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Maximizing infrastructure efficiency by optimising peak energy demand in Australian Metro Railways

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Executive Summary

Rail transportation is one of the most energy efficient methods in connecting people and places over large distances. With a lack of advancement in driving changes in the electrical infrastructure power to the network, this paper aims to investigate a solution that can optimise peak energy demands in the Australian metro railways.

The proposed solution looks to leverage off integrating intelligent systems into the network substations to manage the peak power draw of the train operations.

An on-board Data Collection System (DCS) will obtain real-time data from the rollingstock and communicate with the substation via a secure wireless gateway.

An off-site system will be installed in the substation to optimise power distribution based on the data obtained from the DCS.

The fields of research throughout the world predominantly look at optimising driving styles / algorithms and timetable / route optimisation.

This underscores the innovativeness of the solution as it does not appear to have been a main area of focus around the world.

The solution provides opportunities in cost savings by retrofitting existing infrastructure and its implementation can support decisions made by the rail operator.

Challenges associated with the proposed solution include industry reluctance, managing safety and regulatory compliance, cyber security and risk of cost overruns.

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Definitions

Acronym	Definition
AI	Artificial Intelligence
AS	Australian Standards
CB	Circuit Breaker
CBTC	Communication Based Train Control
COTS	Commercial Of the Shelf
CTA	Chicago's Transit Authority
DCS	Data Collection System
DTRS	Digital Train Radio System
ETCS	European Train Control System
GPS	Global Positioning System
GSM	Global System for Mobile communication
IEC	International Electrotechnical Commission An organisation that prepares electrical related international standards
IED	Integrated Electronic Device. A microprocessor-based controller of power system equipment
MVP	Minimum Viable Product
OCP	Operator Control Panel. This refers to the main HMI of the Rollingstock
OT Cyber Security	Operational Technology Cyber Security
SFAIRP	So Far as Is Reasonably Practicable
TO	Train Optimiser

1 Background

It has long been known that moving people, freight and resources by rail is one of the most energy efficient forms of transportation (Culver, 2024). Nearly all major cities around the world rely heavily on their rail infrastructure to connect people and places and have done so for many years. One major challenge for the rail industry is the desire to maximise existing assets to improve capacity and availability without the need to spend significant capital on new infrastructure (Australian Railway Association, 2021).

Whilst there have been many advancements in recent years for electrified networks such as more energy efficient rollingstock, moving block signalling and driverless systems, little has been achieved on the electrical infrastructure that provides power to the network (Siemens, n.d.)

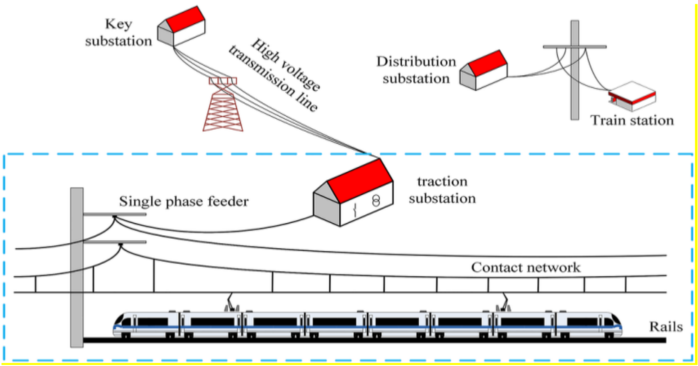

Figure 1: The traction power supply system structure diagram in the high-speed railway: (Liu et al., 2021)

If improvements can be made to reduce the overall peak draw requirements of the electrical infrastructure, the systems can either: support more trains with minimal capital, or future systems can be designed to be smaller and more efficient.

