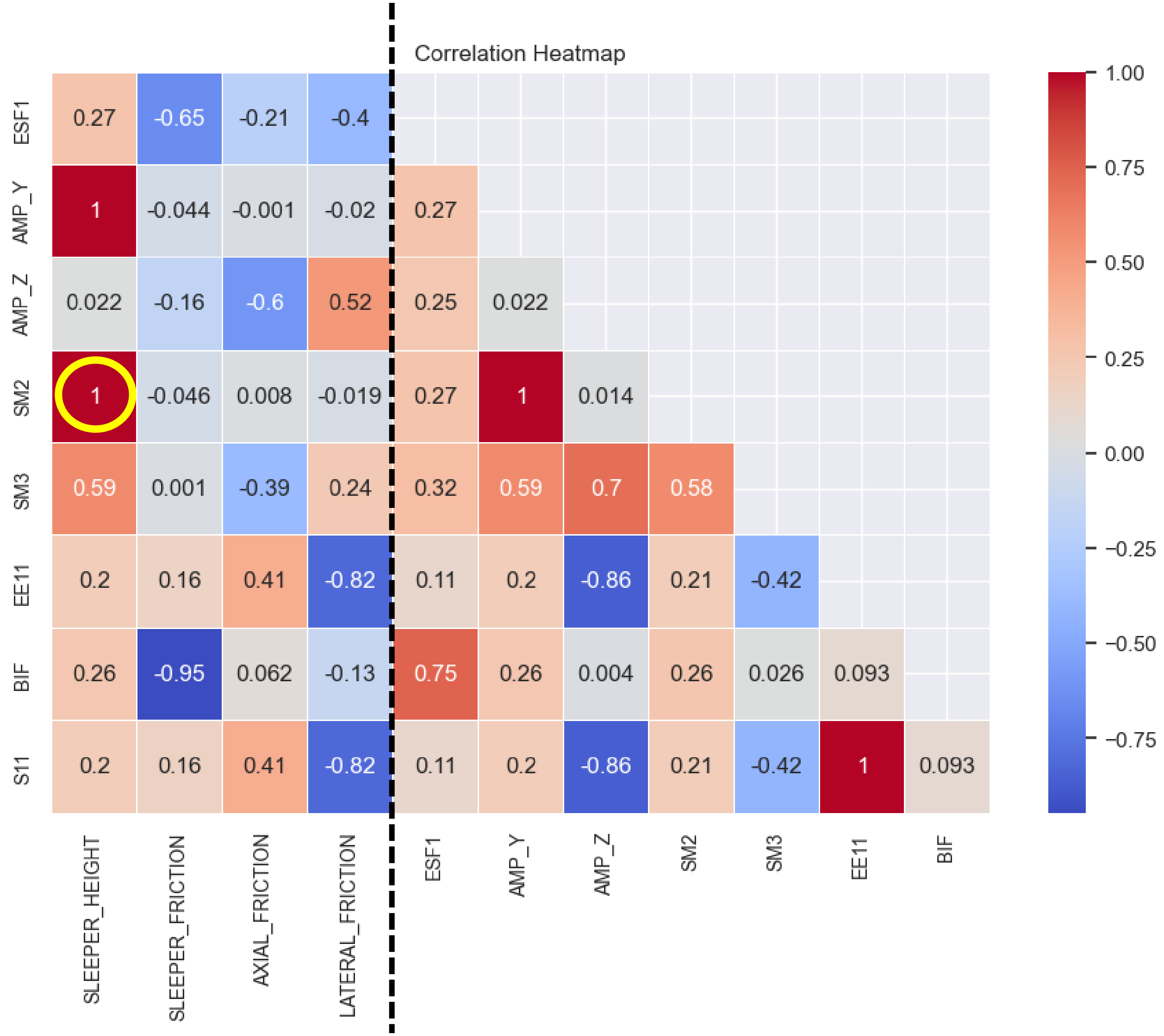




Correlation Plots

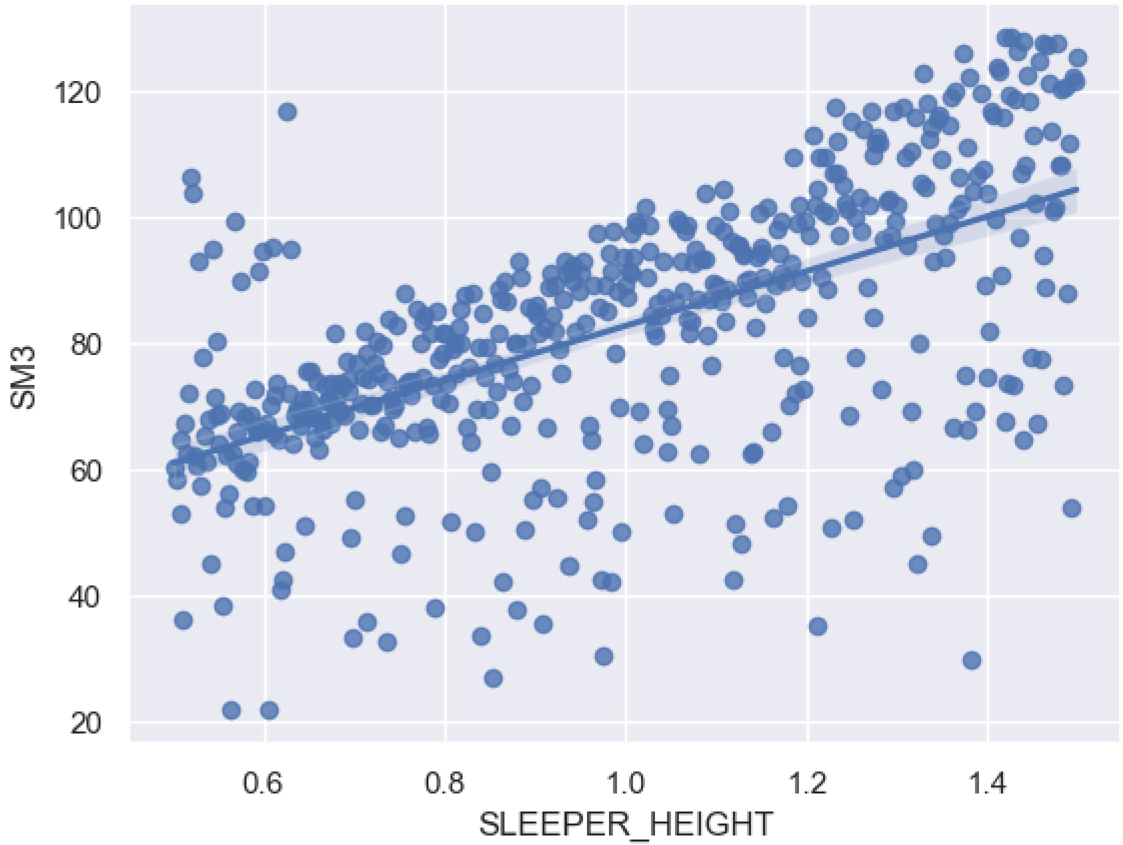
Section Moment (Vertical Plane)

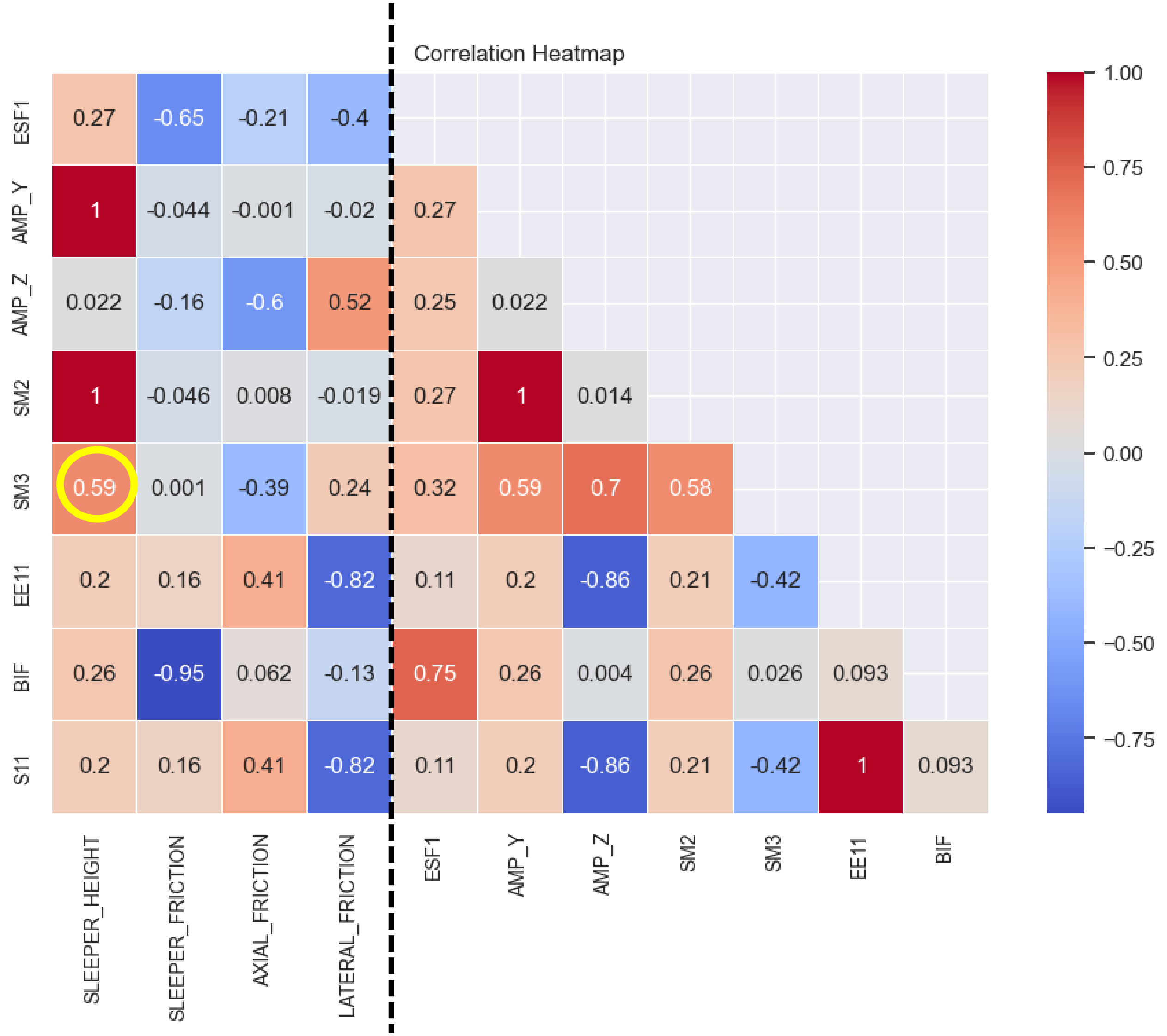




Correlation Plots

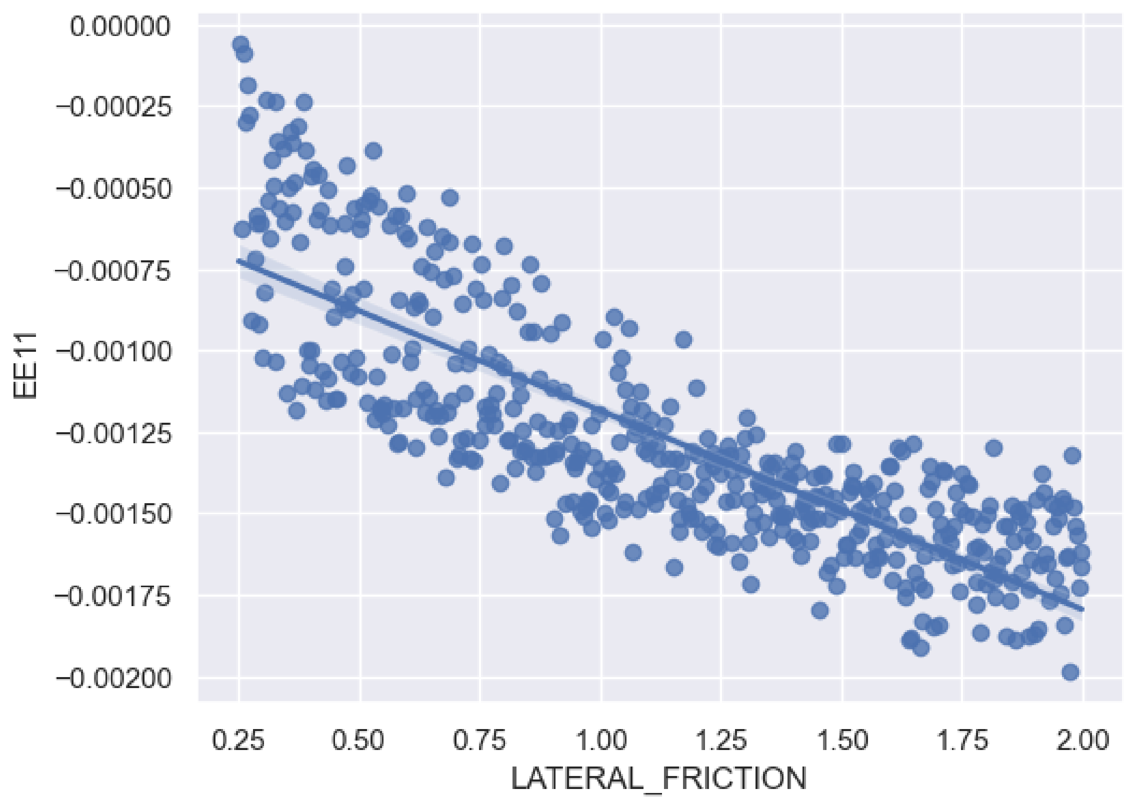
Section Moment (Lateral Plane)

