Energy balance modelling for guiding the transition to battery-electric locomotives

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Introduction

Recent and ongoing advances in battery technology are making the implementation of battery-electric locomotives (BELs) increasingly feasible. Typical heavy haul railways are well-suited to the generation of significant quantities of dynamic braking energy (Knibbe et al., 2022). BELs can charge their batteries using the dynamic braking (DB) energy generated, improving the railway's overall energy efficiency. The remaining net energy requirement can be supplied using either en route or stationary charging infrastructure. This work summarises the development of an energy balance model to determine the potential energy savings and charging requirements associated with the implementation of a BEL fleet on an existing non-electrified network.

Modelling Approach

The modelling approach developed is summarised in Figure 1. The approach consists of two main elements, namely an OpenTrack model and a number of Python scripts and interactive utilities. The OpenTrack model serves as the physics engine to calculate the required tractive effort (TE) and braking force to maintain a target speed profile. The OpenTrack outputs are postprocessed using a number of Python scripts and interactive utilities to simulate the BEL state-of-charge (SoC). The SoC is used to determine the requisite length and location of overhead line equipment (OLE) for en route charging, given a specific set of inputs and limitations.

DB is prioritised over friction braking. Train resistance to motion was modelled using the popular Davis equation, calibrated using historical event recorder data. Powertrain efficiencies similar to those utilised by Iden (2021) were assumed. Battery auxiliary loads are accounted for and are dependant on both battery load and ambient temperature. Finally, the en route OLE location and length is determined through an iterative human-in-the-loop process to ensure that the battery depth-of-discharge and ageing allowances are satisfied.

Results

Figure 2 illustrates the energy balance in the form of a waterfall chart for a complete train cycle (loaded & empty) for one of the investigated routes in the Pilbara region of Western Australia. The four locomotives on the train generate ≈ 58.7 MWh DB energy (55.2 & 3.4 MWh during the loaded & empty trip, respectively). The DB energy produced constitutes ≈ 55% of the TE energy required, after accounting for a powertrain round cycle efficiency of 77%.

Figure 3 illustrates the modelled SoC for the empty leg of the trip both with and without en route charging. Only 38 km of OLE supplying 4 MW total power at the pantograph for each locomotive is required to ensure that the empty train has sufficient energy to complete the journey before charging at the mine again. The energy supplied by the OLE at the pantograph comprises a TE component and a charging component of 1.74 MWh and 0.71 MWh per locomotive, respectively.

Conclusions

Typical pit-to-port heavy haul rail operations have a favourable energy balance that can be exploited through the storage and reuse of DB energy. The analysis of a single route shown herein, shows that ≈ 55% of the TE energy requirement could be supplied from stored DB energy. This may be maximised further through the use of intelligent energy management systems. The remaining TE energy requirement could be supplied using en route charging. The modelling methodology presented herein shows how the location and extent of this en route charging OLE can be determined and emphasises the need for the development of on-the-fly charging hardware and methodologies.

References

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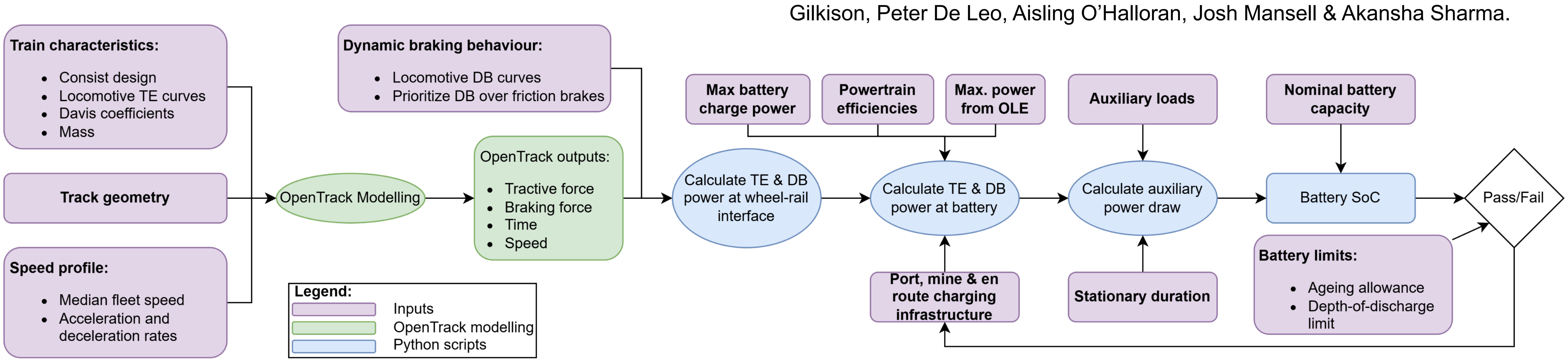