A study into Chicago's Transit Authority (CTA) train energy consumption (with regenerative braking power opportunity) confirms that peak power draw occurs as the trains accelerate (Link). Further expanding on this concept to consider multiple trains accelerating within a track section at once, and the peak draw requirements as a system will be at their highest. When considering upgraded train control systems (e.g., moving block) to increase train frequencies, this means more trains with more power draw. Without optimisation, it is likely that the peak power draw capacity requirements will continue to increase.

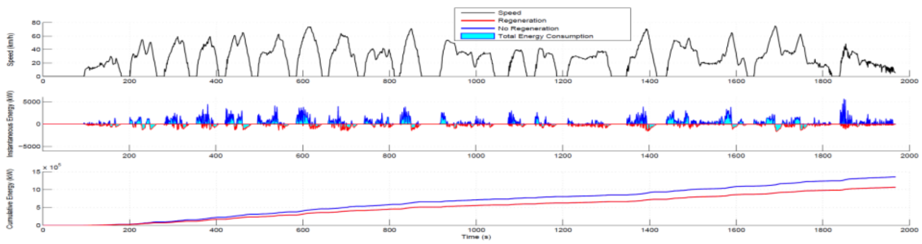

Figure 2: Chicago Brown Line: speed and electric power on the entire cycle (Wang & Rakha, 2017)

The ability to make supporting electrical infrastructure more efficient is necessary to explore as increasing urbanisation and demand for rail travel in Australia has the potential to put major strain on the existing networks.

2 Literature Review

This section provides a high level review of studies throughout the world in the field of energy optimisation with the use of recent innovations such as AI and machine learning.

2.1 Driving Style Studies /Driving Algorithms

Train driving control is a key factor in influencing the traction energy consumption. The theoretically ideal driving control is to minimise the acceleration component and maximising the coasting component of a train journey.

Autonomous driving systems (CBTC and ETCS L2) unlock a trains ability to operate independently with little to no human intervention. This creates a consistent driving style that enables network-wide optimisation of the energy consumption for operating rollingstock.

Therefore, methods to achieve a reduction in traction energy wastage with a standardised and understood behaviour profile can provide practical significance to the overall energy efficiency of the railway system.

Multiple approaches to developing energy efficient driving algorithms. Notably:

- Wang et al. (2020b) used an Approximate Dynamic Programming (ADP) to learn the cost of energy and time over multiple iterations.
- A Driver Advisory System (DAS) was tested at the Yizhuang Subway line in Beijing and was compared with normal driving. A 16% saving in traction energy was observed (Tian, 2017).
- In Madrid, Automatic Train Operation (ATO) was implemented on the metro lines and showed a reduced energy consumption of 13% compared to driver operated trains.

The above systems utilise a static driving algorithm, which may be refined using AI Machine Learning techniques, but they remain tightly constrained applications that are not dynamic at the scale of the network, even if they are dynamic for a given train.

2.2 Trip Optimiser Software /Timetabling and Route Optimisation

TO software can calculate the most energy-efficient route for a train by managing parameters like train speed, acceleration, and tractive effort. This information can be applied in both “simple” and “complex” ways, depending on the capabilities of supporting systems. Some operators have reported saving up to 1.4 gallons of diesel fuel per mile using this method, (Marcin Taraszkiewicz, 2023) and similar energy benefits have the potential to be realised on electric networks.

Timetable optimisation activities can contribute to not only operational efficiency but also energy savings. Innovations such as a primitive AI system that enhances train timetabling in the UK (Fragnelli and Sanguineti, 2014), have shown the potential benefits of using AI for traffic planning and management.

These have demonstrated that train behaviour data, for diverse train designs, can be captured at a level of detail that can be utilised for smart systems.

2.3 Genetic Algorithms

These algorithms can optimise a DC electric rail network by considering factors like storage size, charge/discharge power limits, and train driving style. In one study, this method reduced energy consumption by 15–30% and reduced power peaks. (Nallaperuma, Fletcher, & Harrison 2021)

3 Opportunity Solution

Australia has begun investing in High Capacity Signalling Infrastructure to support digital signalling systems such as ETCS and CBTC.

