Building digital worlds: computational design tools for emulating battery-electric locomotives

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Introduction

As with the fast-growing electrical vehicle (EV) market, the adoption of battery-electric locomotive (BEL) technology is primed to follow a similar trend. Limited modelling software, nor design specifications, are currently available to address this transition. This provides the opportunity to develop highly customizable, data-driven tools to evaluate the technical feasibility of BELs. Viable techno-economic design solutions can be emulated by combining:

1. Field measurement data (instrumented locomotives);
2. Remote satellite monitoring; and
3. Empirical lithium-ion battery performance models.

Computational Design Approach

An Integrated Systematized Design Process was followed (Figure 1) to create *TripView*: an emulation utility to emulate BELs and battery degradation metrics based on historical measurement data and satellite derived meteorology.

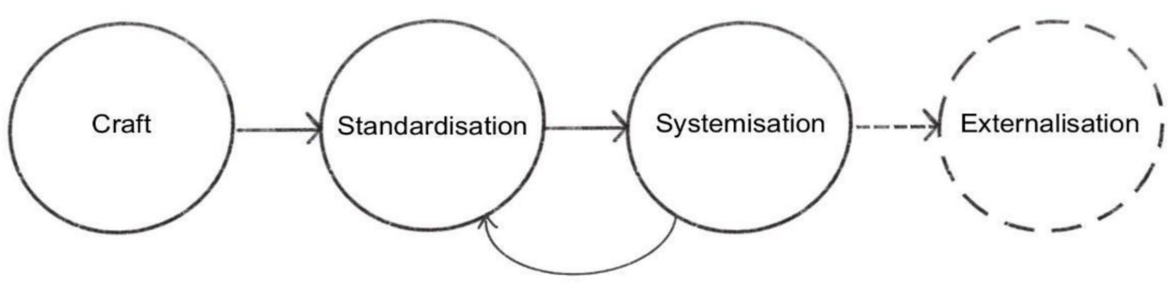

Figure 1. Integrated Systematised Design Process (Van der Laan et al., 2024)

NASA Power Dataset (n.d.) provided historical temperature, wind speed and direction on an hourly basis (Figure 2). A Python script queried the API to retrieve one-hour temporal data spanning a 5-year period (2018-2023). These measurements map directly to the auxiliary power consumption of the BEL, comprising battery cooling in addition to standard locomotive power requirements (air compressors, operators' cabin and electrical equipment).