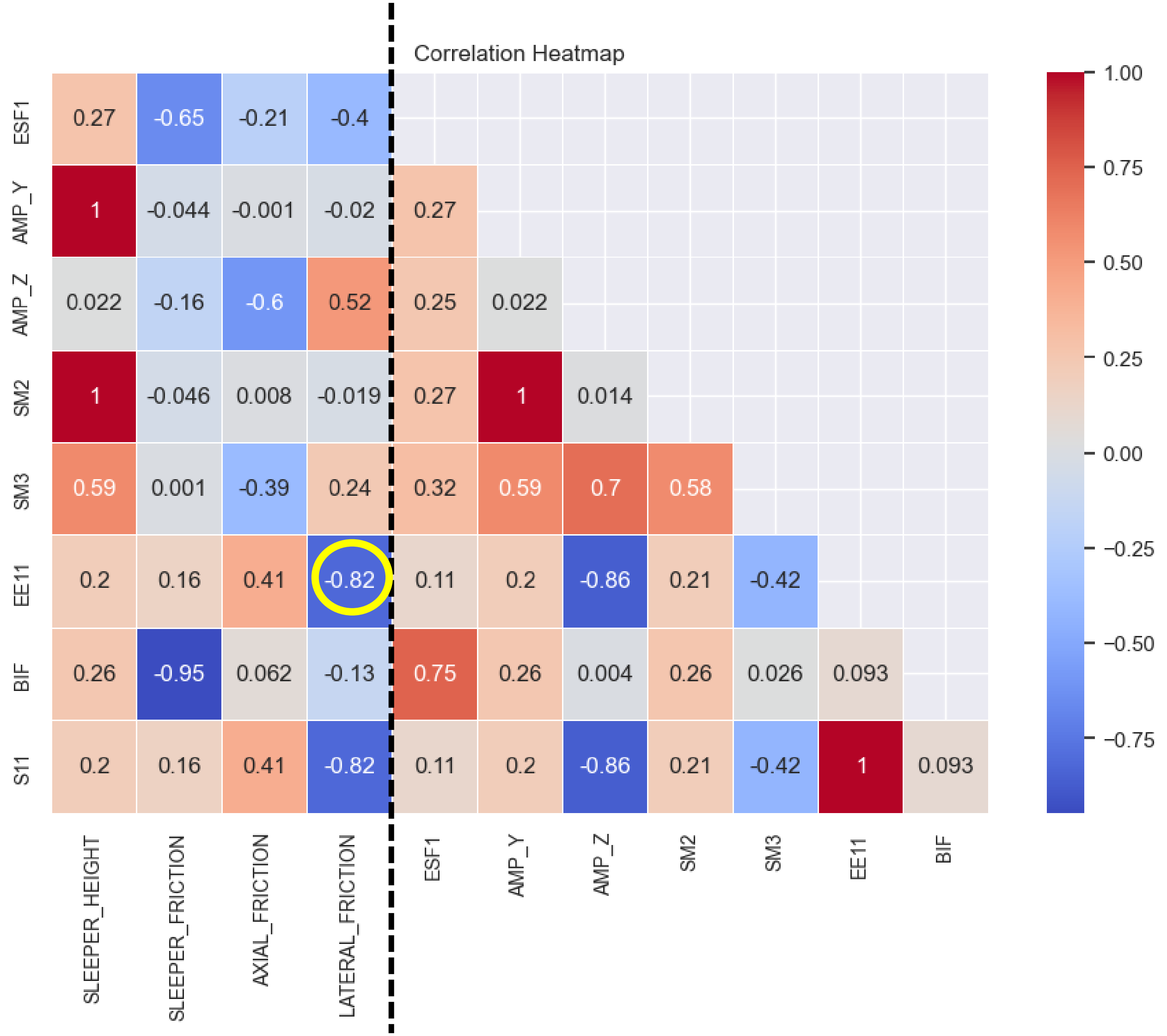




Correlation Plots

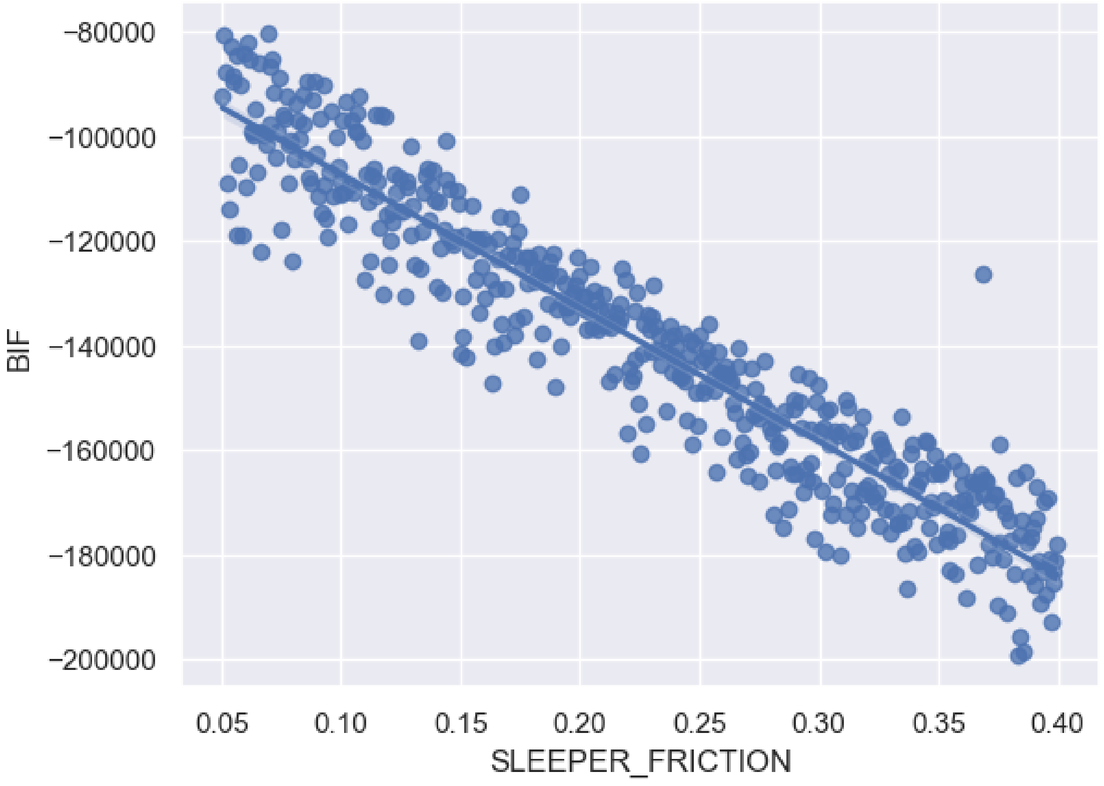
Elastic Strain

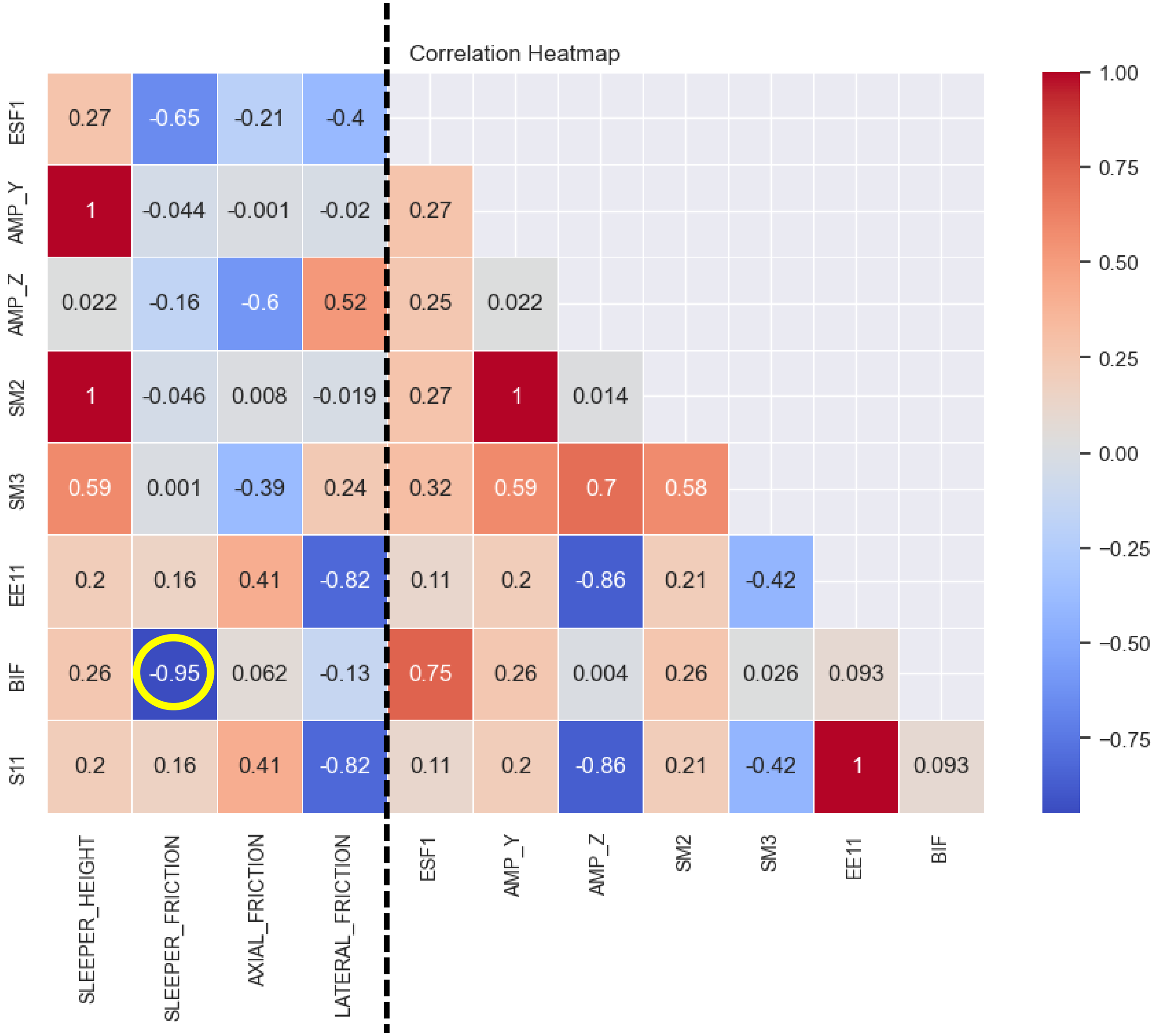




Correlation Plots

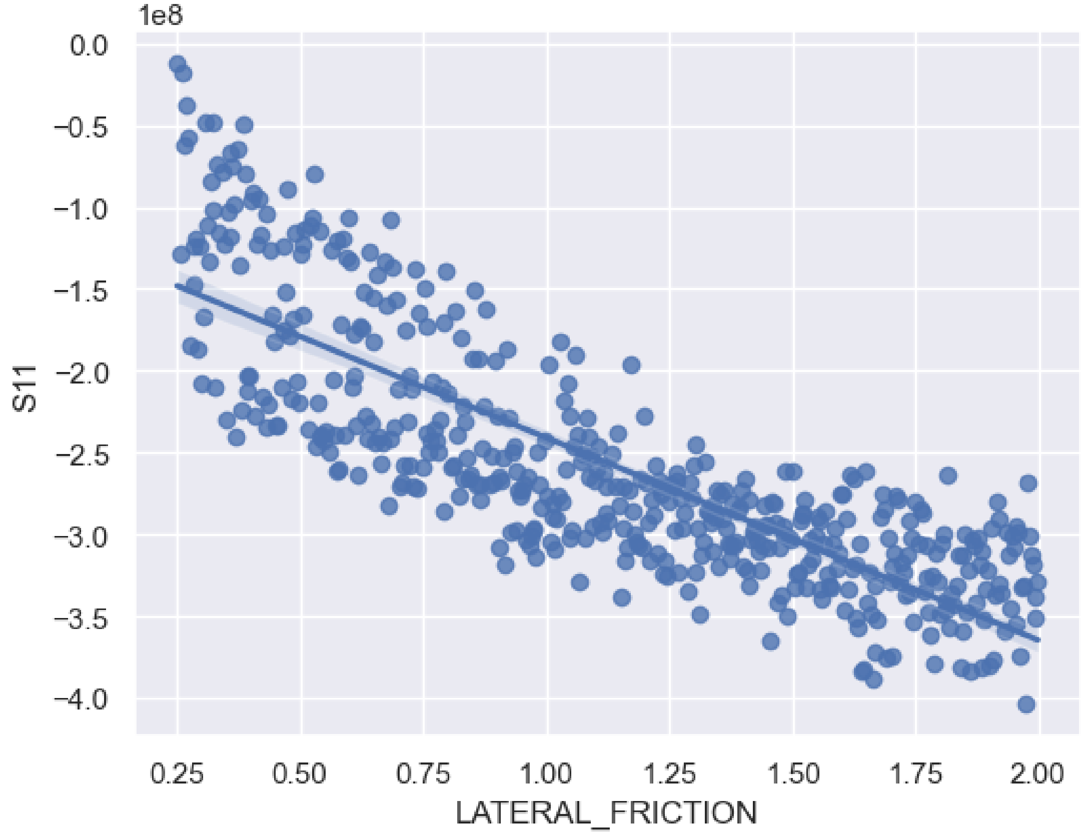
Buckle Initiation Force

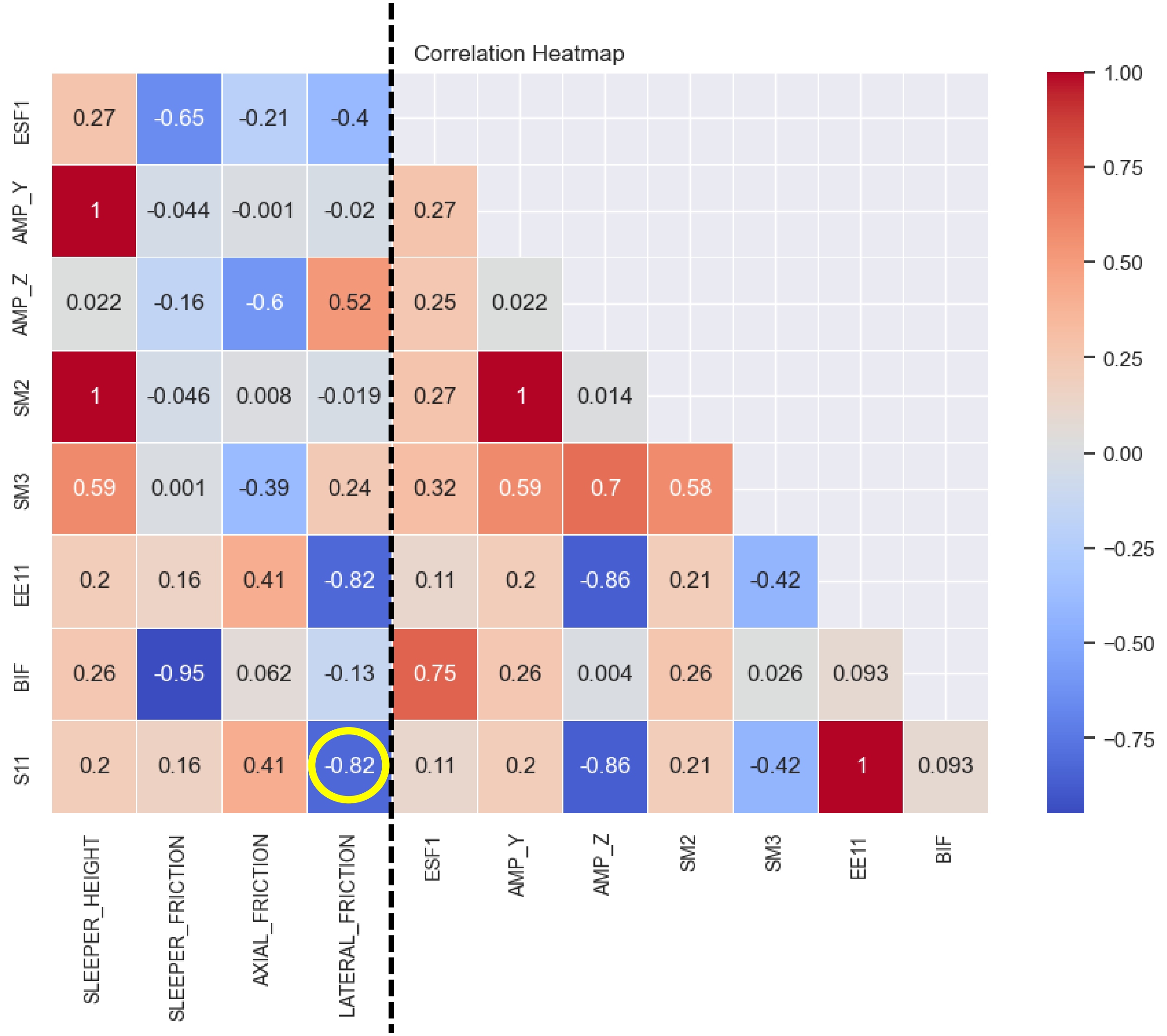




Correlation Plots

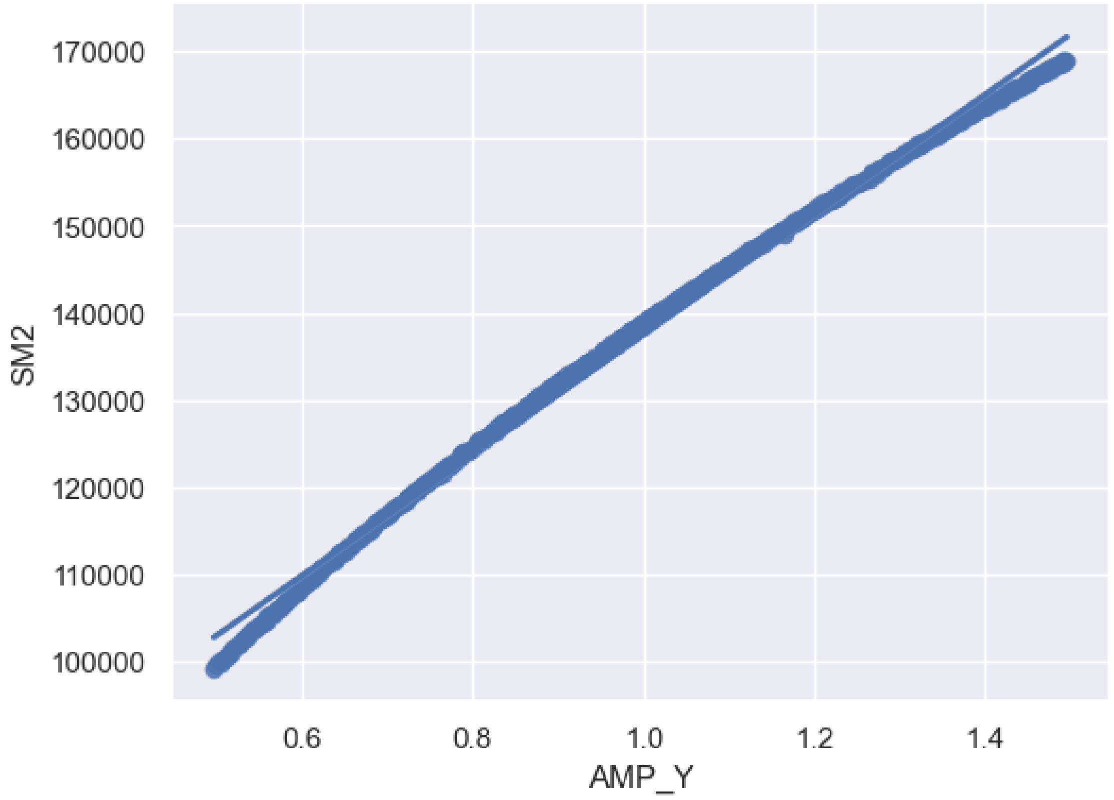
