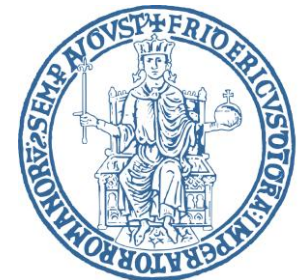


LINKING TRAFFIC CONGESTION TO VEHICLE COMPONENTS WEAR: A PREDICTIVE MAINTENANCE PERSPECTIVE

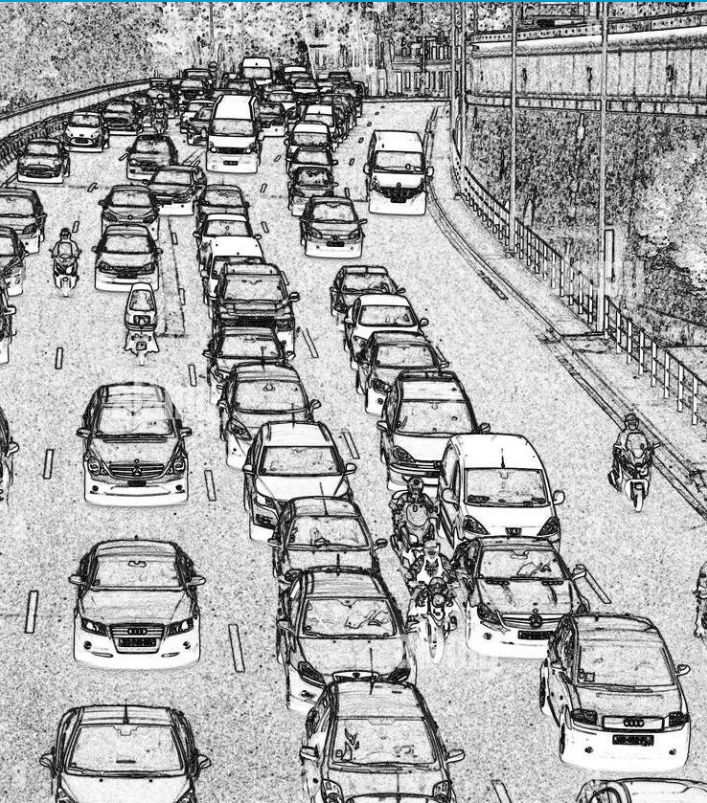
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Background



Sustainable mobility is associated to the reduction of **environmental impact**

*“The main challenge that **battery industries** have to face is the production of high-performance devices capable to **prevent aging**.” [1]*

*“For clean vehicles also the non-exhaust **emissions** caused by the **abrasion of** components like the **brakes** must be considered.” [2]*

Intelligent Transport Systems technologies are crucial to reduce **traffic congestion** and **component degradation** for a sustainable mobility



[1] Şen M et al. *A review on the lithium-ion battery problems used in electric vehicles*. Next Sustain 2024; 3:100036.

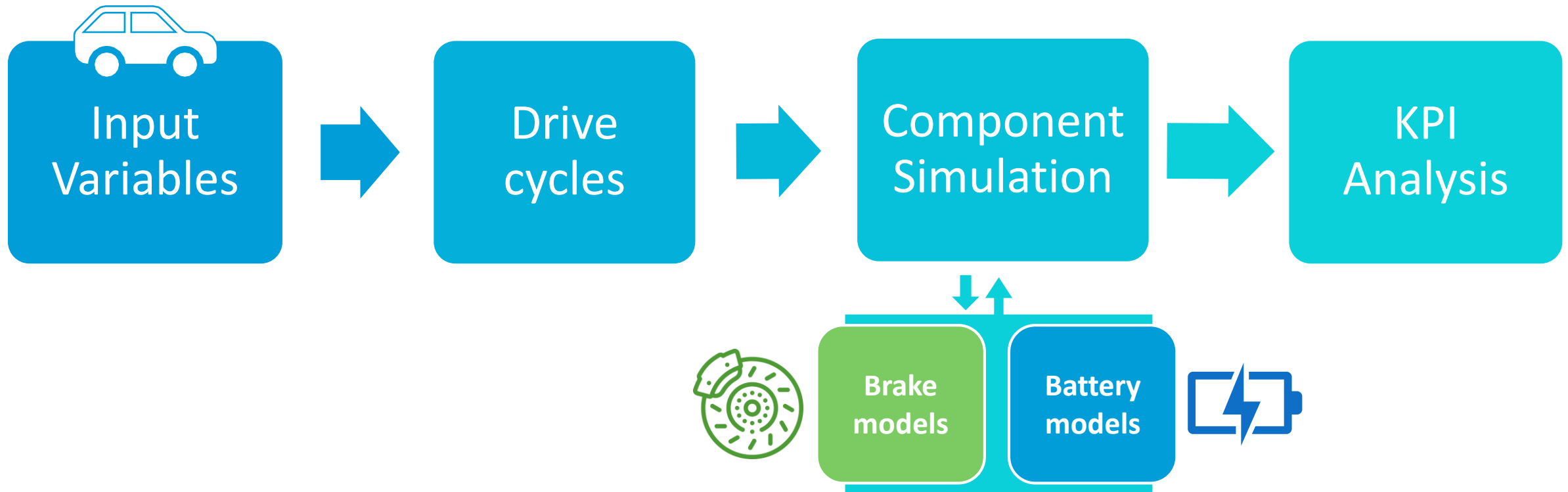
[2] Automotive Engineering, *Europe’s dust buster*, 2023-05-19, Bill Visnic

The question is...

Does a correlation exist between the traffic demand and the degradation or loss of performances of vehicle components?