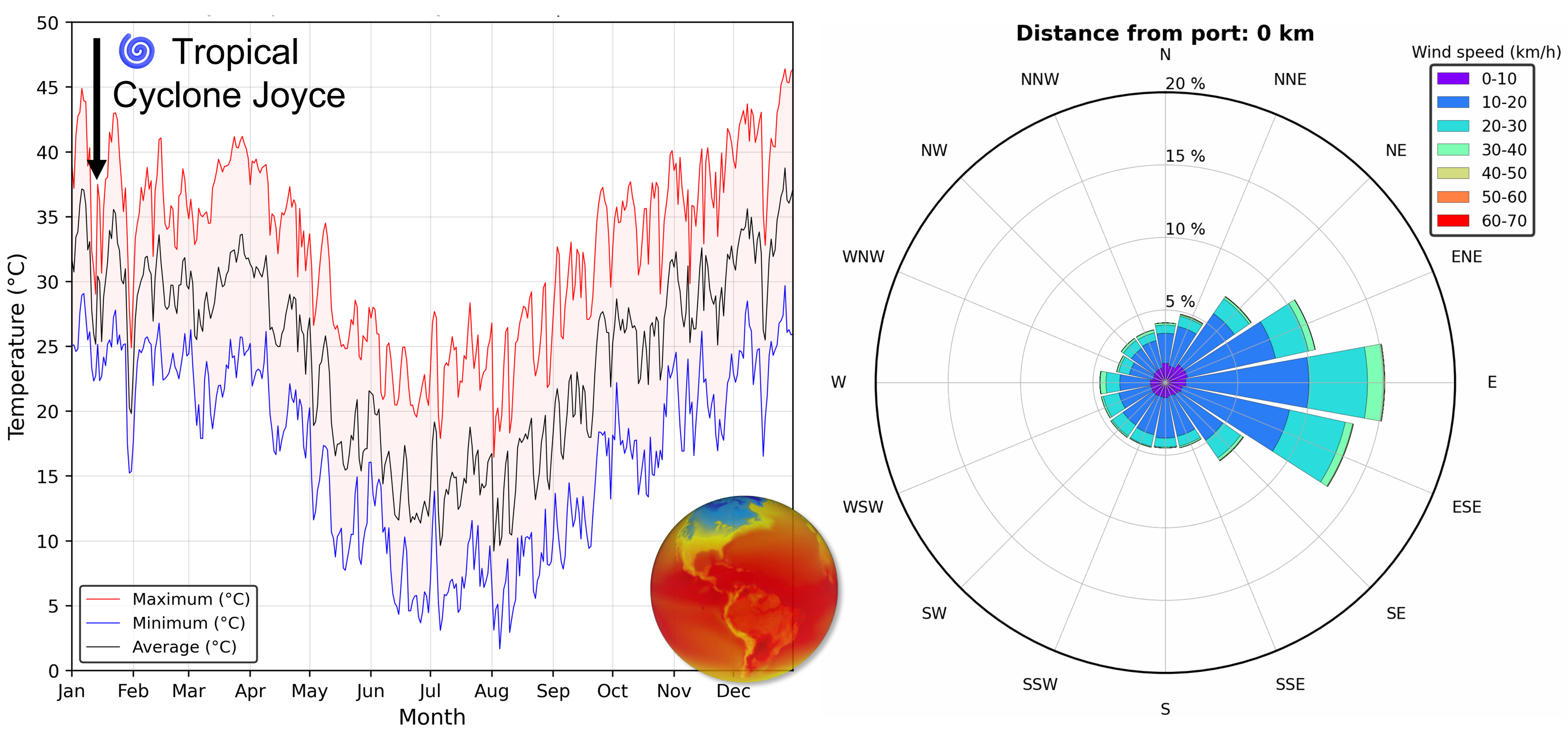

Figure 2. Daily temperature history for 2018 (Port Hedland (*left*) and corresponding wind rose along the mission route (*right*)

TripView

Using the available historical measurement data (defining complete missions for both empty and loaded trips), combined with auxiliary power consumption, an equivalent BEL's battery performance can be emulated (Figure 3). Note the expected BEL performance and power train efficiencies closely matches that of the diesel electric locomotive fleet. A distribution of state-of-charge (SoC) curves are produced from which the equivalent full charge cycles (EFC) can be derived. Mid-journey charging (MJC) sections are designed to minimize the infrastructure requirement whilst allowing for unhindered operations for more than 99% of the missions. The missions that do fail (SoC below the minimum depth-of-discharge criteria) can be adjusted in their operation to complete the mission. A select number of failed missions represent unexpected operating conditions such as extended idling time or a faulty locomotive set to idle.