Axial Stress

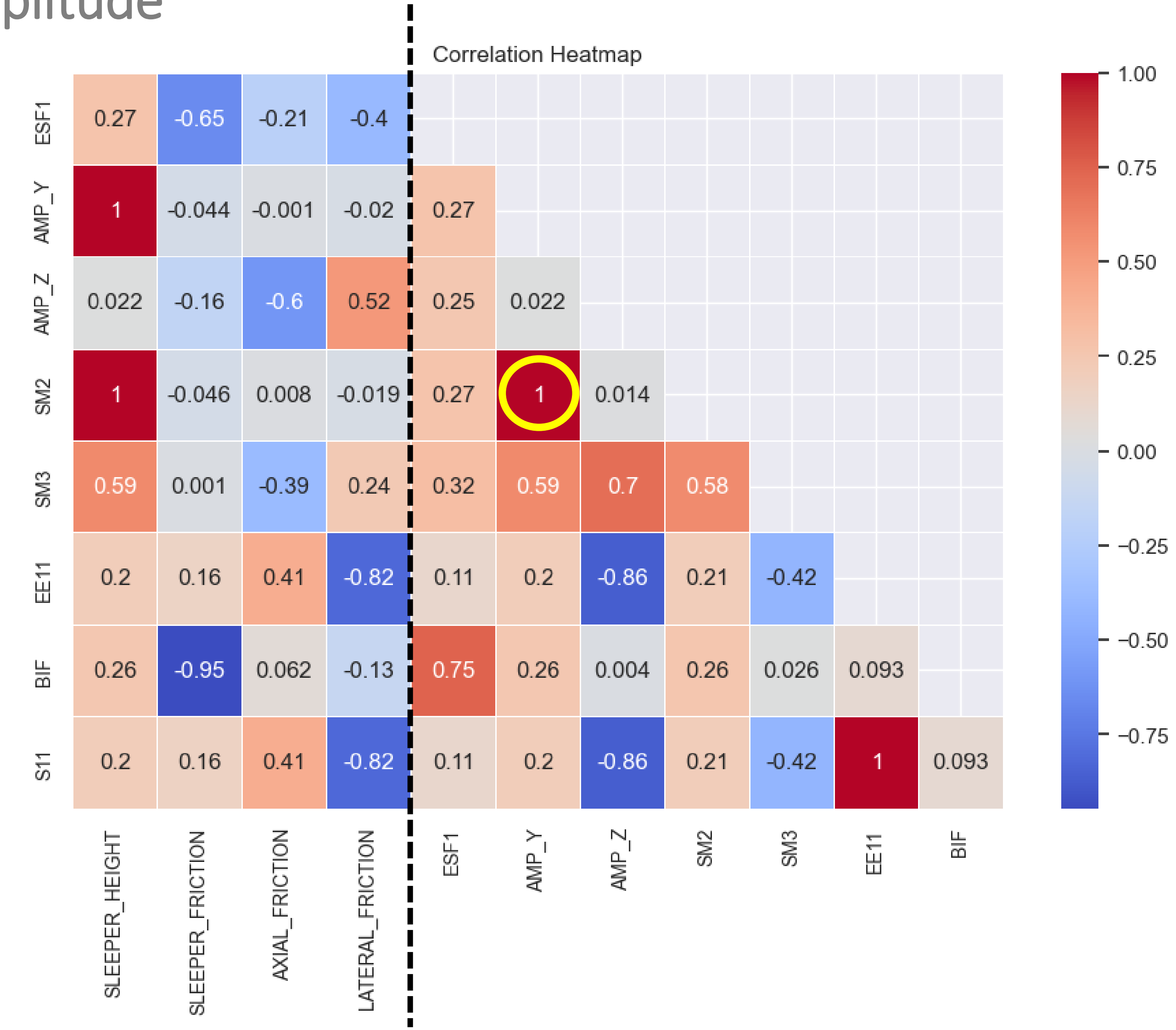




Correlation Plots

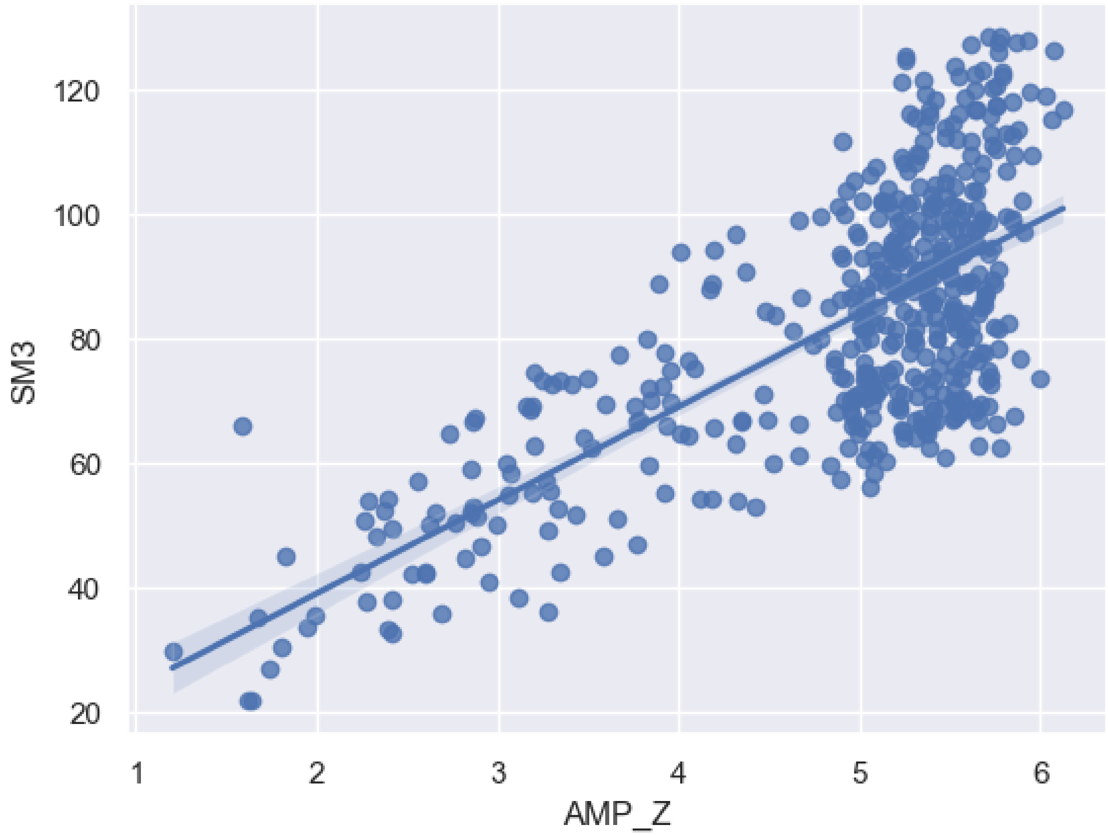
[Vertical] Section Moment vs Buckle Amplitude

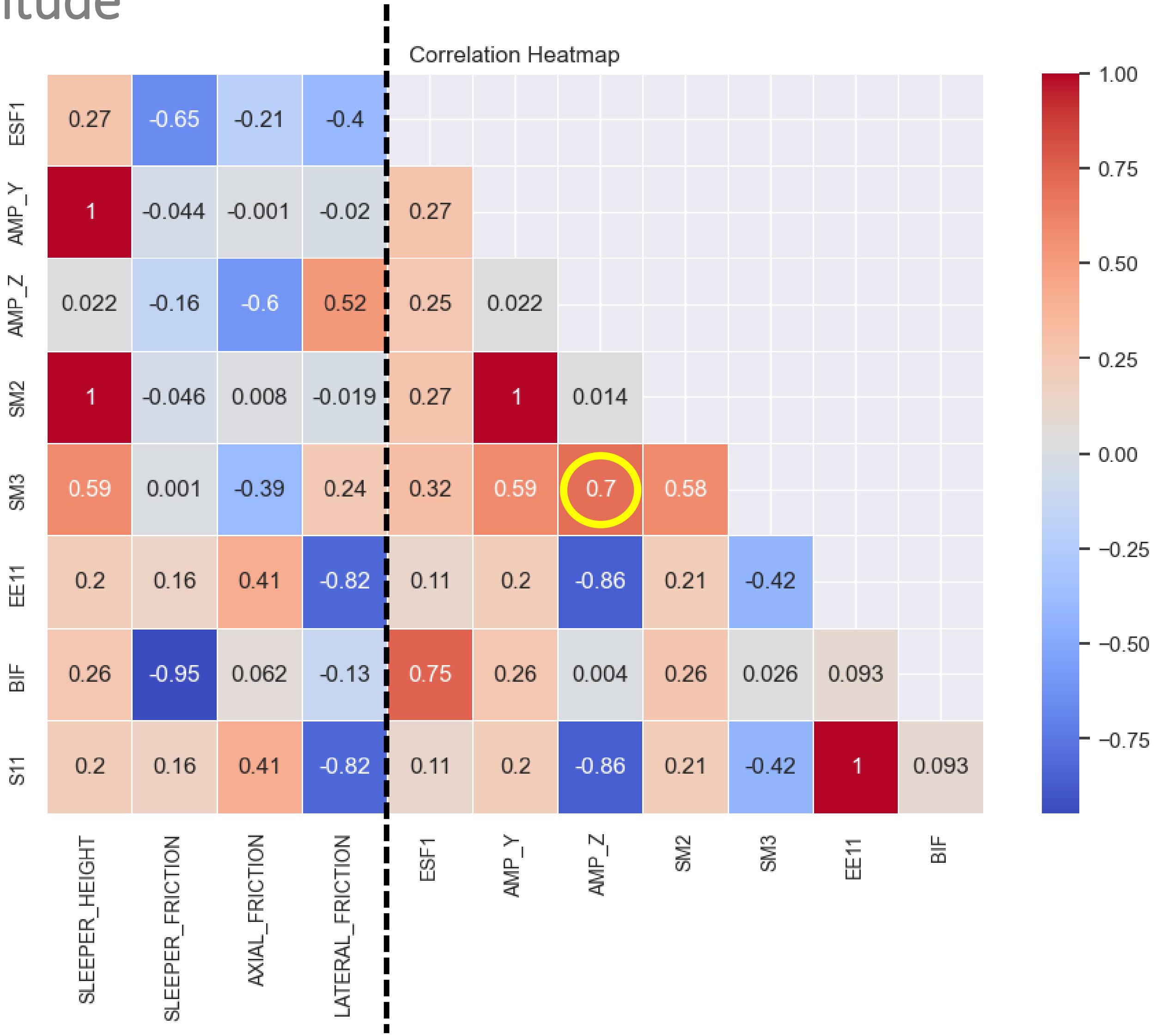




Correlation Plots

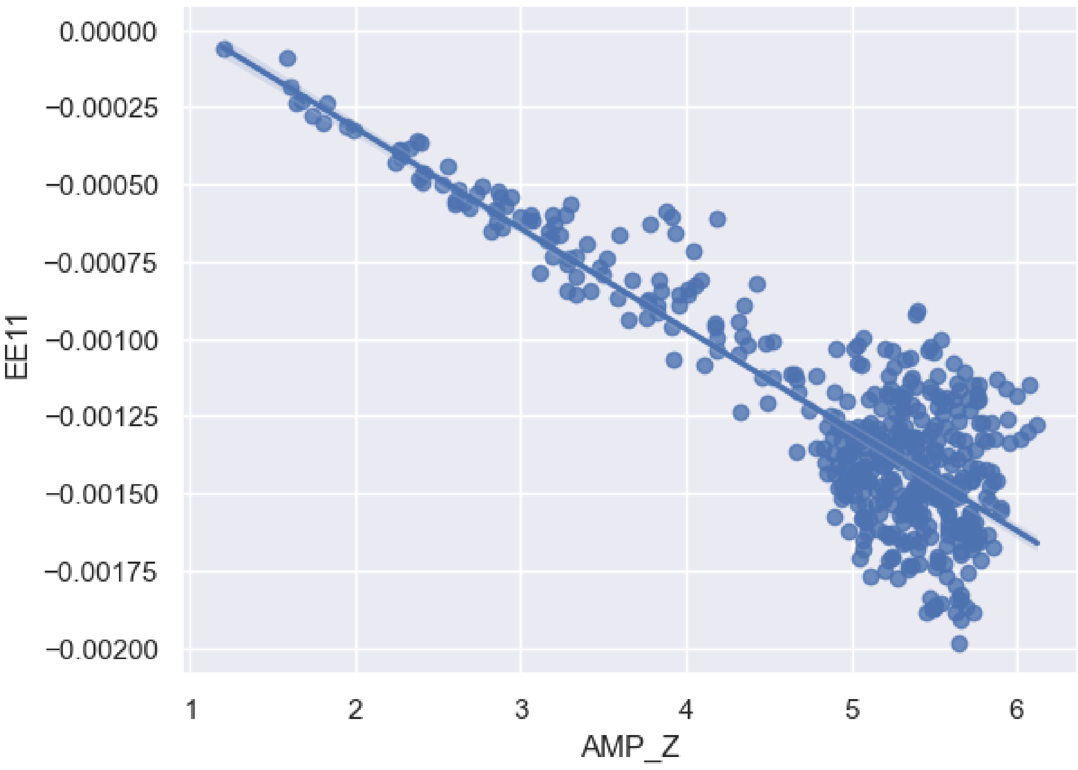
[Lateral] Section Moment vs Buckle Amplitude