A simulation approach is used for the components and the traffic modeling. Statistical methods are used for the design of experiments and the data analysis.

Methodology



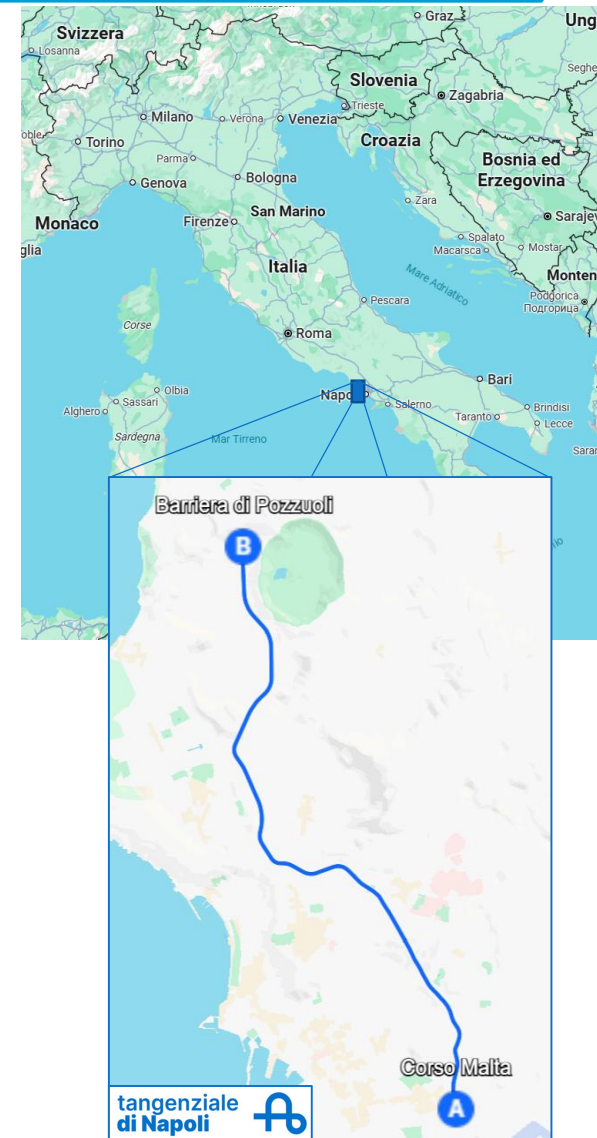
KPI: Key Performance Indicator

Methodology /Route and vehicle characteristics

- The controlled vehicle moves across the **tangenziale di Napoli** from Corso Malta (A) to Pozzuoli Toll Plaza (B)
 - Travelled distance: about 12 km
 - Travel time in free-flow conditions: 500 s (about 10 minutes)
- Traffic Demand synthetically generated
 - Total Generation Rate = 1500 vehicles to insert per hour (almost empty road) [3]
- Human-driven vehicles behaviour [4]
 - Acceleration range = $[-5, 2]$ m/s²
 - Length = 5 m
 - Standstill distance = 1.5 m; gap-distance = 1.2 s
 - Desired Speed is normally distributed between 80% and 120% of the legal speed limit.
- Insertion time of controlled vehicle: 600 s



from

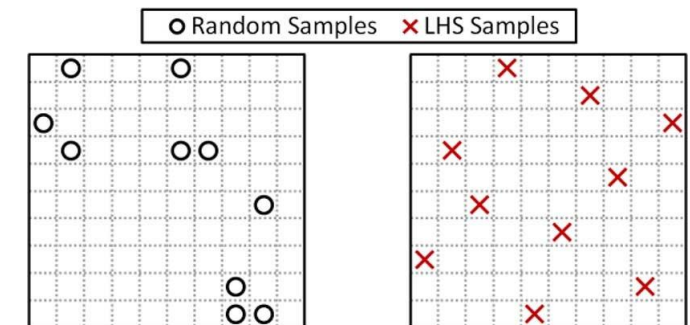


[3] Guastella, D. A., and Gianluca B., "Traffic modeling with SUMO: A tutorial." arXiv preprint arXiv:2304.05982 (2023).

[4] Coppola, A., Di Costanzo, L., Pariota, L., & Bifulco, G. N., "Fuzzy-based variable speed limits system under connected vehicle environment: A simulation-based case study in the city of Naples." IEEE Open Journal of Intelligent Transportation Systems, 4, 267-278 (2023).

Methodology / Variables and DoE

- 1 Input variable
 - 0-D Scale factor of the Traffic Demand $\in [1, 7]$
- 6 Output Variables used as Key Performance Indicators
 - Battery State of Charge (SOC) [%]
 - Energy for Battery Cooling [J]
 - Battery Capacity (Q) loss [%]*
 - Brake Pad Consumption (h) [mm]
 - Brake Heat [J]
 - Brake Pad State of Health (SOH) [%]
- Design of Experiment
 - Latin-Hypercube-Sampling (LHS) approach is used to generate a multidimensional homogenous space of input factors [5]
 - 100 simulation runs, each of which is characterized by a different value of *Scale factor*



[5] Song, Chenxiao, and Reiichiro Kawai. "Monte Carlo and variance reduction methods for structural reliability analysis: A comprehensive review." Probabilistic Engineering Mechanics 73 (2023): 103479.