Figure 1: Summary of the energy balance modelling process to calculate the required length and location of OLE for en route charging

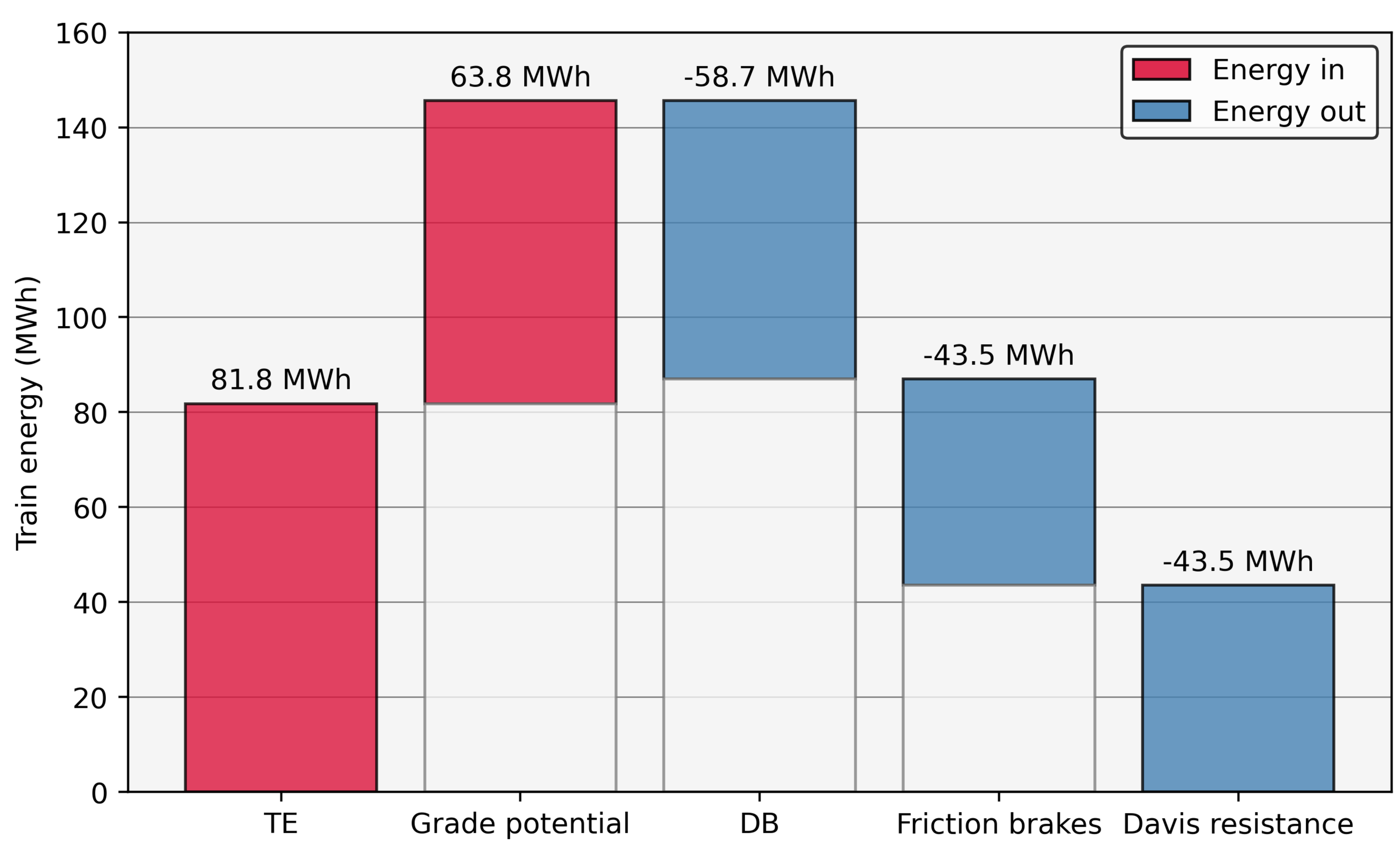

Figure 2: Energy balance for a train cycle (mine → port → mine)