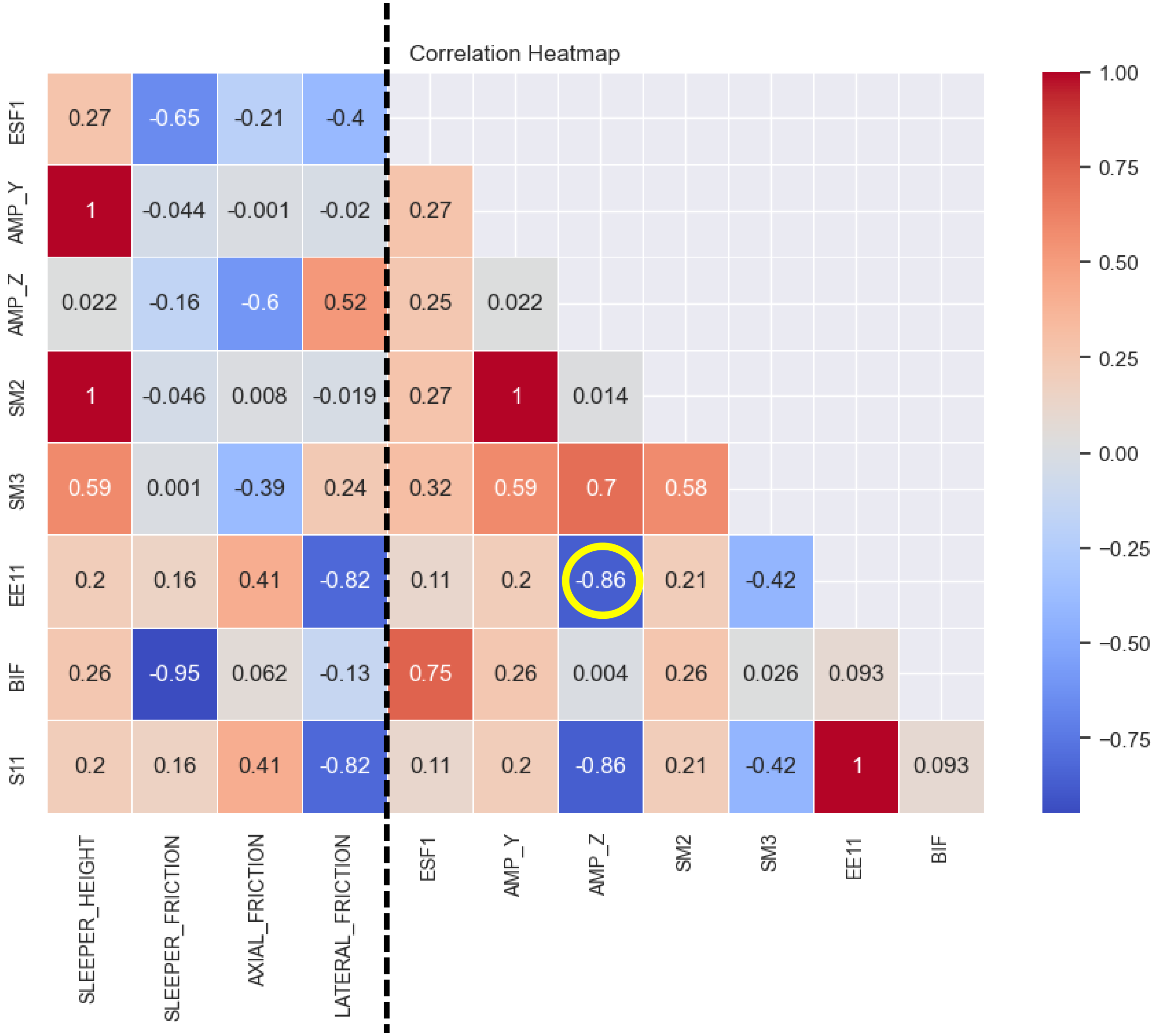




Correlation Plots

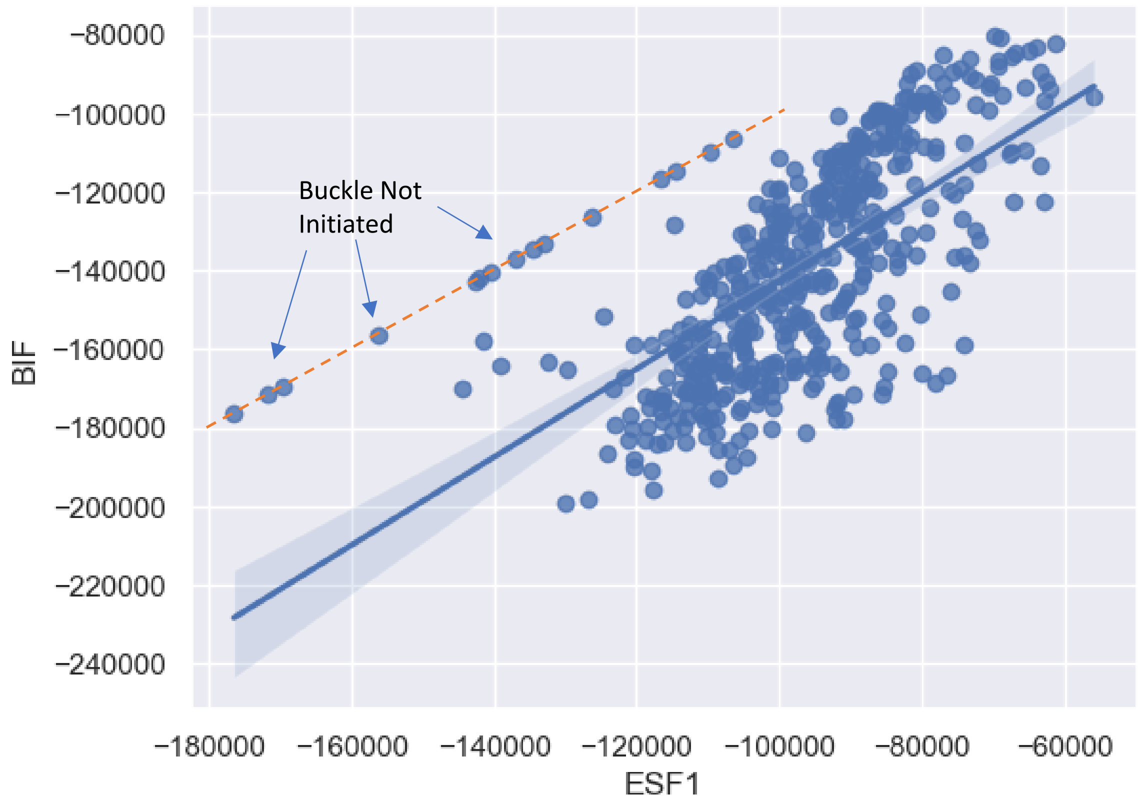
Elastic Strain vs Lateral Buckle Amplitude

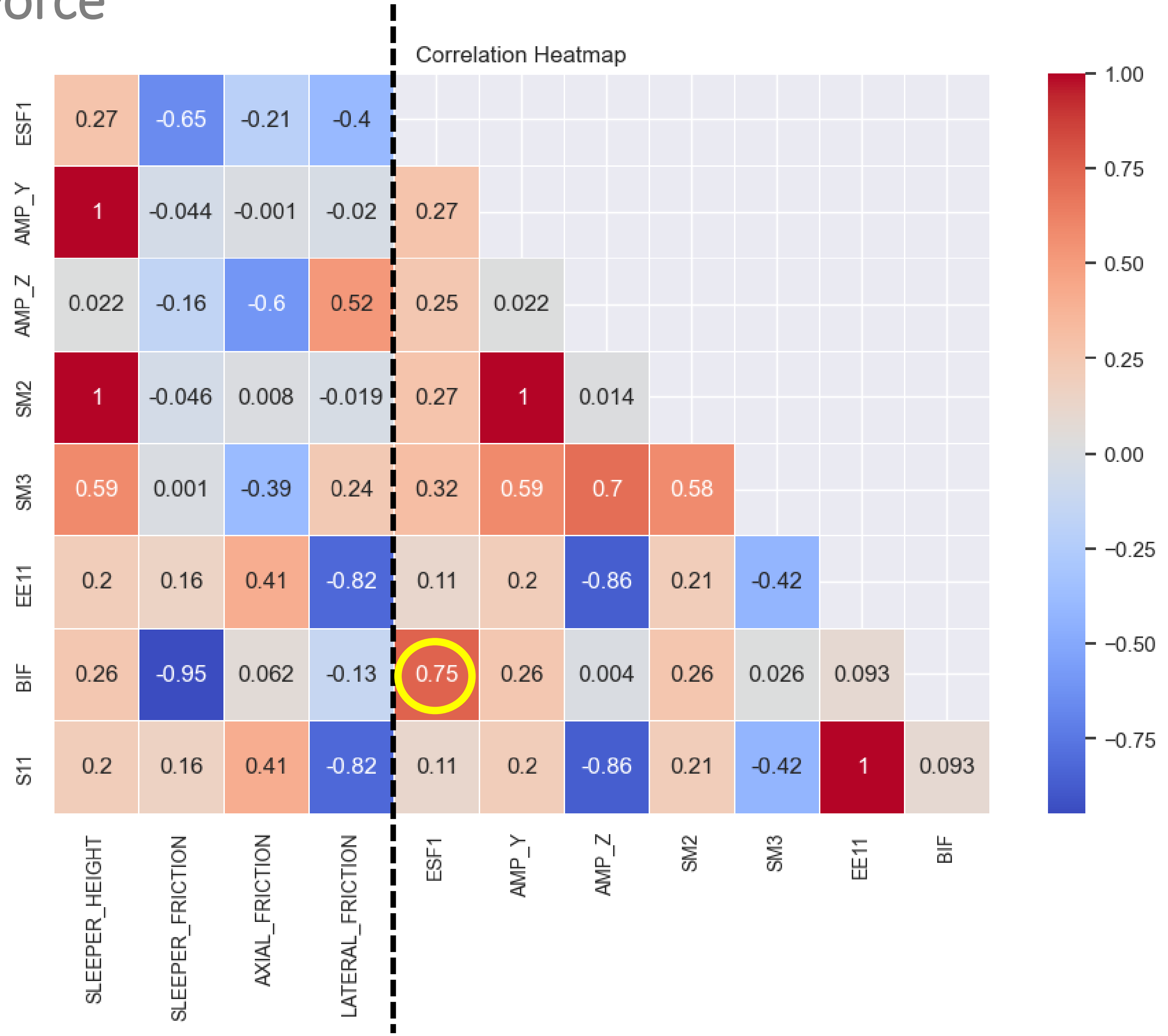




Correlation Plots

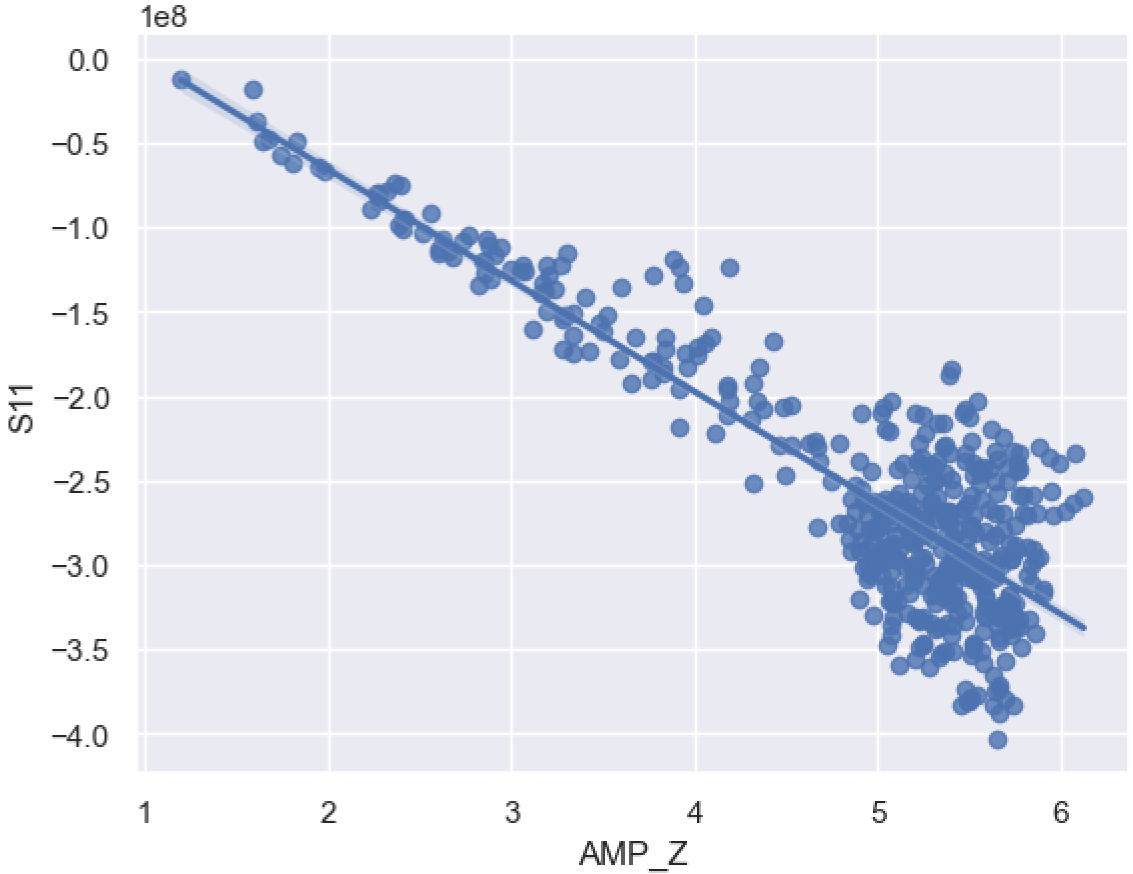
Buckle Initiation Force vs Effective Axial Force