* Only Q loss is not relative the 1 cycle but 1500 consecutive cycles

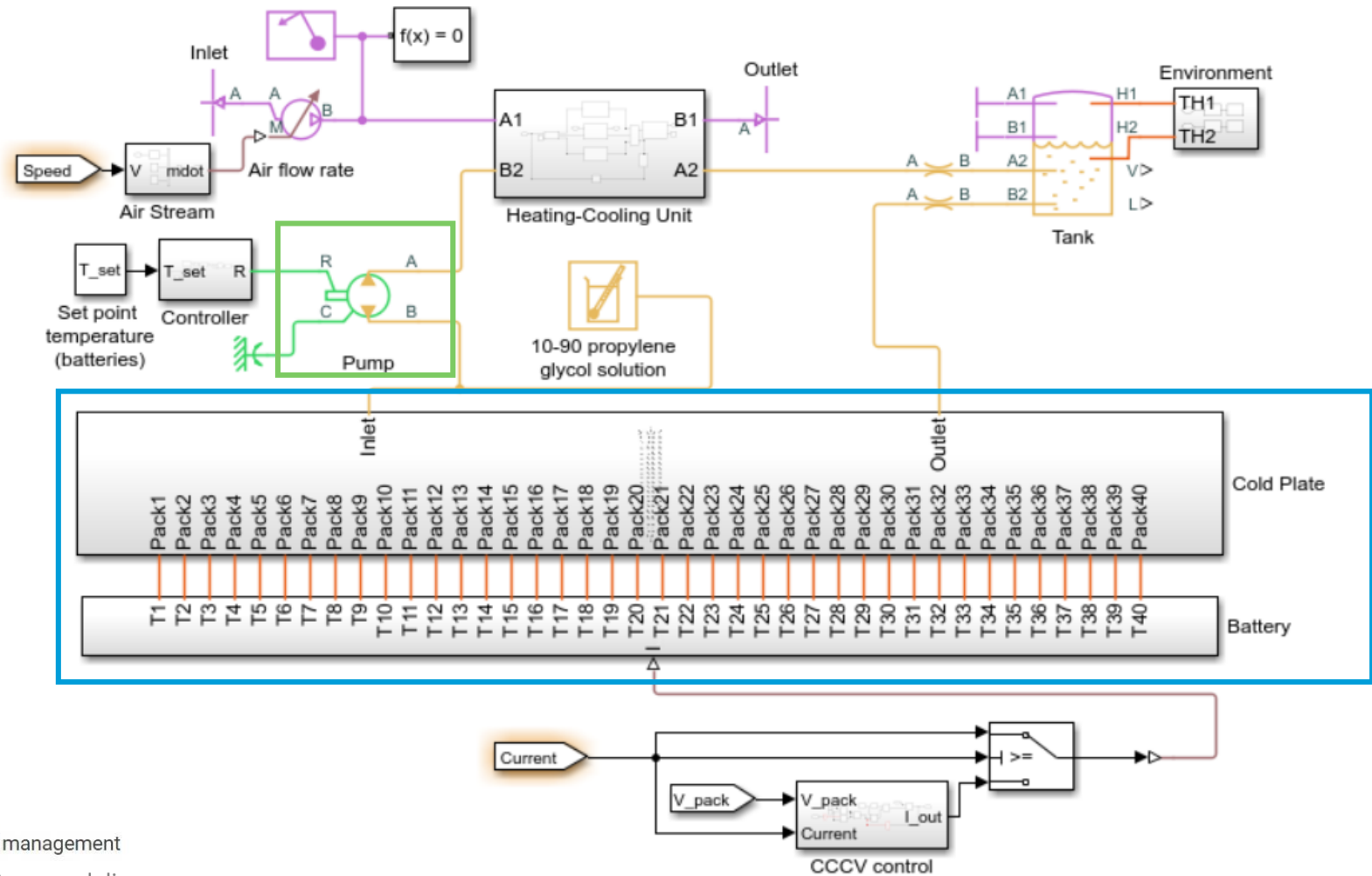
Methodology / Model of the battery

Battery State of Charge (SOC) [%]
Energy for Battery Cooling [J]

The model is available online [6] and has been tuned on purpose [7]

The blocks in the colored-squares represent:

- Battery and Cold plate
- Liquid cooling pump



Battery Modeling

version 1.27 (2.16 MB) by Javier Gazzarri **STAFF**

Lithium ion battery characterization, state estimation, cell balancing, and thermal management

[6] <https://it.mathworks.com/matlabcentral/fileexchange/36019-battery-modeling>

[7] Sequino, L., Mancaruso, E., and Vaglieco, B. M. (2021). *Modeling study of the battery pack for the electric conversion of a commercial vehicle*, SAE Paper 2021-24-0112.

Methodology /Model of the battery

Battery Capacity (Q) loss [%]

$$Q_{loss} = B \cdot \exp \left[\frac{-31700 + 370.3 \cdot C_{rate}}{RT} \right] \cdot (A_h)^{0.55} \quad [8]$$

where:

B=30330 (tuning parameter from [8])