This will improve the efficiency of power used on the network. However, there is an opportunity to improve the sustainability of the electrified metro rail networks through integrating an intelligent system into the rail network substations to manage the peak power draw of the trains operation in the network. This is achieved by interfacing the trains with the substation to provide information of the power supply requirements.

A proof-of-concept system has been developed, governed by the fundamental requirements below. For simplicity, Rollingstocks are referred to as Trains, and Substation referred to as Master.

Functional Requirements:

1. Maximum capacity for the network is a constant “CAPACITY”.
2. Maximum acceleration current is a constant “STARTUP”. This would be parameterized in more complex models.
3. Current available to a moving train cannot be reduced until its demand requirements are also reduced.
4. Trains which are stationary cannot be permitted to accelerate unless acceleration capacity can be guaranteed within a given set of parameters.
5. Trains accelerating from low speed are in mode 1 (if available) otherwise they will claim mode 0.5.
6. Mode 0.5 represents stationary trains wishing to accelerate or slow-moving trains which can’t claim mode 1.
7. Trains moving at high speed are always in mode 2.
8. Mode 1 represents the highest-priority load, and only 1 train within a section can claim this mode.

Train System Requirements:

1. Maintaining which Mode, it is operating in.
2. Submitting demand, speed and mode information to the master.
3. Relinquishing Mode 1 when prioritisation is no longer required.
4. Mode 1 becomes Mode 2 or Mode 0.5 (depending on speed) after 10 seconds in the simple model. These values could be parameterized and adjusted in real time by AI, and many more modes could be included.

Master System Requirements:

1. Prioritising load requests from trains within the network.
2. Bestowing Mode 1.
3. Calculating and submitting available current to each train.
4. Preventing the movement of stationary trains if capacity is being encroached.

Figure 3 below illustrates the dataflow for this concept solution. Refer to Appendix A for more detailed breakdown of the proposed logic diagrams that describe the software applications at both the rollingstock and substation interfaces.

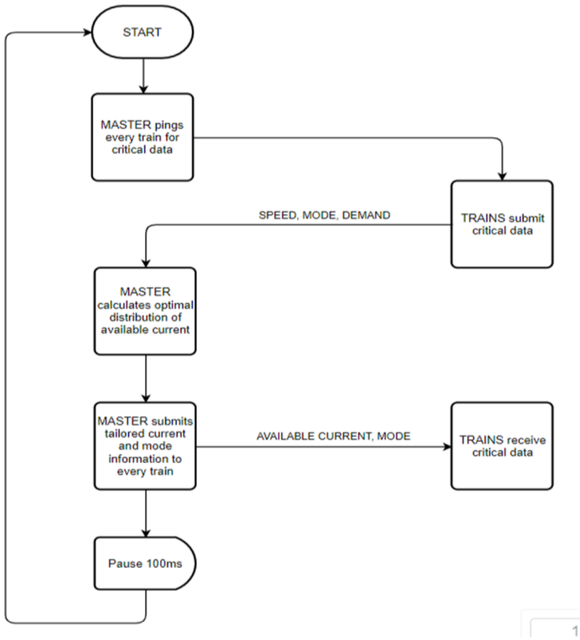

Figure 3: Overall Data Flow Diagram of Opportunity Solution

4 Minimal Viable Product

Figure 4 presents a high-level data flow of the proposed system, which can be implemented in networks with digital signalling systems (such as ETCS or CBTC).

However Australian metro rail networks have only recently started to implement digital signalling systems, and only across certain areas or running lines.

Furthermore, only a small proportion of Australia's metro rollingstock fleets, those introduced after 2018, are compatible with these digital signalling systems.

Therefore, the most viable product solution is one that can be easily retrofitted to any metro rollingstock fleet and implemented on any rail network section. Treating the proposed proof of concept as a stand-alone system, then there are only two critical interfaces that need to be taken into consideration; the rollingstock units occupying a section of track and the traction substation that supplies power to them.