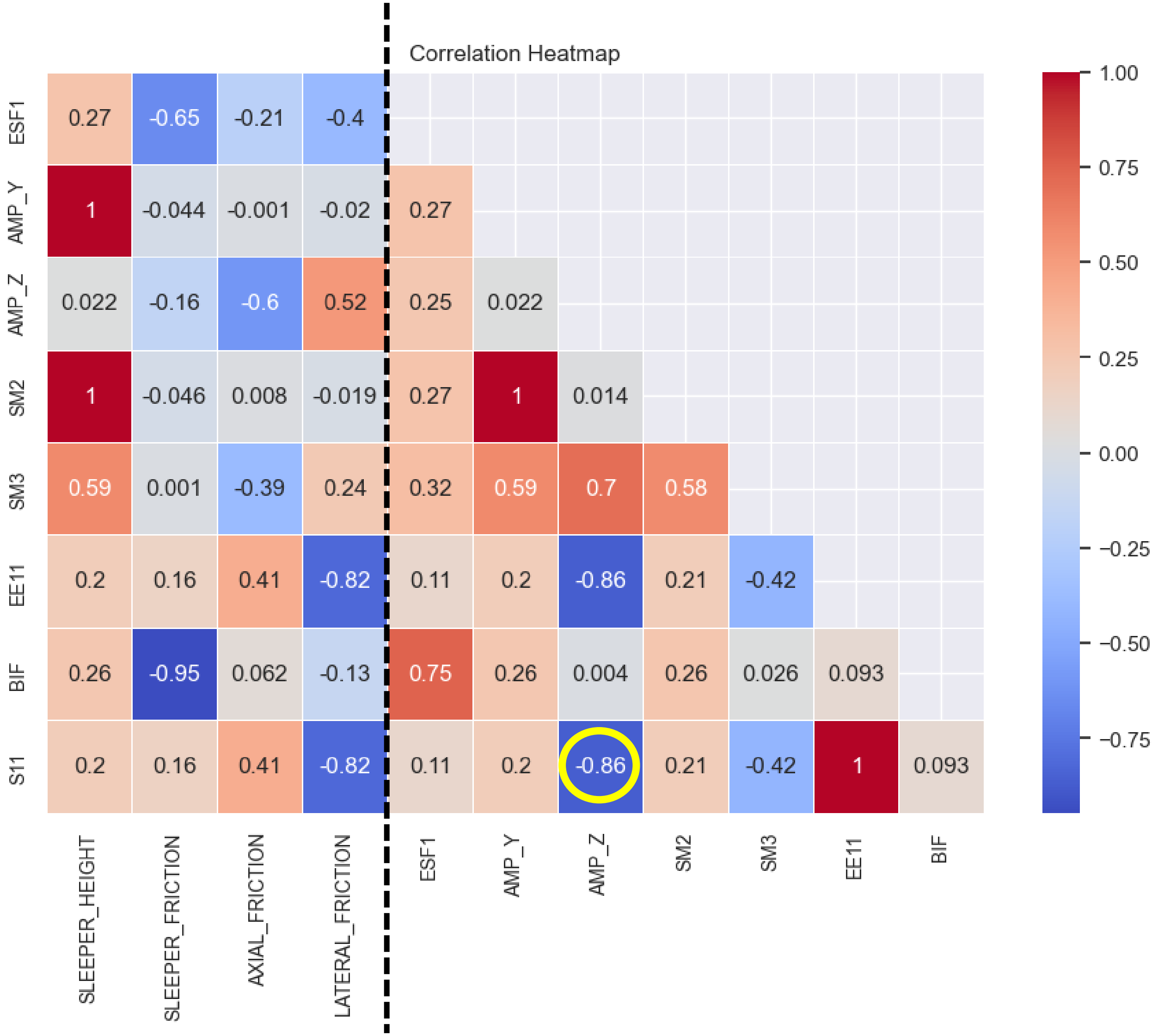




Correlation Plots

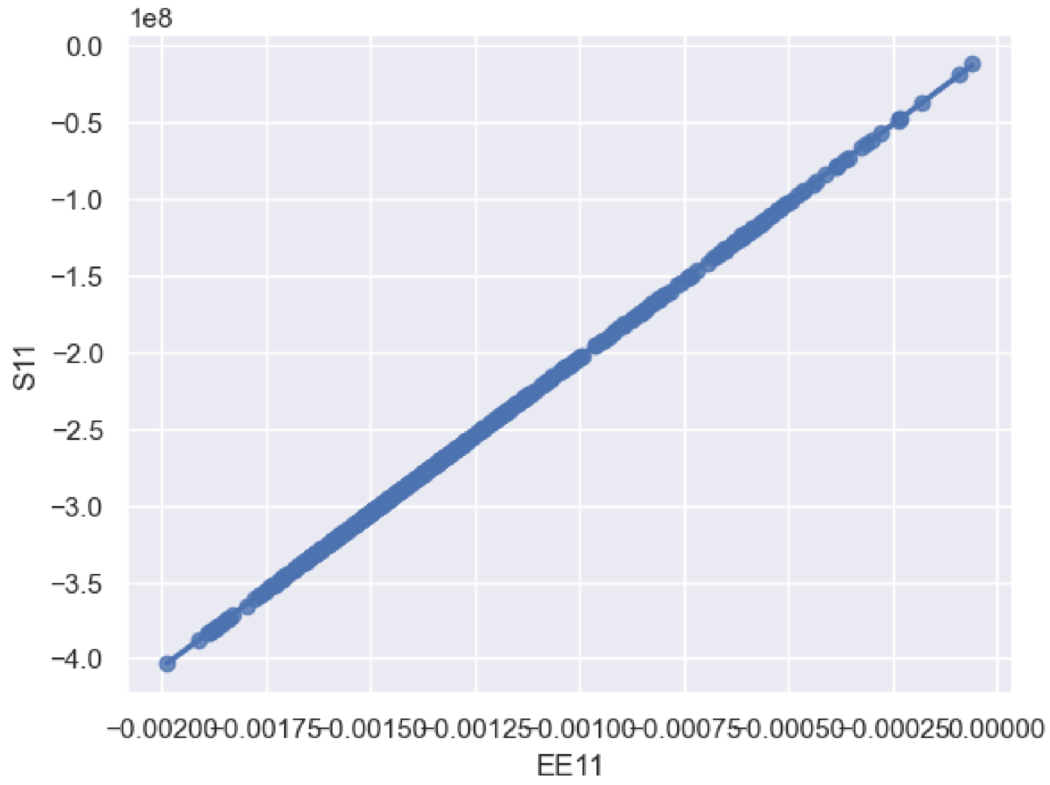
Axial Stress vs Lateral Buckle Amplitude