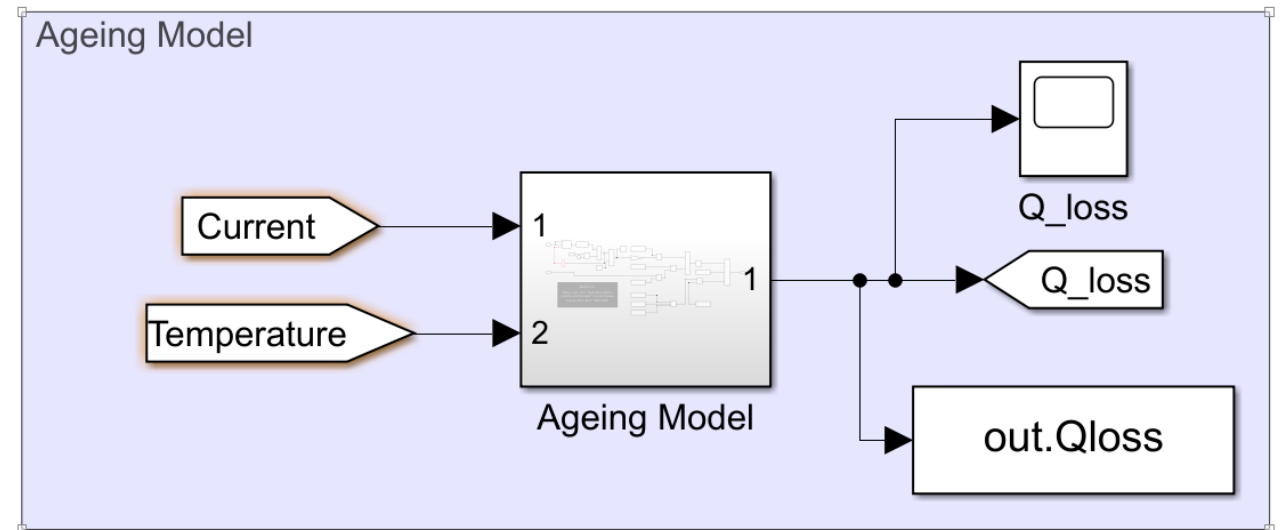
R=8.314 Jmol⁻¹K⁻¹

Ah= N*DOD*Capacity

and:

N= 1500 (One charge-recharge cycle each 3 days for 10 years)

DOD (Deep Of Discharge) = 0.8



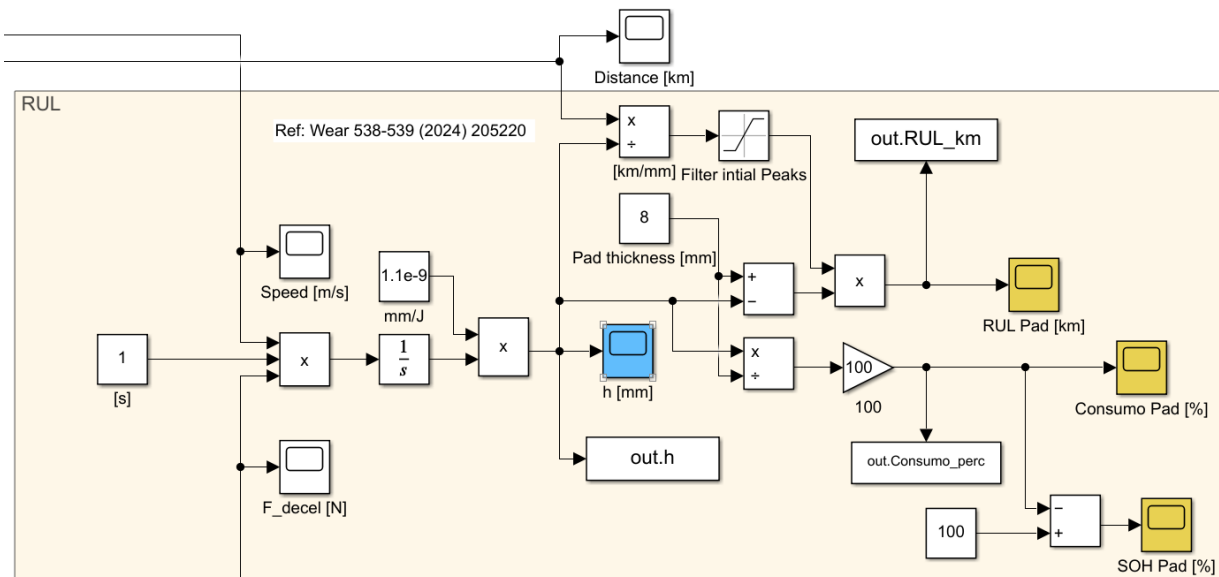
[8] Wang J. et al. "Cycle-life model for graphite-LiFePO4 cells", J. of Power Sources 196, 8 (2011)