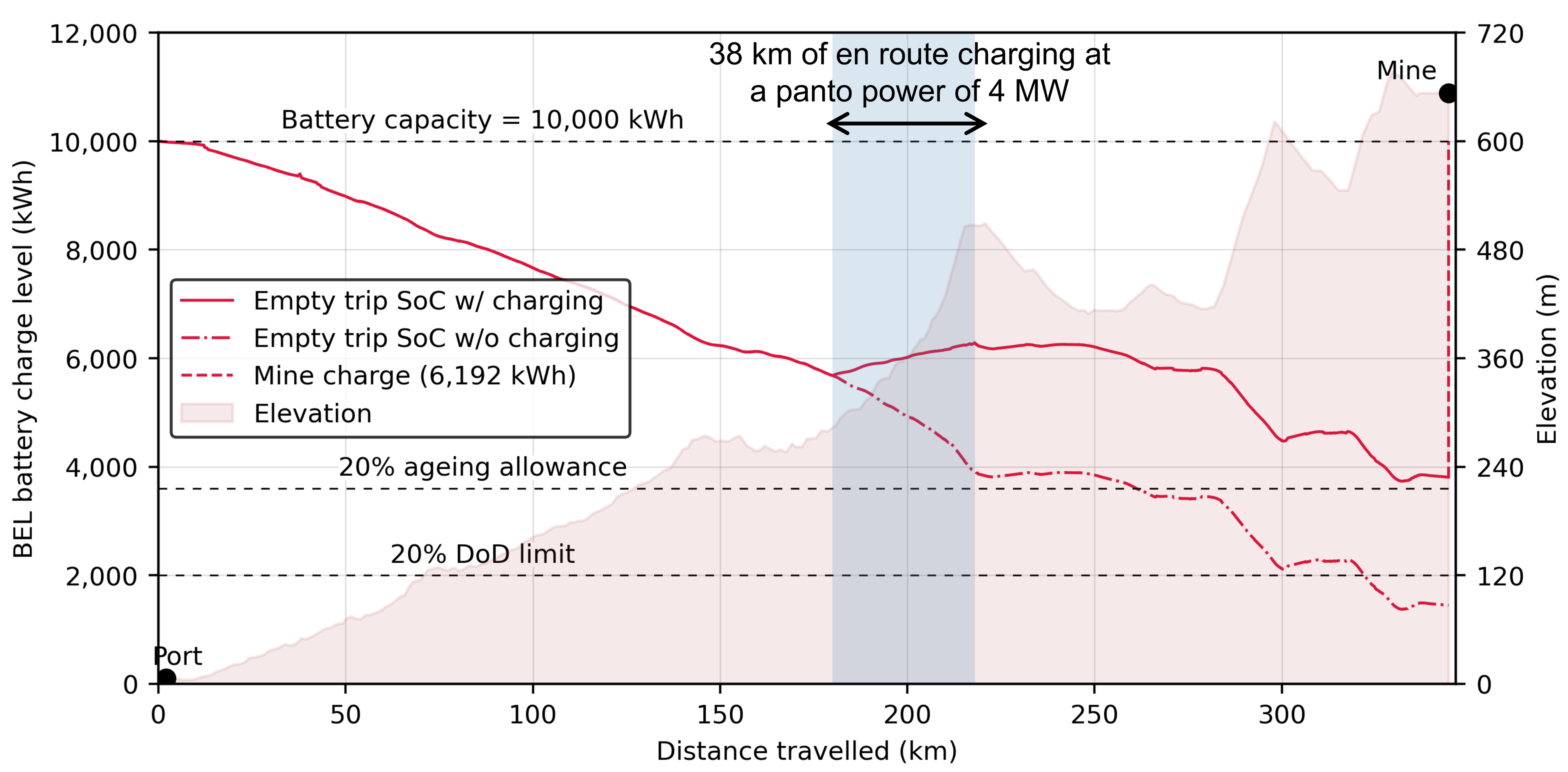

Figure 3: Simulated battery SoC for an empty trip with and without en route charging

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