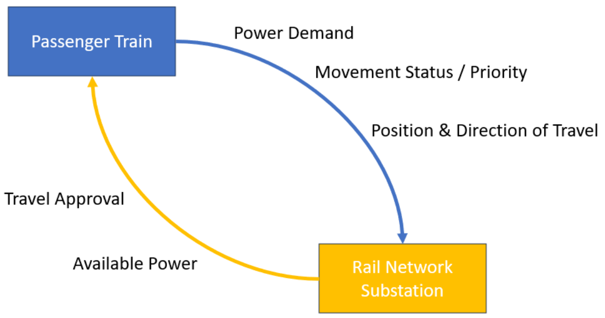

Figure 4: Dataflow between Metro rollingstock and Substation

4.1.1 Rollingstock Data Signals

Table 1 depicts the data required for operation of the solution, and how it can be collected from the train. Most existing rollingstock fleets are already fitted with sensors, and on-board data systems so that the RSO's can closely monitor fleet performance and reliability, however this is not always the case for more ageing rollingstock fleets. In these situations, the sensors can be retrofitted.

Signal	Signal Location	Description
Train Position & Direction of Travel	GPS or OCP	Train position based of GPS location
Train Speed	Wheel Speed Sensor, Tacho, Doppler-radar, OCP	There are several reference signals to determine train speed.
Movement Status	Throttle Position, OCP	Throttle position indicates whether the train is accelerating or braking.
Power Demand	On-board Energy Meter ECOMeter / ECOCOM	Energy measurement by device called ECOMeter which measures the consumed and regenerated active or reactive energy, as well as line voltage and line current.

Table 1: Data signals required from Rollingstock

4.1.2 On-board System Architecture

The on-board system is designed to collect rollingstock data signals outlined in Table 1 determine whether the train requires power prioritisation, then communicate this information back to the substation interface.

Figure 5 below illustrates the data flow across the on-board system. The Key component is an on-board Data Collection System (DCS), which collects the required data signals from both the multi-purpose vehicle bus and the Operator Control Panel (OCP), then through a secure wireless gateway, transfers this data back and forth to the Substation counterpart system. The DCS will also interface with the OCP to communicate with the operator / driver the available power and any movement restrictions enforced by the Substation. Note that these movement restrictions are a passive signal indicator to the driver. This can later be upgraded to automatic train control for rollingstock fitted with ETCS / CBTC.

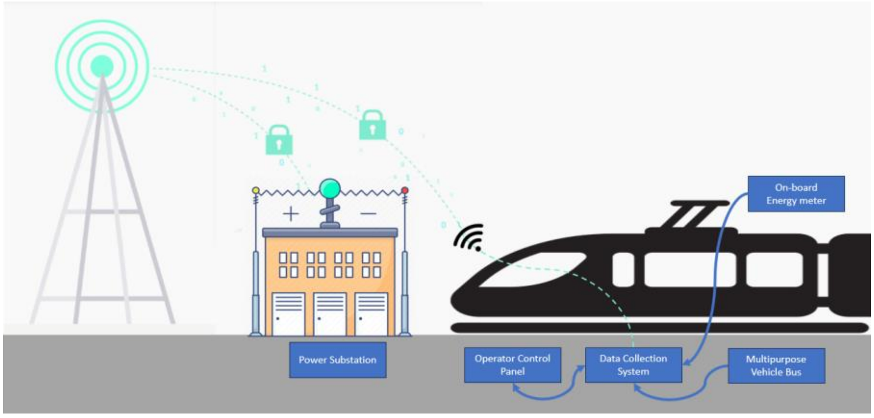

Figure 5: On-board System Architecture

There are several off-the-shelf remote data monitors available that could be implemented as a DCS. These data monitoring systems are designed to be compatible with wired signals and all types of bus interfaces, as well as boasting secure wireless gateways to enable automated on-board to off-board data transfer through selectable communication channels.