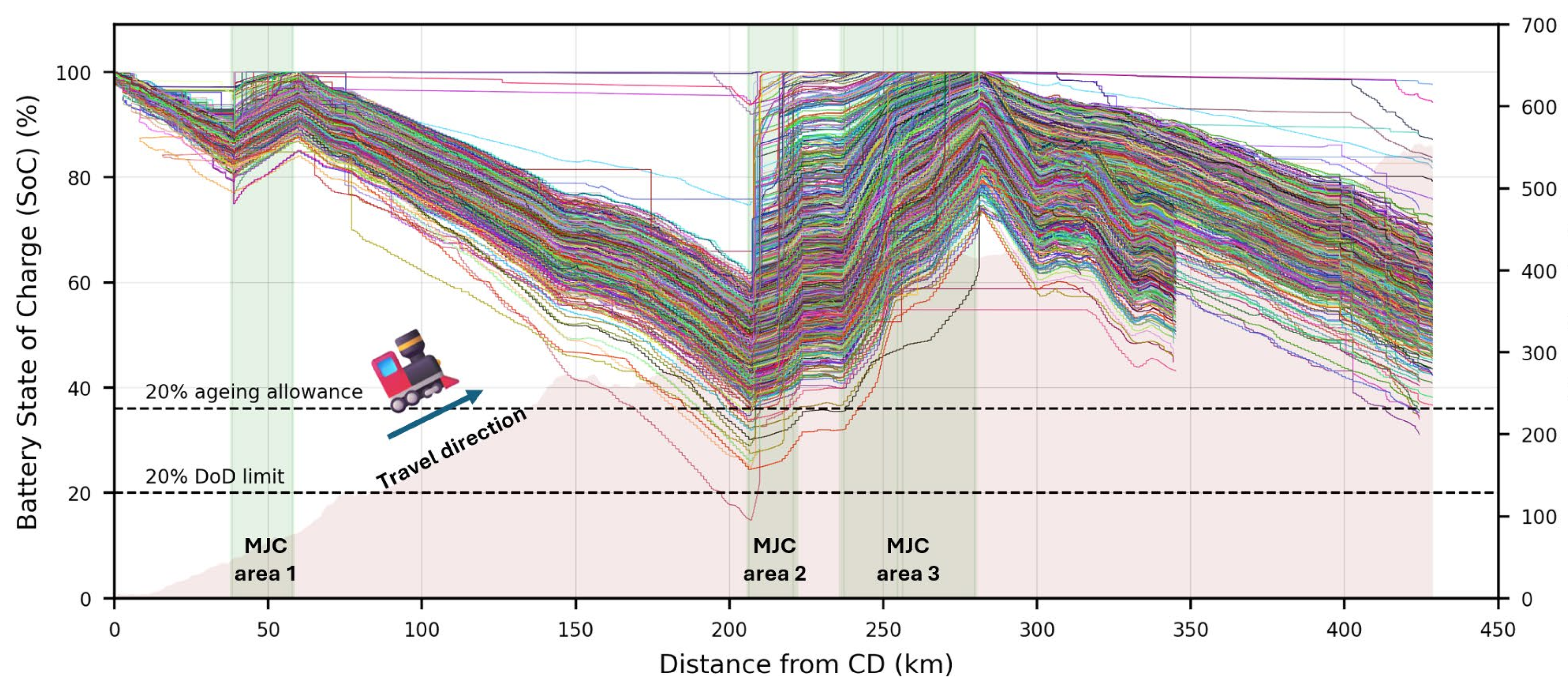

Figure 3: Emulated battery SoC (empty leg) over a calendar month

Nvidia's GPU (Graphical Processing Unit) acceleration was employed to achieve an order of magnitude speed advantage in processing speed (Nvidia Corporation, n.d) for the dataset (more than one billion data rows). The collection of missions are highly parallelized in nature and suited for parallel, sequential execution on SMs (streaming multiprocessors), interfaced using the CUDA (Compute Unified Device Architecture) software framework via the CuPy API (Figure 4).

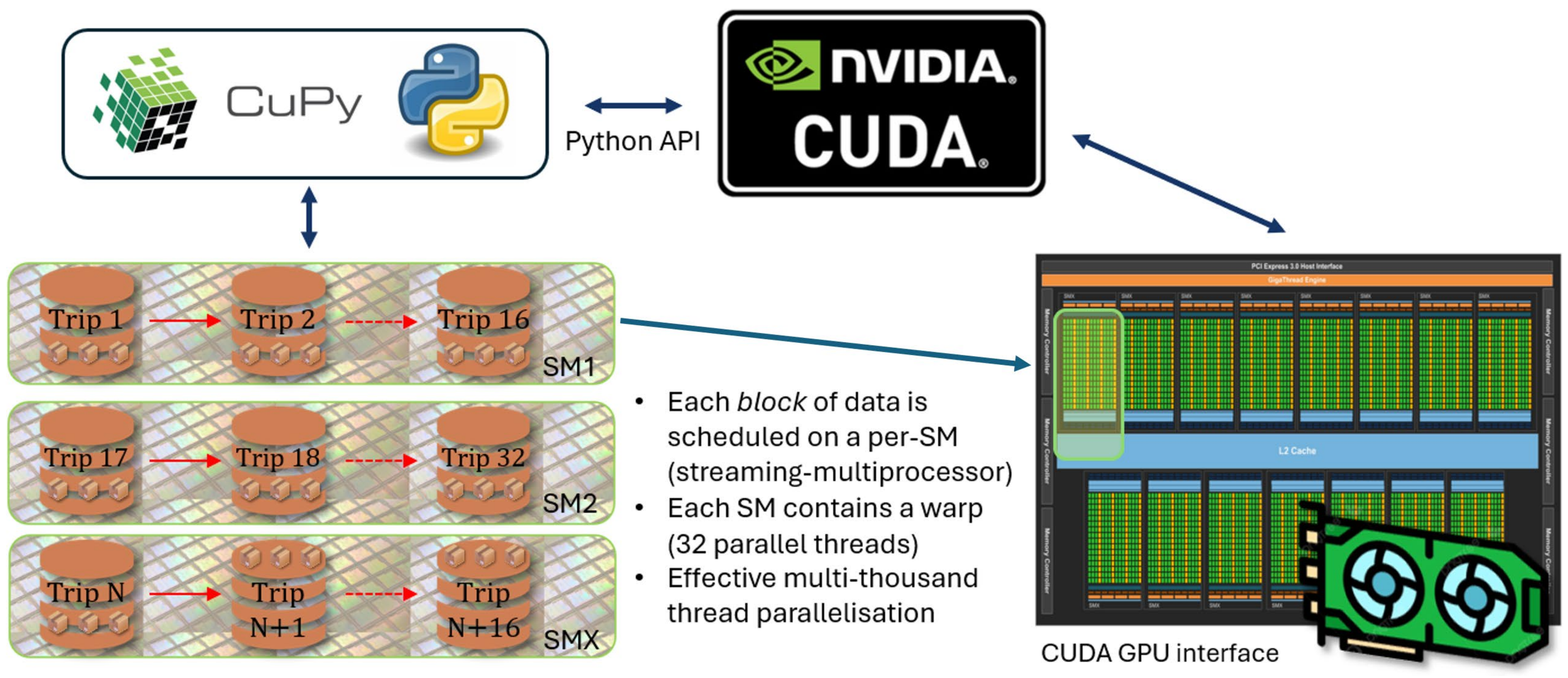

Figure 4: GPU acceleration with Nvidia CUDA and CuPy

Conclusions

Vast quantities of data can be integrated for accurate emulation for the expected performance of BELs, including battery life estimation. These results aid in the design of MJC infrastructure and its optimal locations along the route. The resulting distribution of data refines estimates for the expected lifetime of batteries which varies significantly as a function of SoC, temperature and cell chemistry.

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