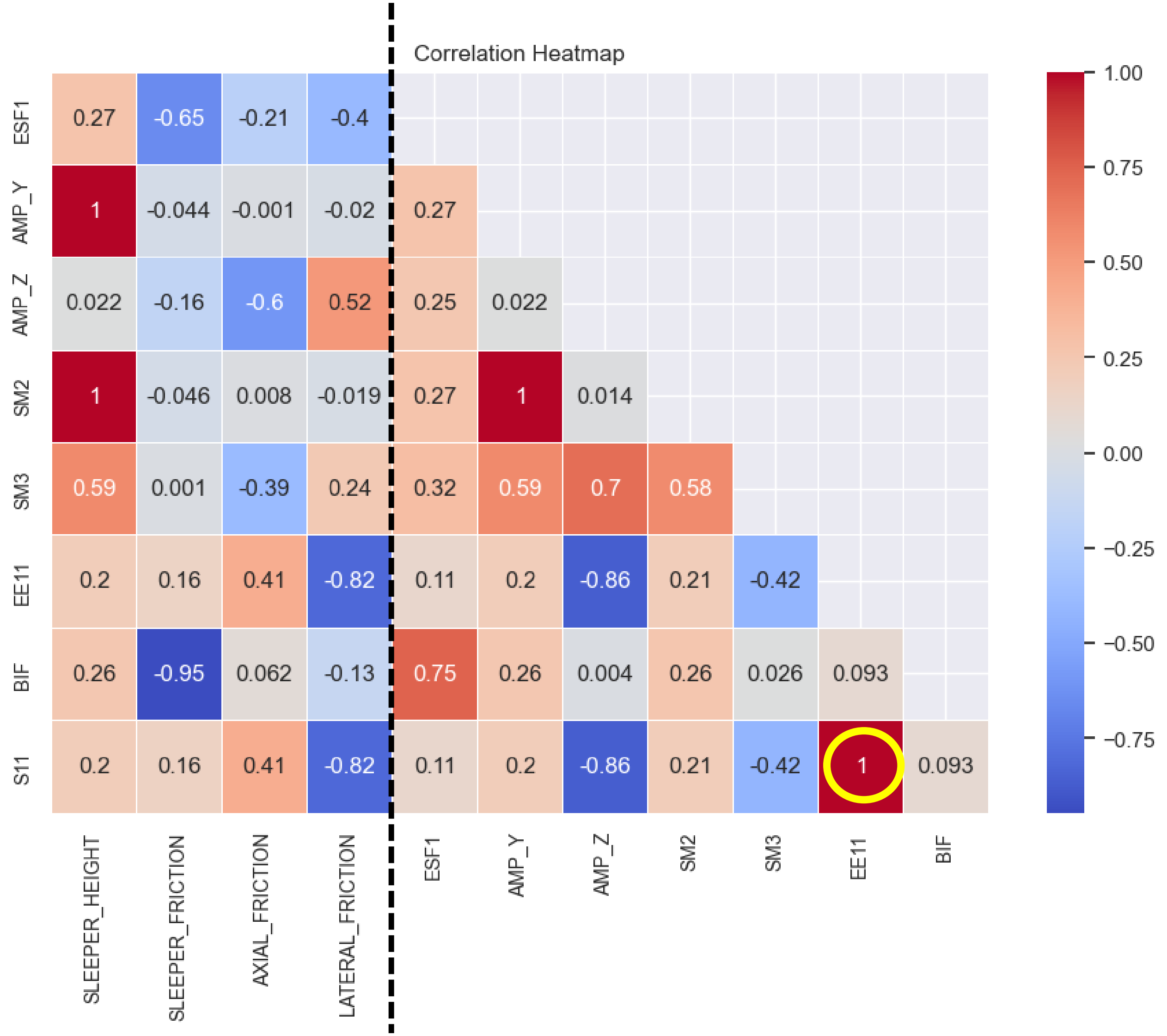




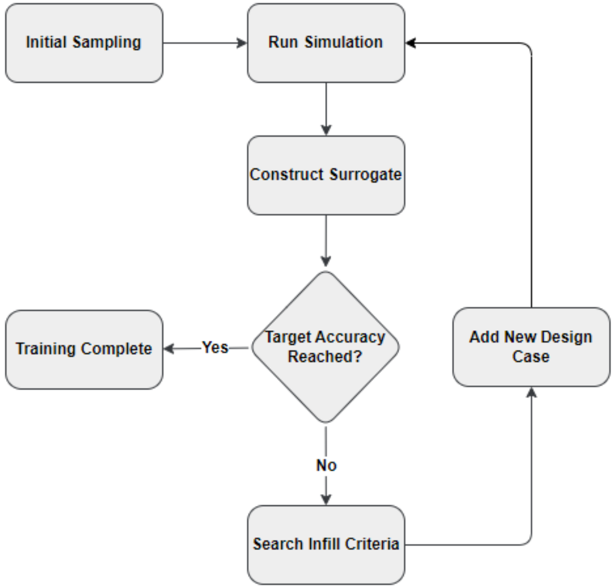
Correlation Plots

Axial Stress vs Elastic Strain

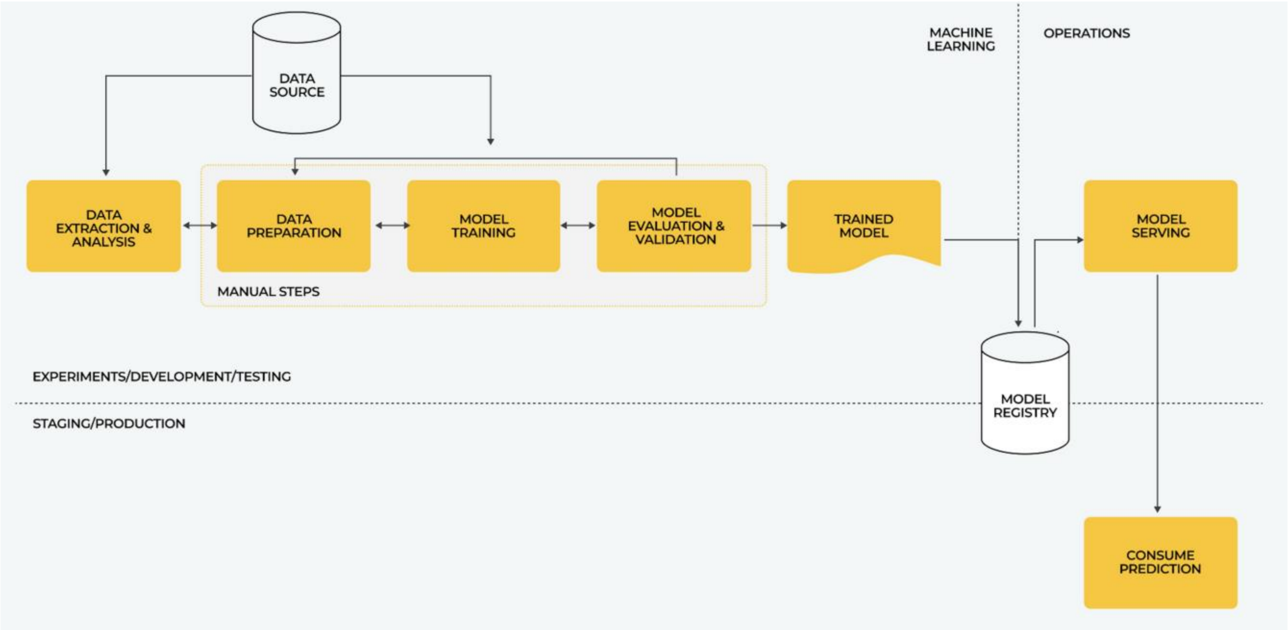




Surrogate Model Development and Serving



Model Training

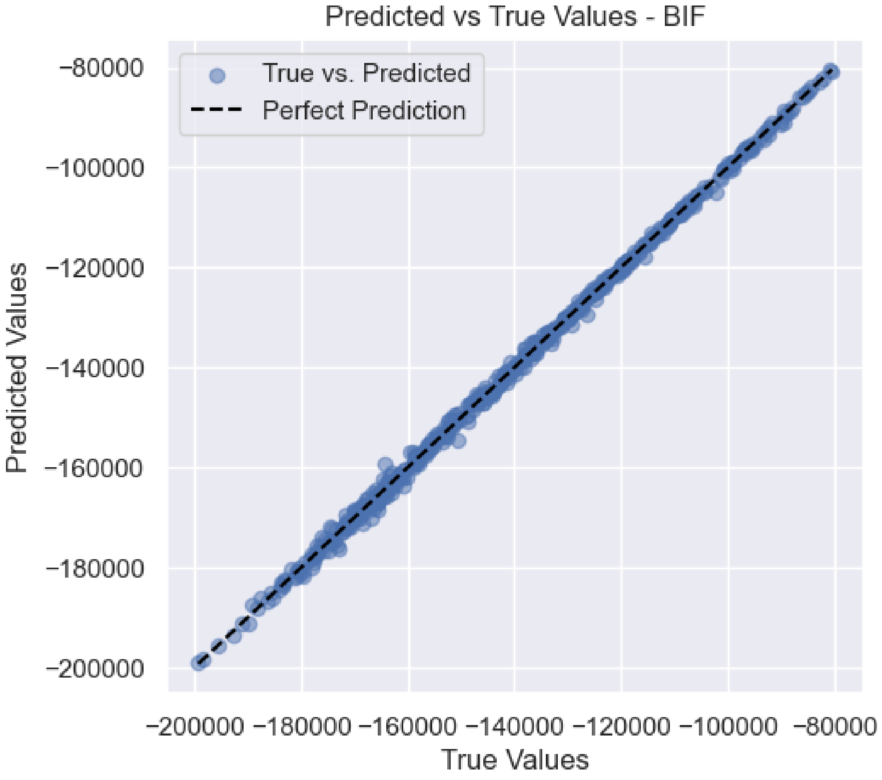


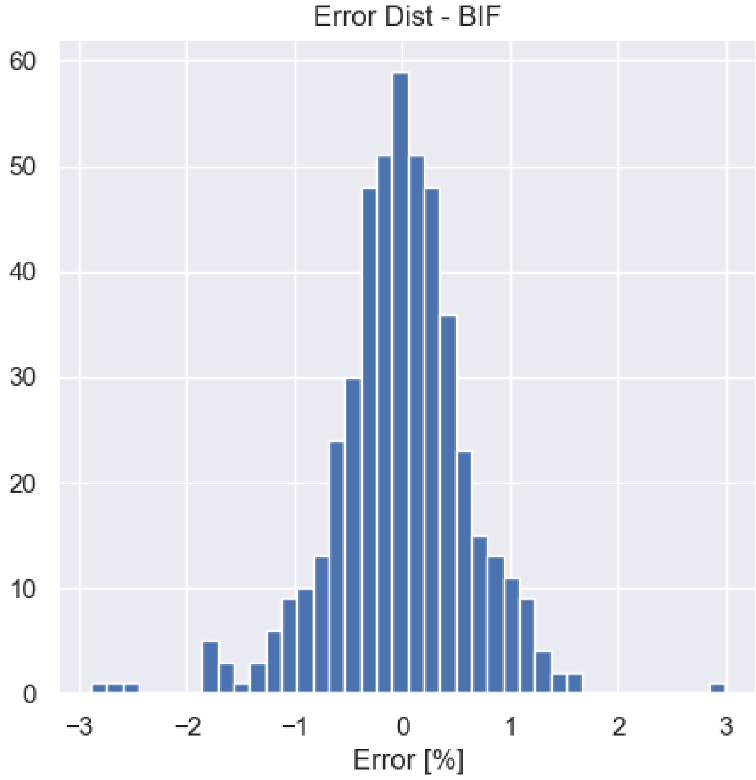
ML Pipeline

Results

Buckle Initiation Force (min ESF1)

```
Train/Test Ratio: 83/1000
Median Value: -140.5 kN
Error 2xSTD : [-0.9208 kN, -0.9311 kN]
```





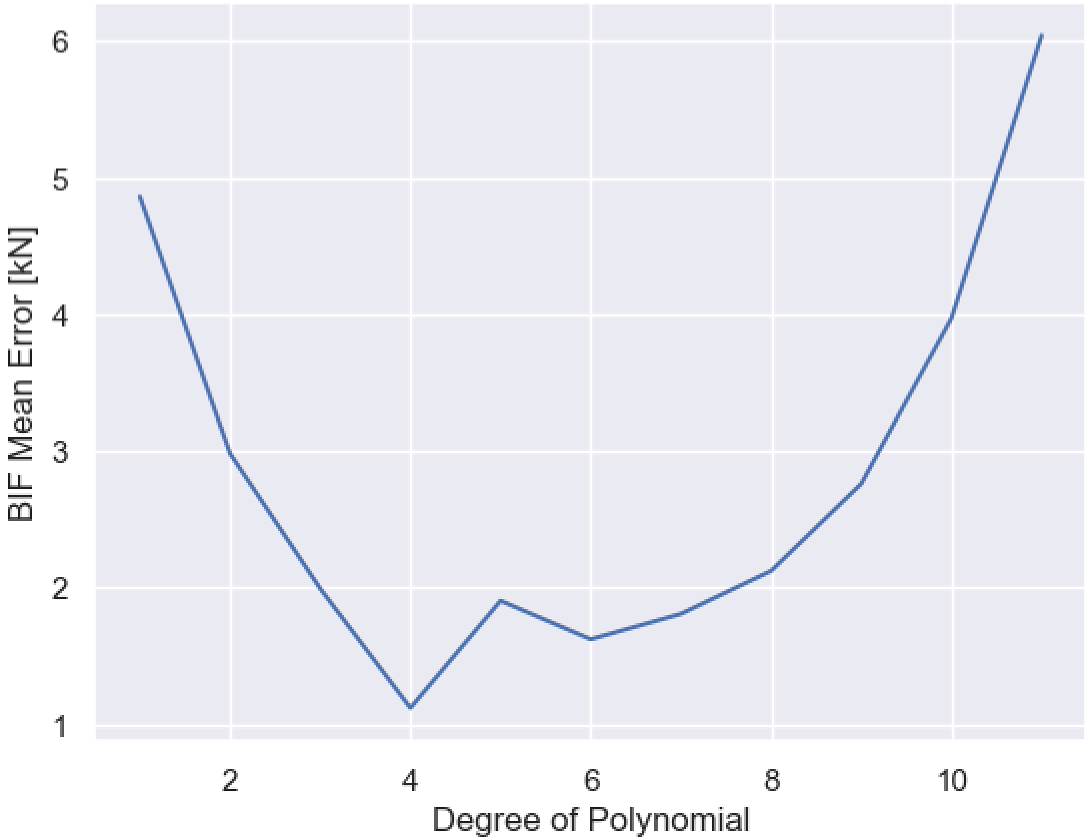
Results

Analytical Equation - BIF

BUCKLE_INITIATION_FORCE

(Polynomial Degree = 2; 15 Parameters)

8953.177 + 122121.43 * *SLEEPER_HEIGHT* -410.68 * *SLEEPER_FRICTION* + 628.01 * *AXIAL_FRICTION* - 117.21 * *LATERAL_FRICTION* -26079.75 * *SLEEPER_HEIGHT*^**2** + 1415.82 * *SLEEPER_HEIGHT* * *SLEEPER_FRICTION* -168.37 * *SLEEPER_HEIGHT* * *AXIAL_FRICTION* + 200.59 * *SLEEPER_HEIGHT* * *LATERAL_FRICTION* 2724.85 * *SLEEPER_FRICTION*^**2** -1499.433 * *SLEEPER_FRICTION* * *AXIAL_FRICTION* -188.181 * *SLEEPER_FRICTION* * *LATERAL_FRICTION* -158.17 * *AXIAL_FRICTION*^**2** + 185.08 * *AXIAL_FRICTION* * *LATERAL_FRICTION* -119.39737 * *LATERAL_FRICTION*^**2**

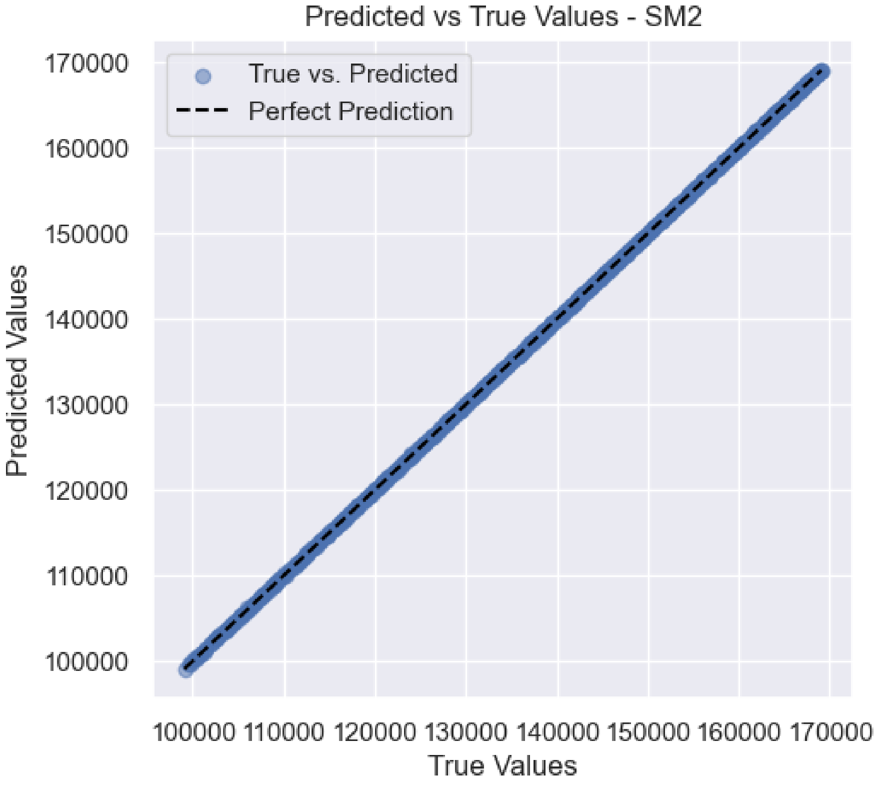


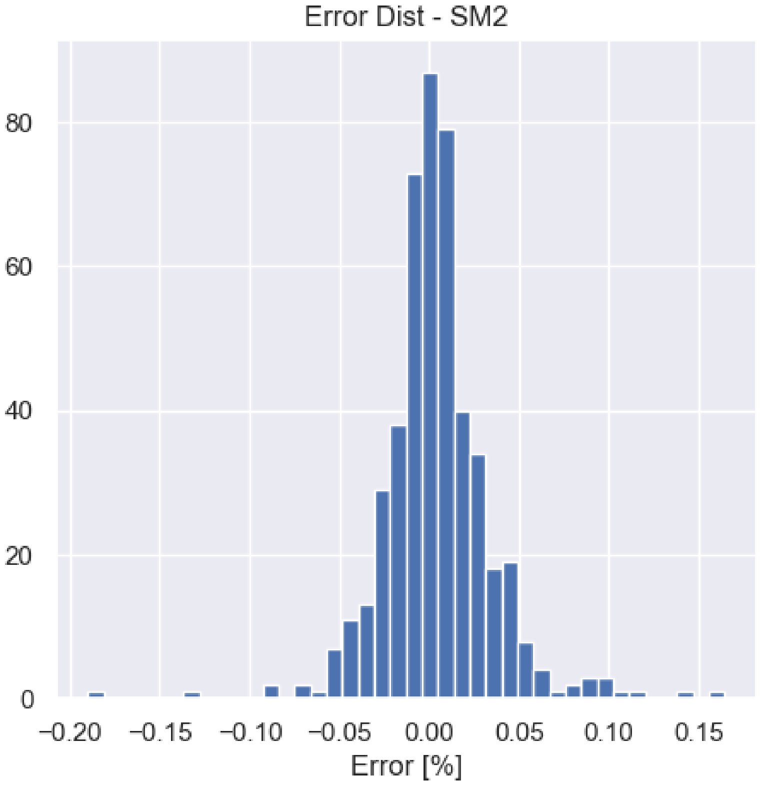
(Polynomial Degree = 4; 70 Parameters)

Results

Section Moment (SM2)

```
Train/Test Ratio: 52/1000
Median Value: 138.3 kN.m
Error 2xSTD : [0.0208 kN.m, 0.0136 kN.m]
```