Supplier	Product	Link
Siemens Mobility	Railigent Connect RS	Connectivity & data transmission for rail systems - Siemens Mobility Global
IMT / Wabtec	CLT20-Ex	Home - IMT (intermodaltelematics.com)
MV Technology Solutions	HaslerRail TELOC®	Onboard Rollingstock Equipment - MV Technology Solutions
EKE Electronics	Trainnet® systems	EKE-Trainnet-Brochure-full_20220826.pdf (eke-electronics.com)

Table 2: Data Collection System Suppliers

4.1.3 Off-site System Architecture

The off-site system is designed to optimise the power distribution supplied to the section of rail network, based on the real-time data communicated from the rollingstock fleet. Figure 6 below illustrates the hardware and software architecture to implement the off-site system at existing substation infrastructure. Many new substations are built to IEC 61850, which would suit the implementation of our system seamlessly. In such cases, the control panel would be connected via ethernet to every IED within the substation and could extract the required real-time data with little additional hardware. For older, more conventional substations, current and voltage transducers may need to be retrofitted to the traction circuit breakers.

As a proof of concept, the Power Optimisation software application is fitted to a stand-alone workstation with a dedicated Data Handling Server.

Once the concept is proven, the software can be fully integrated to run off the main Substation server and workstation. Machine-learning algorithms can be employed to streamline the process and improve the response rate.

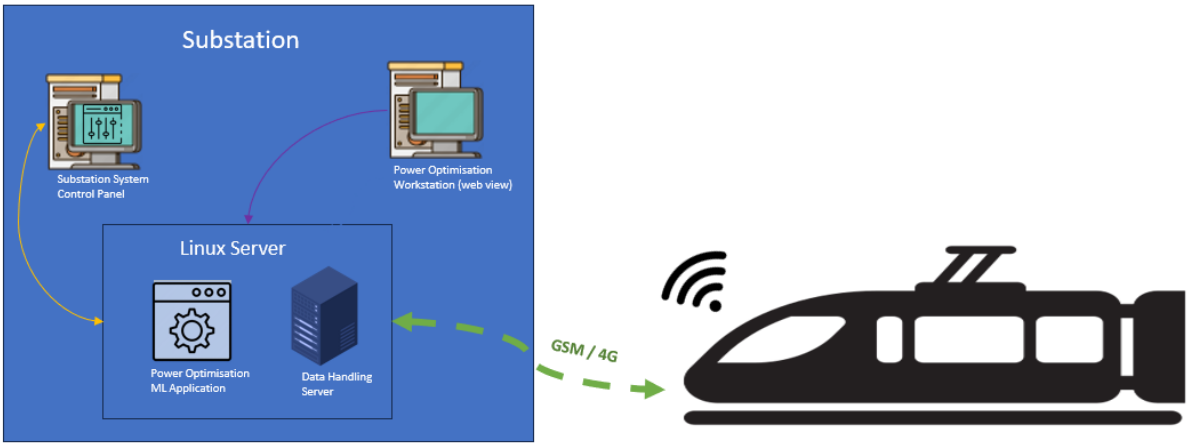

Figure 6: Off-Site System Architecture

5 Risks, Opportunities & Constraints

5.1 Risks

5.1.1 Safety & Regulatory Compliance

The main barrier to implementation is ensuring the safety of persons using the rail infrastructure in which the solution is deployed. Potential issues with the solution not operating as intended include loss of power of rollingstock in hazardous locations (e.g., within tunnels), pantograph arcing resulting in fires, among others.

Implementation of the solution would be a unique challenge, as it must to comply with industry safety standards and legislation, such as 50126 and Rail Safety National Law, to demonstrate that all potential safety risks have been identified and managed at each stage of the project SFAIRP for AI systems, which are not properly legislated.