Methodology /Models of the brake

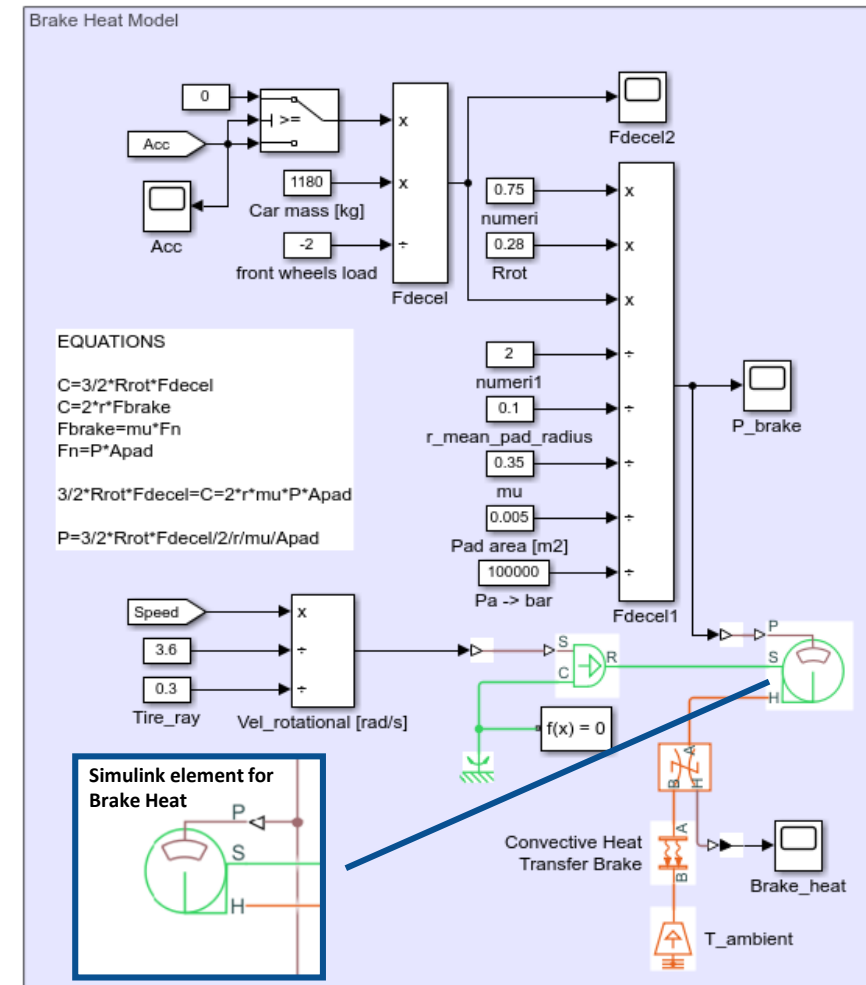


Brake Pad Consumption (h) [mm]
Brake Pad State of Health (SOH) [%]

$$\left(\sum_n h_n \right) = k_i \left(\sum_n F_{t,n} \Delta d_n^{brake} \right) \quad [10]$$



Brake Heat [J]



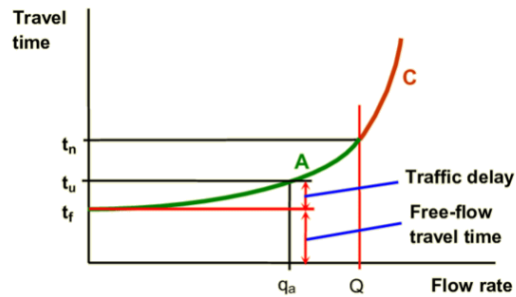
[10] Jensen, K. M. et al. (2024). Estimation of brake pad wear and remaining useful life from fused sensor system, statistical data processing, and passenger car longitudinal dynamics. Wear 538.

Methodology /Data Assessment

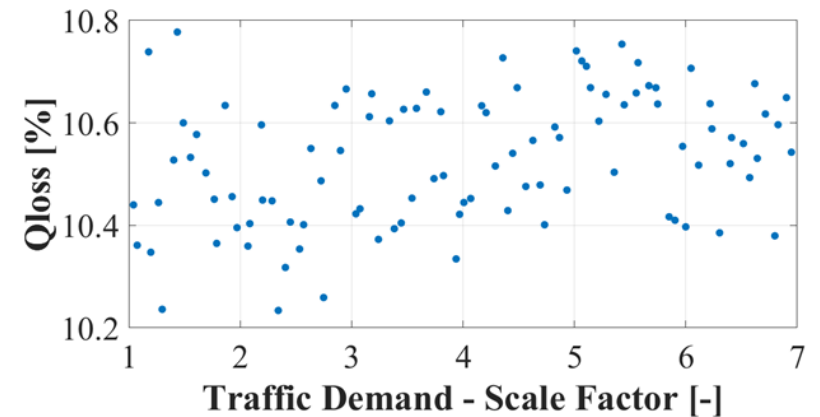
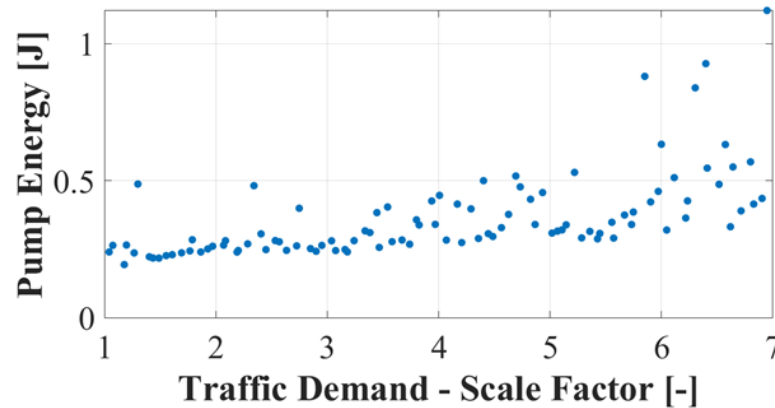
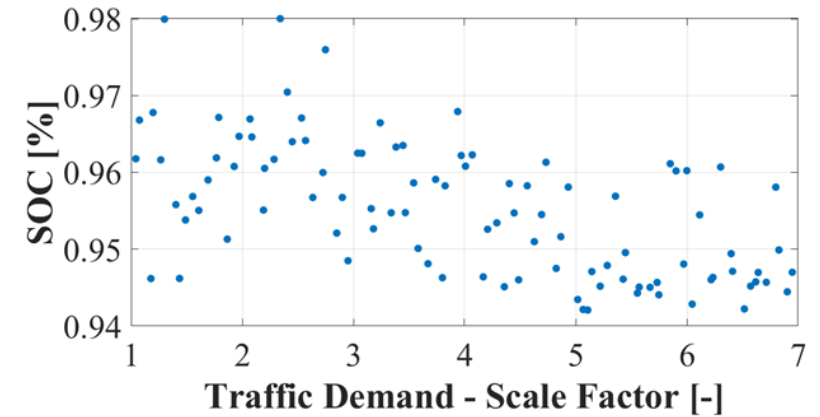
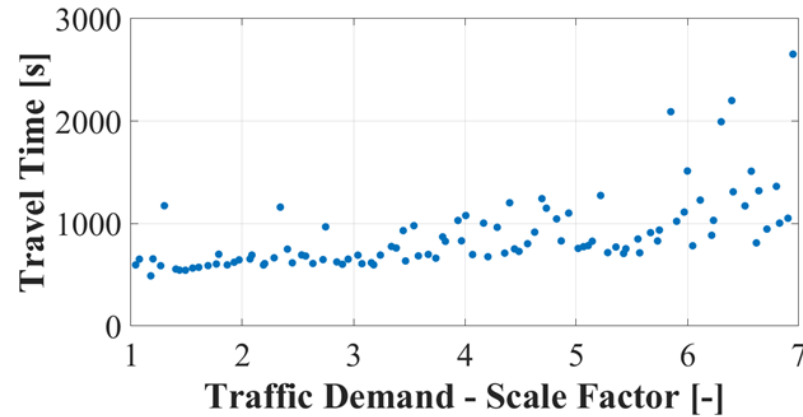
- Qualitative assessment
 - Scatter plots of the Input variable (Traffic Demand) against the 6 Output variables
- Quantitative assessment
 - Analysis of each Input-Output relationship via data fitting; considered models are:
 - 1-degree Polynomial (linear),
 - 2-degree Polynomial,
 - 1-term Exponential,
 - 2-terms Exponential,
 - 1-term Sum of Sine,
 - 1-term Power,
 - 1-term Gaussian.
 - Normalized Root Mean Squared Error (NRMSE) is used to determine the best fit.
 - Comparison among the linear and the optimal model