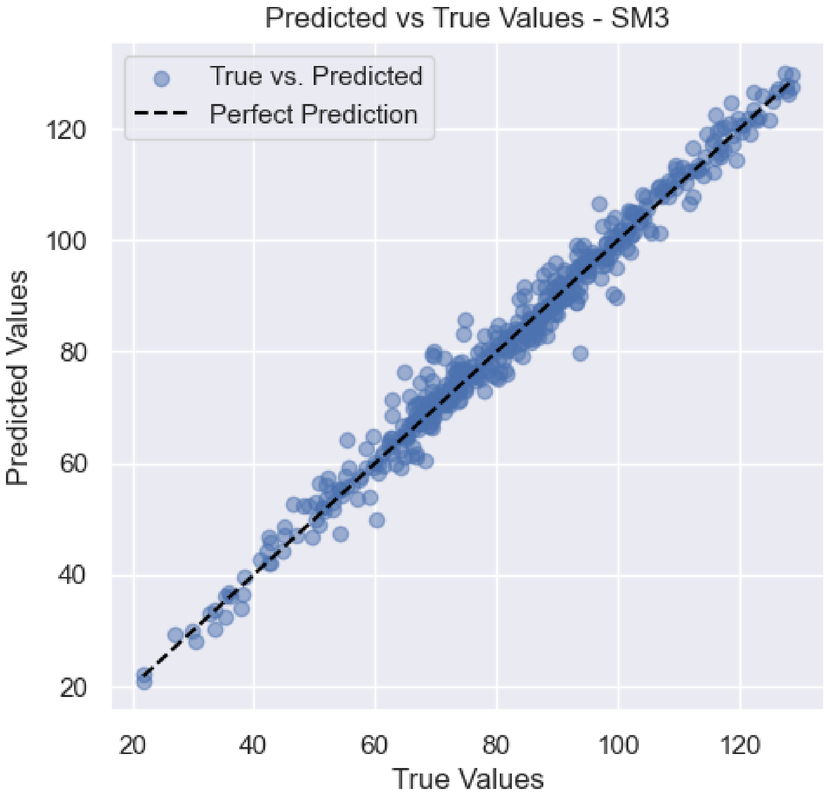


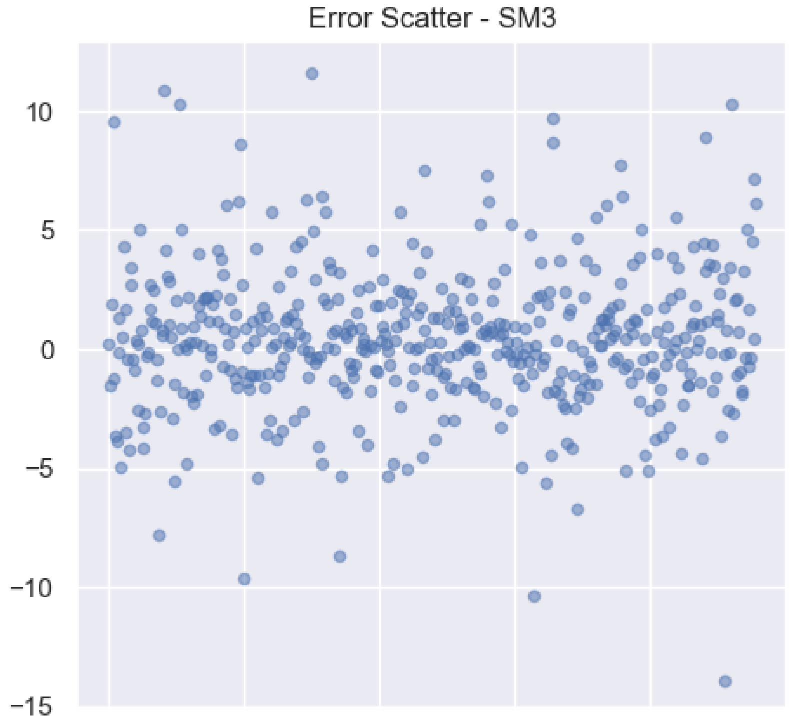


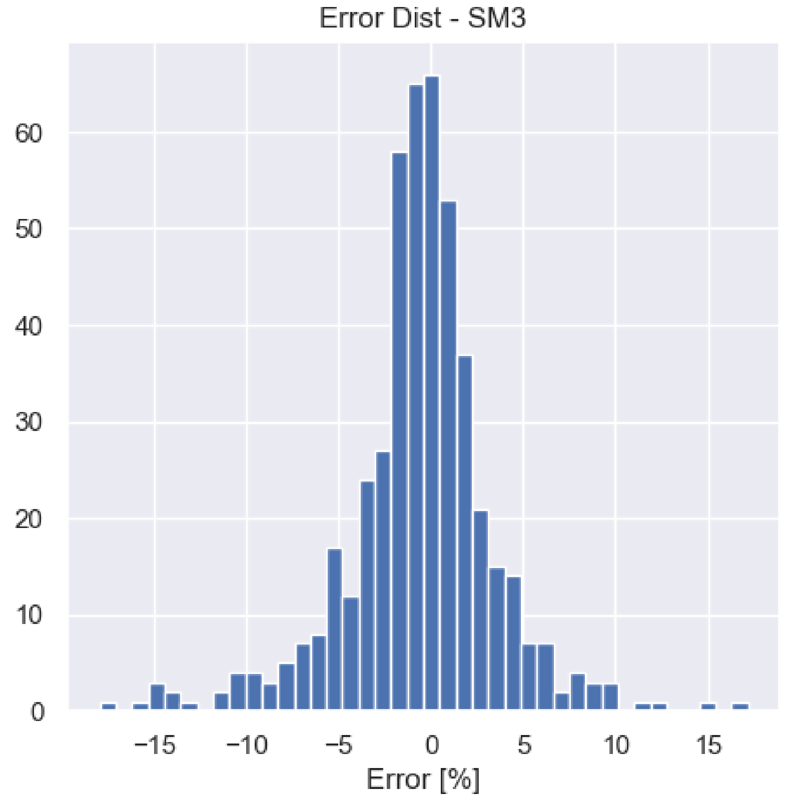
Results

Section Moment (SM3)

```
Train/Test Ratio: 95/1000
Median Value: 82.47 kN.m
Error 2xSTD : [0.0111 kN.m, 0.0112 kN.m]
```



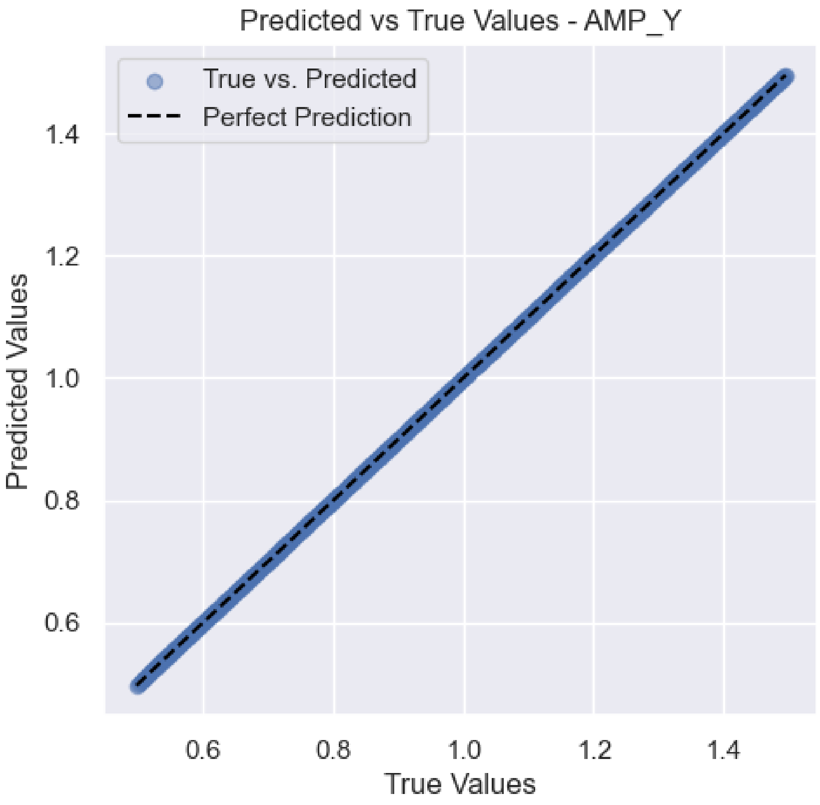


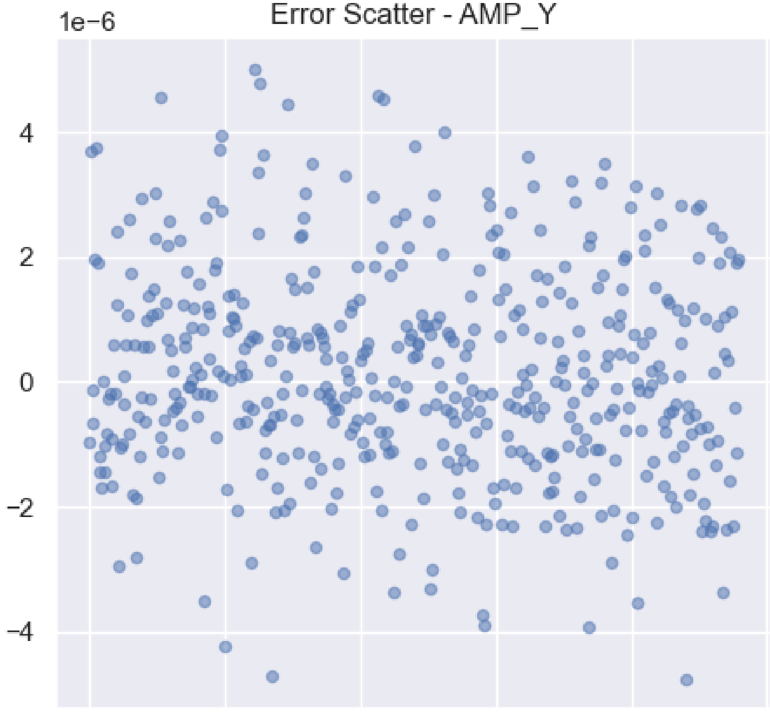


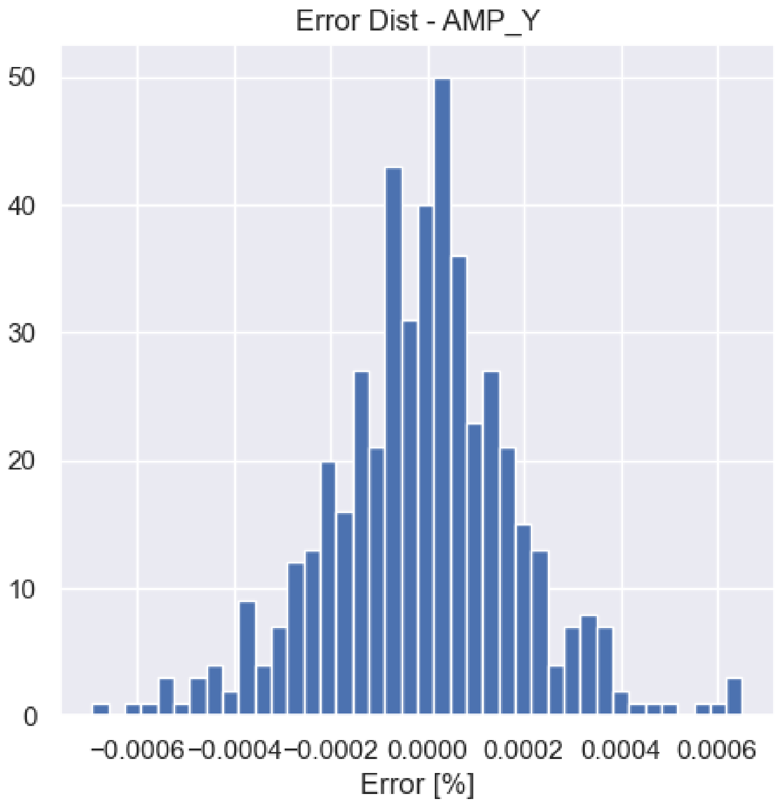
Results

Vertical Amplitude (AMP_Y)

```
Train/Test Ratio: 29/1000
Median Value: 1.01 m
Error 2xSTD : [0.00051 m, 0.00053 m]
```



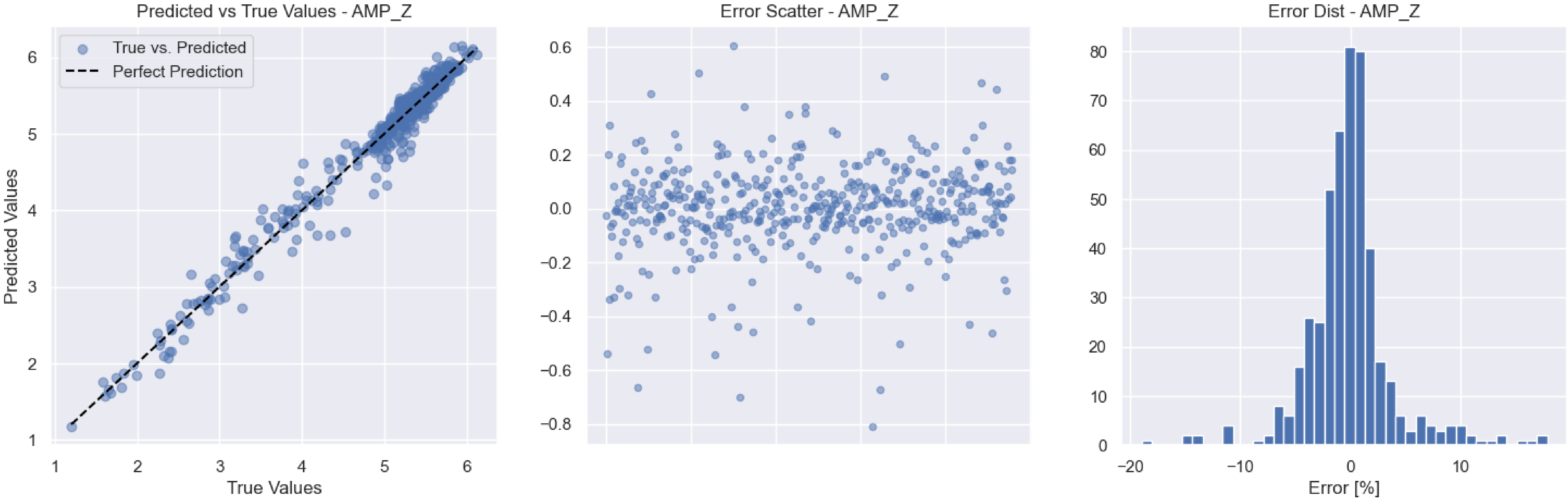




Results

Lateral Amplitude (AMP_Z)

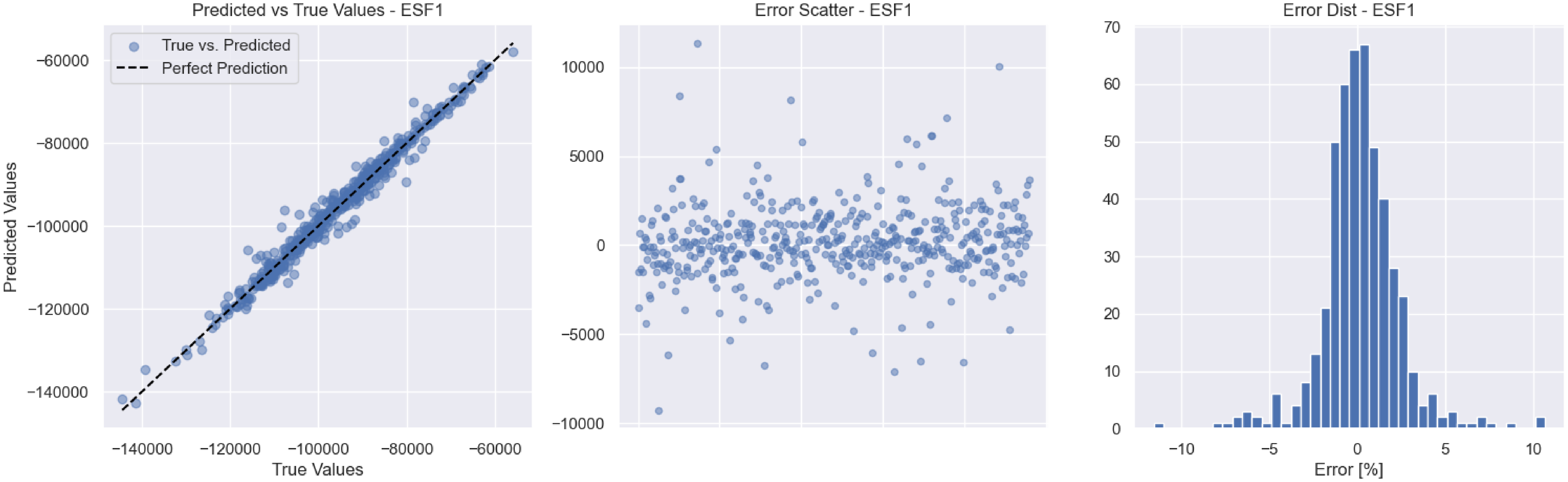
```
Train/Test Ratio: 100/1000
Median Value: 5.25 m
Error 2xSTD : [-0.051 m, -0.053 m]
```



Results

Effective Axial Force (ESF1)