Results /Qualitative Assmt. for Battery Variables

- **Travel time:** positive trend with TD. Abrupt increase at 6.

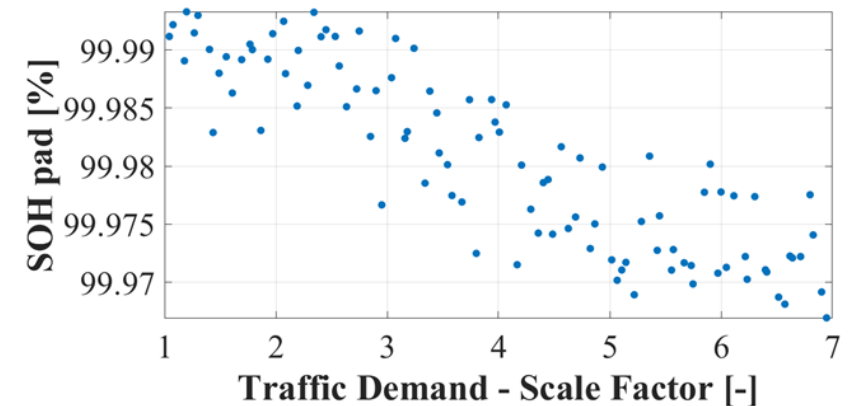
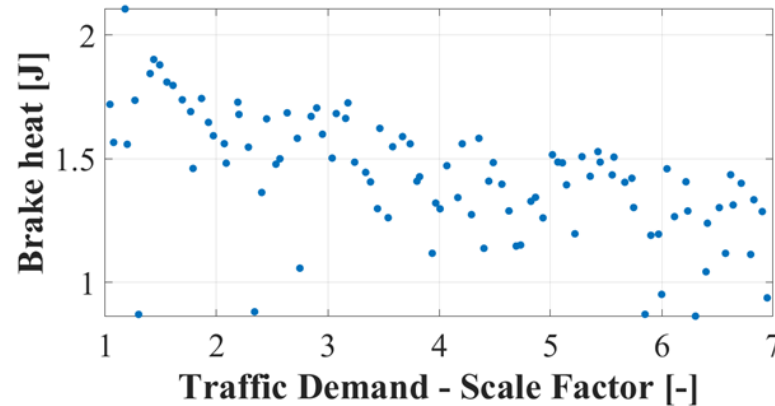
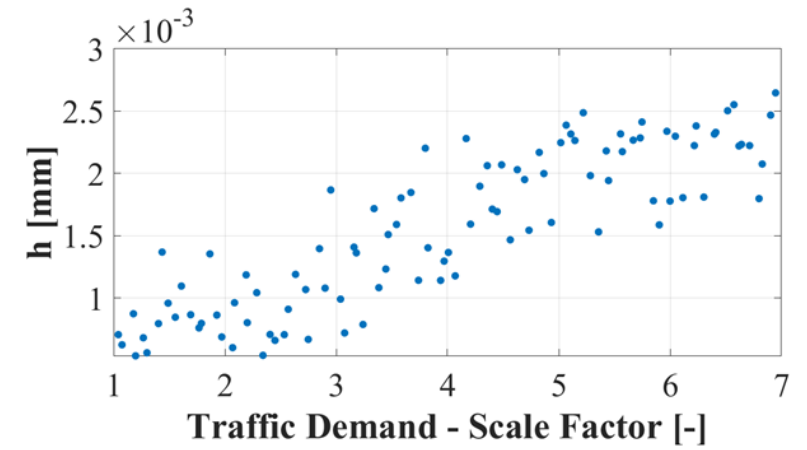
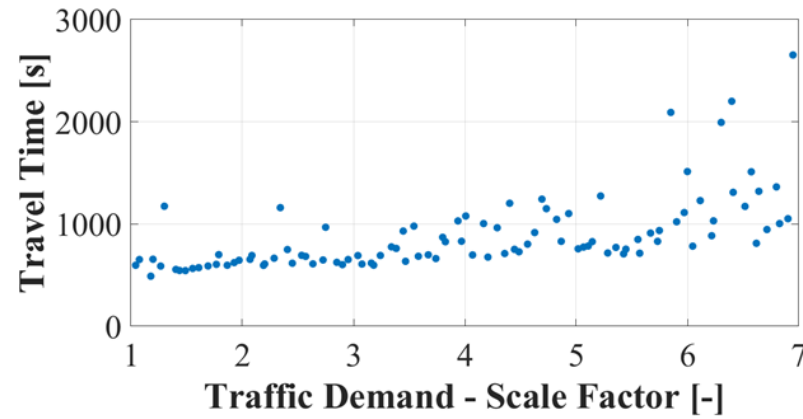


- **Battery SOC:** negative trend with TD. Higher TD implies highly variable energy supply.
- **Battery cooling energy:** the pump is always active, same trend of the travel time.
- **Battery loss of capacity:** slightly positive trend. Higher TD and variable energy supply are detrimental for battery ageing.



Results /Qualitative Assmt. for Brake Variables

- **Travel time:** positive trend with TD. Abrupt increase at 6.
- **Brake pad consumption (h):** positive trend with TD. Higher TD implies more frequent brake events (30000 - 90000 km).
- **Brake heat generation:** negative trend with TD. It is linked to disk velocity. For low TD, the initial disk velocity is higher.
- **Brake Pad SOH:** negative trend with TD. It is derived from “h”. The pad wear increase for frequent brake events.



Results /Quantitative Assessment

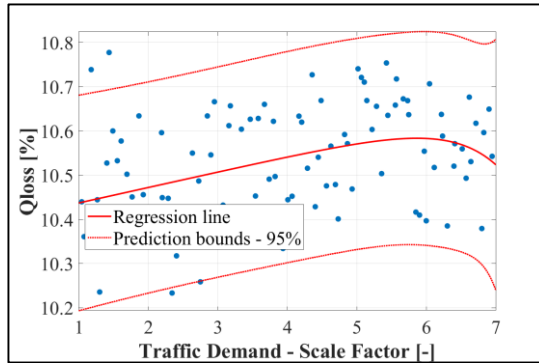
Each Input-Output relationship is analyzed via curve fitting using the following models:

- a. 1-degree Polynomial (linear),
- b. 2-degree Polynomial,
- c. 1-term Exponential,
- d. 2-terms Exponential,
- e. 1-term Sum of Sine,
- f. 1-term Power,
- g. 1-term Gaussian.

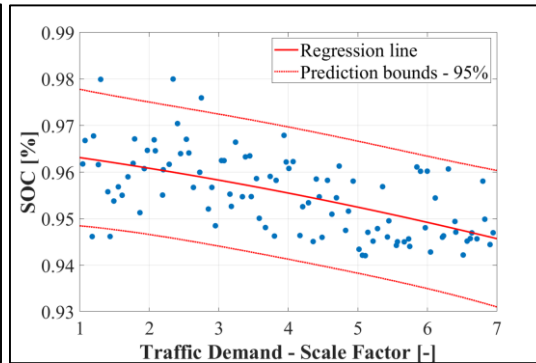
The NRMSE is used to find the best fit. Then a comparison among the linear and the optimal model is performed to simplify future data elaborations

Results /Quantitative Assessment

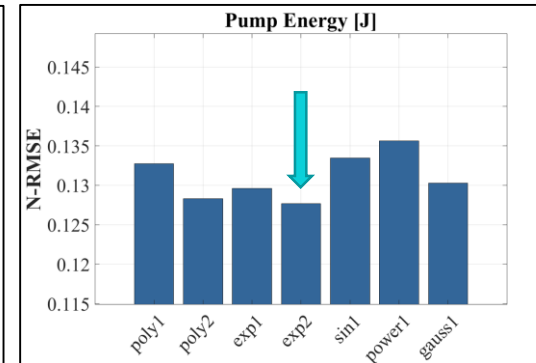
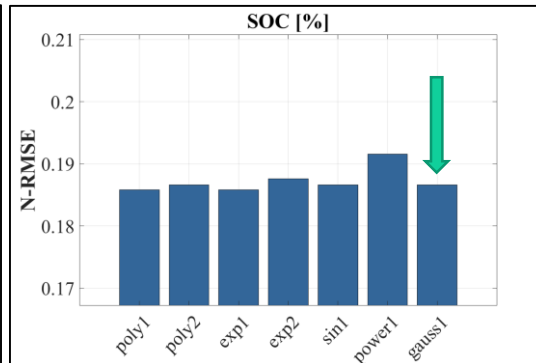
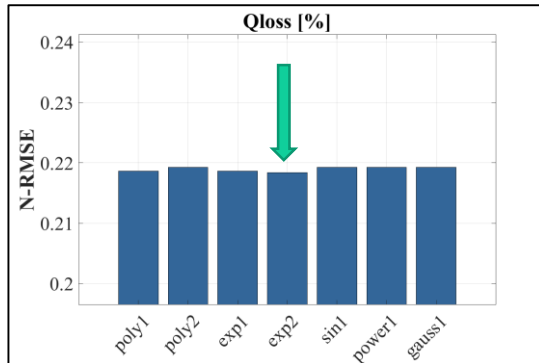
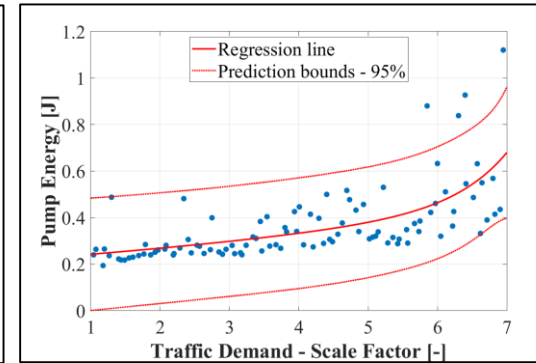
Positive