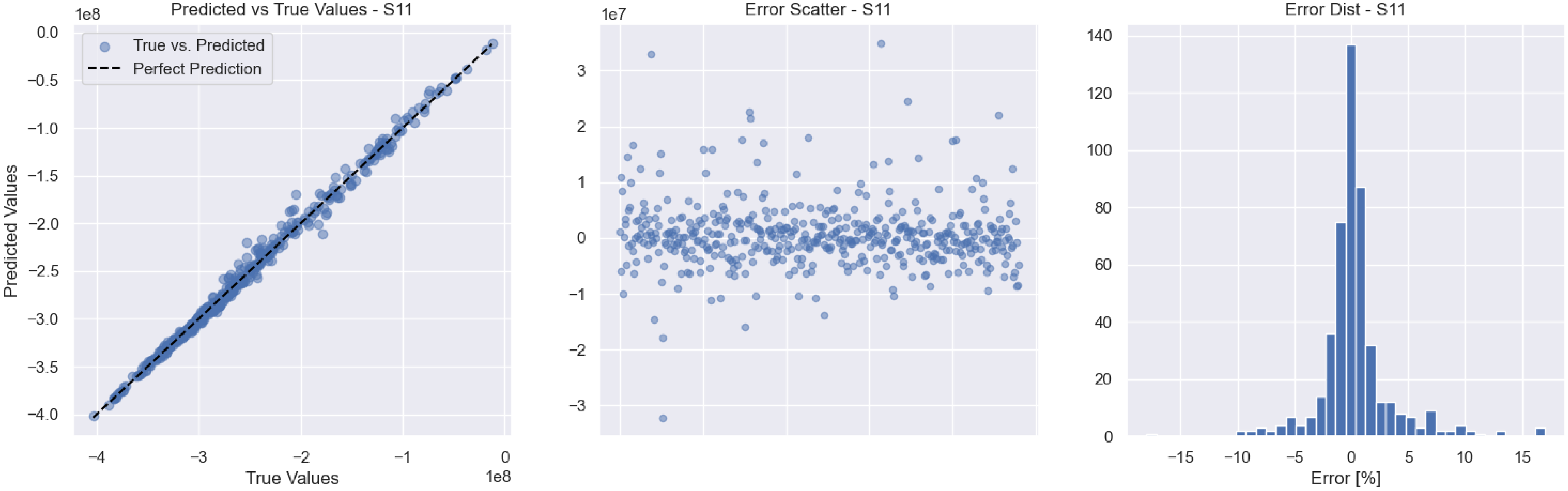
```
Train/Test Ratio: 100/1000
Median Value: -96.32 kN
Error 2xSTD : [1.841 kN, 1.834 kN]
```



Results

Axial Stress (S11)

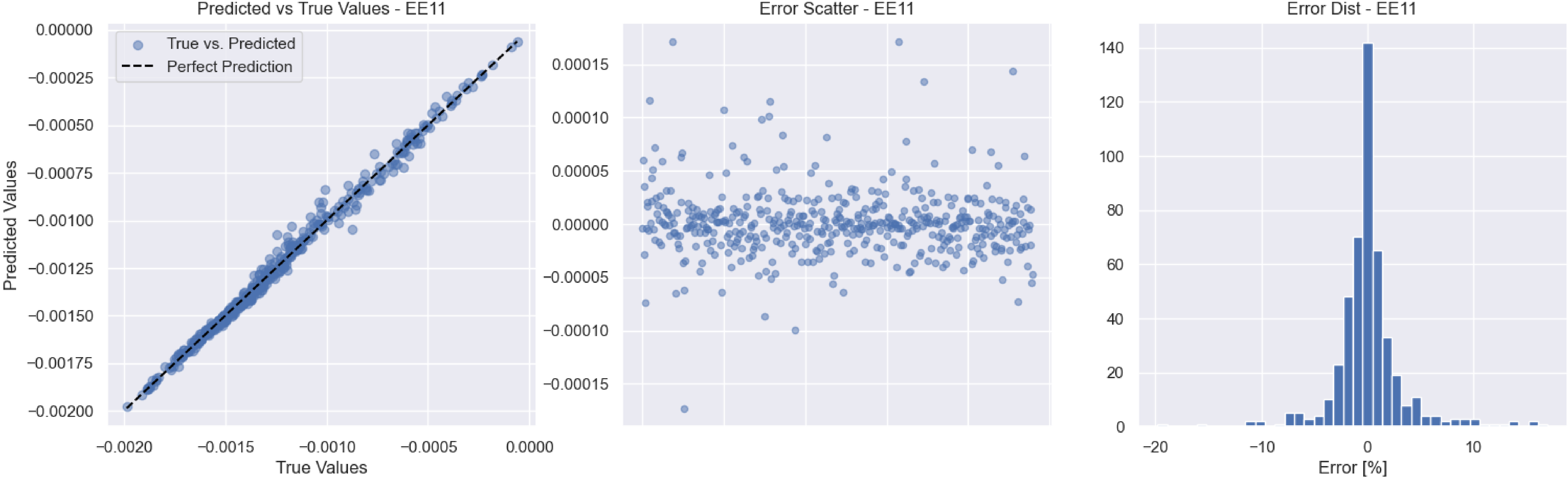
```
Train/Test Ratio: 87/1000
Median Value: -275 MPa
Error 2xSTD : [-0.0834 MPa, -0.0837 MPa]
```



Results

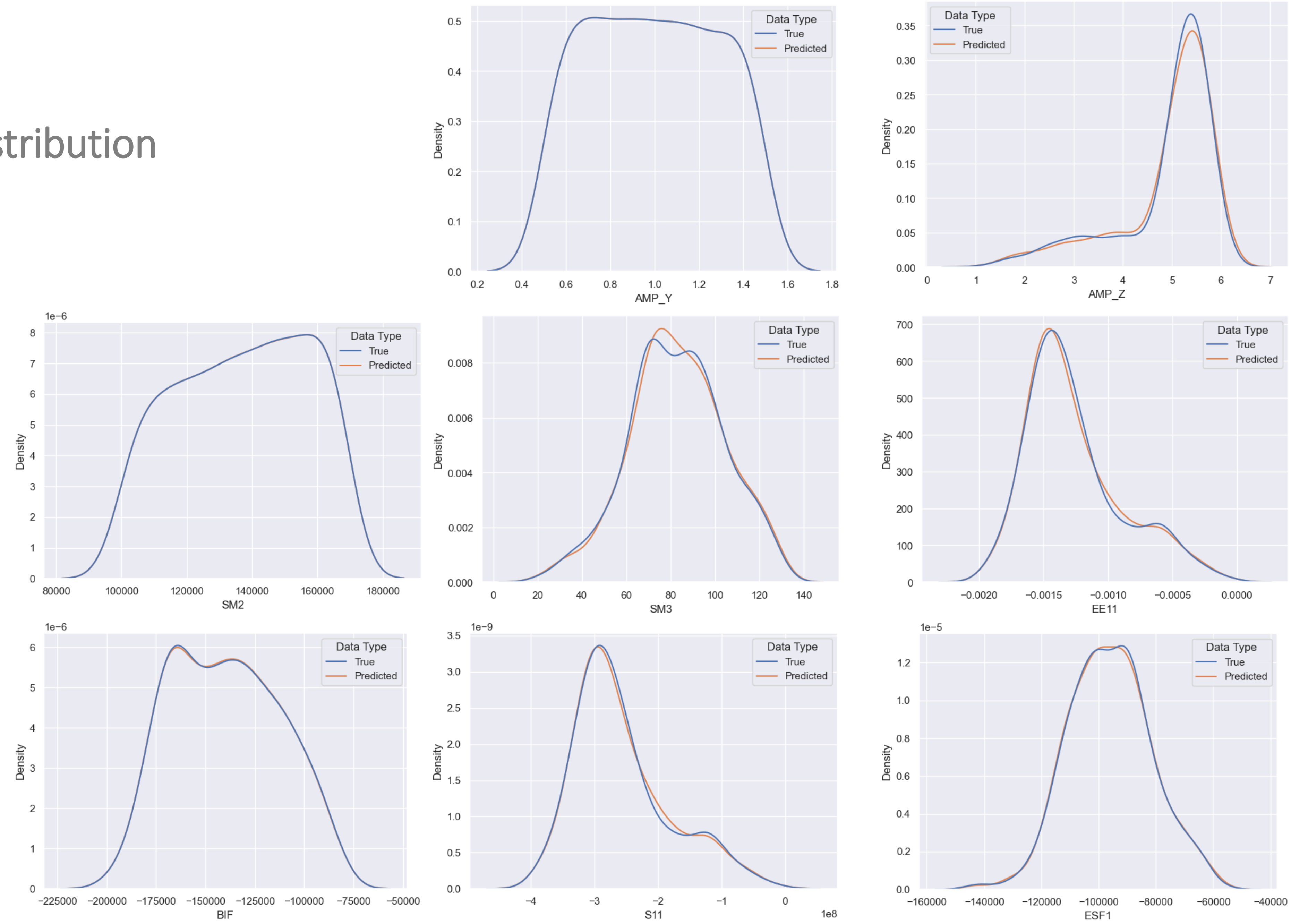
Total Strain (E11). PE11 = 0

```
Train/Test Ratio: 69/1000
Median Value: -0.001353
Error 2xSTD : [0.0000365, 0.0000364]
```

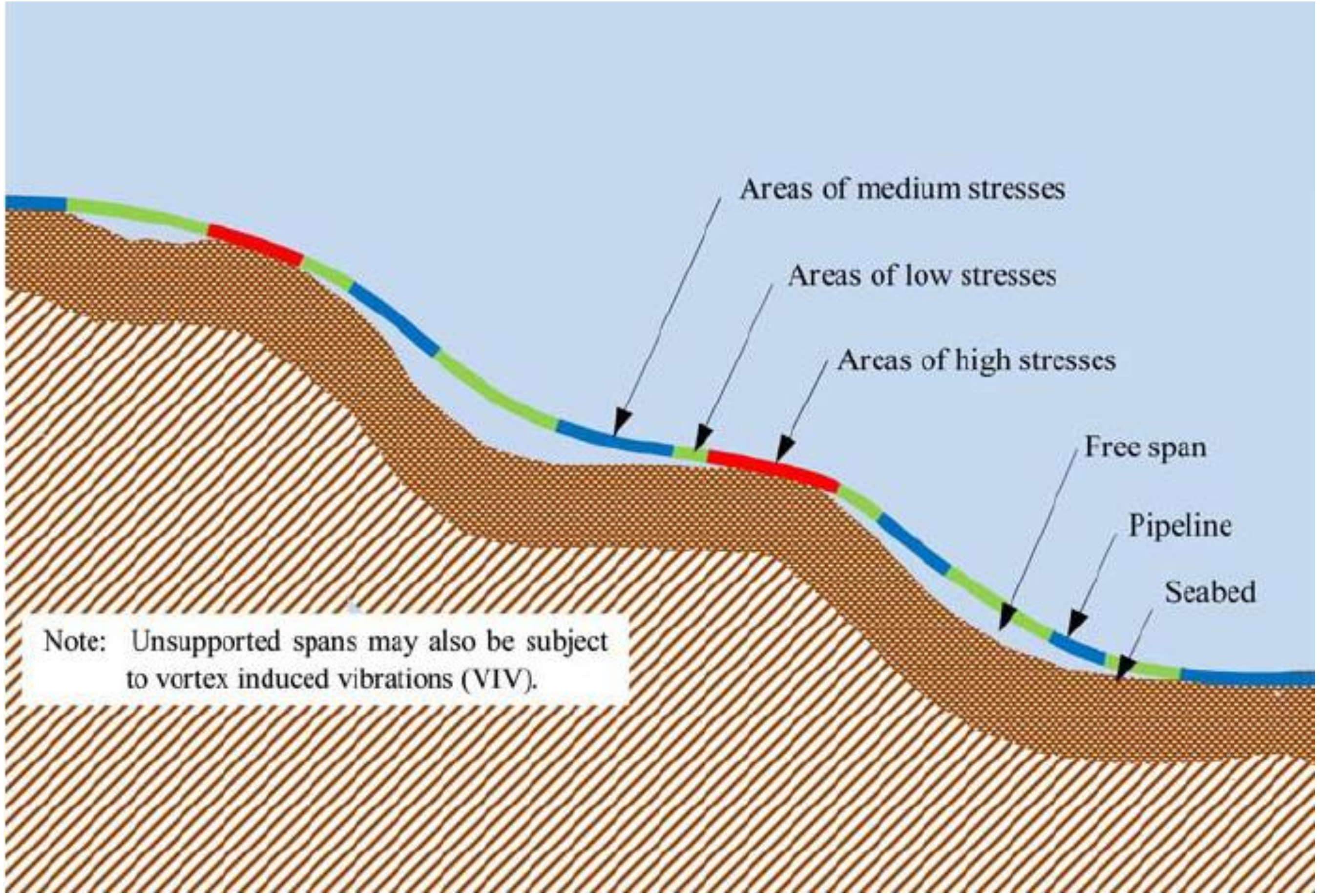


Results

True vs Predicted Distribution



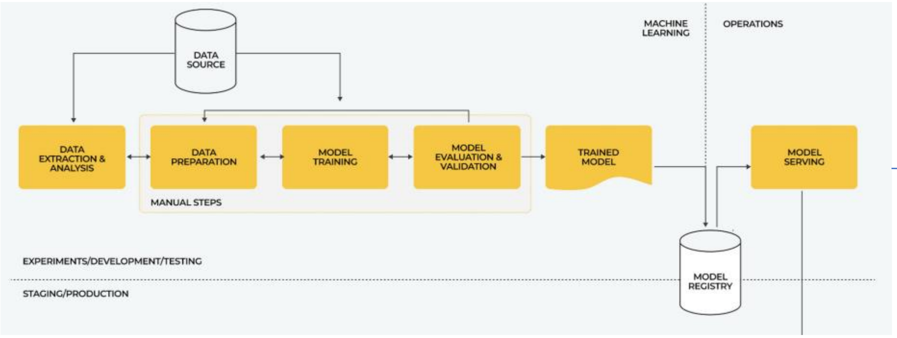
Seabed Topography



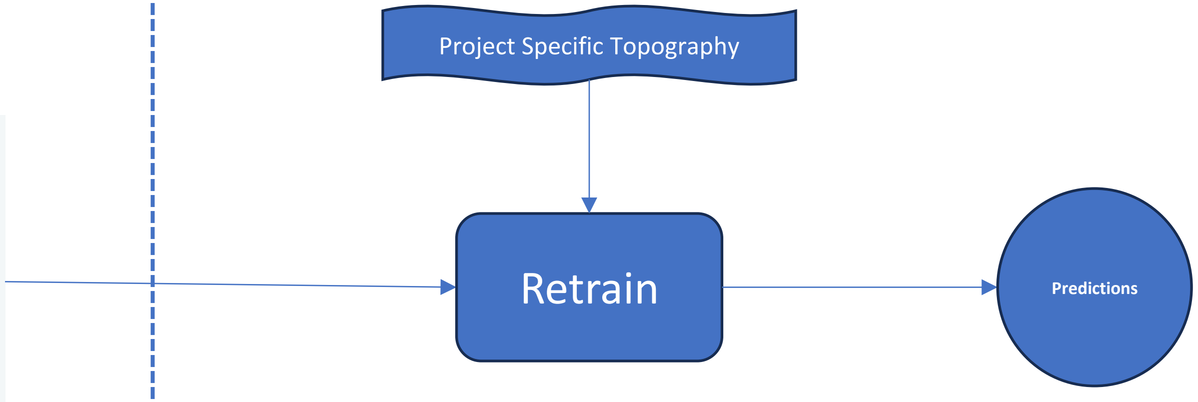
ML Pipeline for Uneven Seaved

Offline

Online



Pre-trained Model



Retrain on each project

Thank you