Negative



Positive



2-terms Exponential: 0.218

Linear: 0.219

1-term Gaussian: 0.187

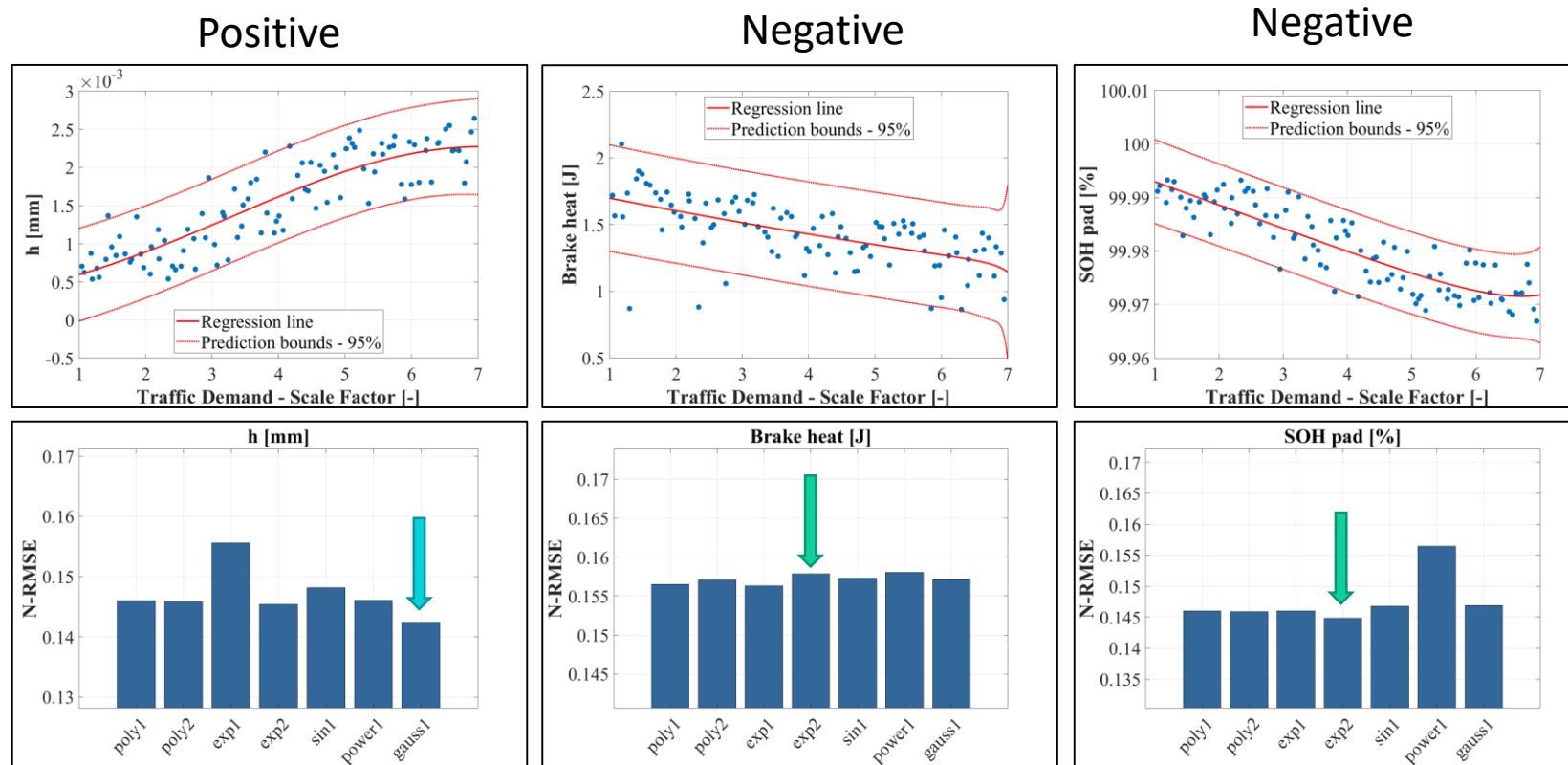
Linear: 0.186

2-terms Exponential: 0.128

Linear: 0.133



Results /Quantitative Assessment



1-term Gaussian: 0.142
Linear: 0.146



2-terms Exponential: 0.158
Linear: 0.157



2-terms Exponential: 0.145
Linear: 0.146



Main outcomes

Wear sources

TIME

- *Energy for cooling*

UNSTATIONARY CONDITIONS

- *SOC*
- *Q_{loss}*
- *Pad wear*

SPEED

- *Brake heat*

Wear behavior

The trend has a **2 terms Exponential** behavior

The trend has likely a **Linear** or **Gaussian** behavior but higher traffic conditions must be investigated

Conclusions

Some correlations exist between the traffic demand and the degradation of different vehicle components

To answer to this question, a numerical approach was used by combining **Urban Simulation and Multi-Domain models**. While a **statistical approach** was used for the data analysis.

- The methodology set up for this work is ready-to-use also for more input variables (only traffic is used here)
- The battery and brakes performance parameters were obtained from free-flow to saturated traffic flow
- Some correlations between the traffic demand and the selected parameters were actually found.
- Linear, Exponential, and Gaussian trends were found. Often a liner behavior can be accepted using a greater degree of approximation.
- The energy required for battery cooling depends on the operation time and then it showed a 2-terms exponential trend. Optimized thermal management strategies can help.
- The battery SOC, Capacity Loss, Brake Pad Wear and Heat are linked to non stationary conditions and speed. And they showed a linear or gaussian correlation to the traffic demand. Higher traffic conditions must be tested.

Further implementation of the results are in progress. The present work highlights that the knowledge of the traffic conditions can effectively be used for the prediction of the vehicle components wear.

THANK YOU FOR YOUR ATTENTION

Linking Traffic Congestion to Vehicle Component Wear: A Predictive Maintenance Perspective

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