5.1.2 Cyber Security

Signals to and from the rollingstock requires data transmission that is timely and secure. Cyber Security risks for the solution include reduced availability of the rail infrastructure, continuous disruptions resulting in reputational damage to the operator, and malicious use of the system leading to safety risks as previously outlined.

Consideration should therefore be given into OT cyber security to support safe and secure operation of assets. Cyber security has rail industry standards, such as to IEC 62443 series, providing guidance on how to identify and manage OT cyber security risks.

5.1.3 Cost, Feasibility and Scalability

Risk in the form of cost overruns should be considered. This includes specialist engineering (e.g., signalling), potential development delays, type of equipment (e.g. COTS or bespoke products) etc.

An additional risk of emerging innovations is demonstrating that the solution is feasible in consuming less energy than the savings made by reducing peak consumption, and that the solution can be scaled to a whole rail network. Older rail networks may not be able to be retrofitted with the solution or can only be upgraded at large-scale costs.

Further, the solution must be scalable from an MVP upwards to at least a whole local rail network, which may impose challenges on the system. For example, Cross River Rail integrates a new section of train track fitted with ETCS, which connects to the Queensland Rail network fitted with traditional signalling. In this scenario, the system would have to be able to operate in both environments and the cost of this design still must make the solution a worthy proposition, and it must be done so safely.

5.1.4 Operational Impact

To ease the energy loading on the network, AI may force trains to slow down or stay at rest for longer than anticipated. It is presumed this would have minimal operational impact, since the delay would only be a delay in state-change to avoid overrunning.

5.1.5 Environmental Risks

The main environmental risk for this project is related to the power consumption of the AI system and the whole IT infrastructure needed to operate it, as it would have to be offset by the energy savings in traction power to be environmentally feasible. Although this risk seems low, a detailed study would provide assurance that the project is environmentally viable.

5.2 Opportunities

5.2.1 Existing Infrastructure

Existing infrastructure could be retrofitted to mitigate the cost impact of the proposed solution. For example, the radio antennas required for communication to trains can be installed on top of existing signal masts as opposed to a purpose built communication infrastructure (4G, 5G, GSM-R, etc.).

5.2.2 Decision Support Utilities

If the information gleaned from the operation of this sort of power optimisation system is captured effectively, then there exist substantial opportunities to plan and optimise future operations with the use of various decision support tools by factoring in the effects of weather, asset condition, and geography into an integrated analysis suite.

5.3 Constraints

5.3.1 Industry Reluctance

The railways are generally very slow to adopt new and innovative solutions. For example, the type approval procedure in most railway operators is a lengthy and costly process.

Success of this proposal requires consideration into the different disciplines that are affected by this proposal.

6 Conclusion

In conclusion, maximizing infrastructure efficiency and optimizing peak energy demand in Australian railways can be achieved through the integration of leading-edge technologies and AI-driven solutions as per our recommendations.

Based on the literature reviews, the following findings were:

- Approximate Dynamic Programming (ADP) has been promising in modelling energy and time costs for enhancing train operations (Wang et al., 2022).
- Driver Advisory Systems (DAS) can reduce traction energy consumption by up to 16% (Tian, 2017).
- Significant fuel savings have been visible with TO software, including 1.4 gallons reduction of diesel fuel per mile (Taraszkiewicz, 2023).
- Timetable optimization and AI systems have been prospective to improve operational productivity and energy savings (Fragnelli & Sanguineti, 2014).
- Digital Twin technology enables better train modelling, as demonstrated by the UK's HS2 project (CFMS).
- Genetic algorithms and station-based infrastructure optimization have decreased energy consumption by 15-30% (Nallaperuma, Fletcher, & Harrison, 2021; Mohajer & Mousavi, 2023).

There is increased interest in traversing the use of AI to enhance power distribution, leveraging its potential to improve efficiency, reduce energy waste, and improve grid management. As a first step towards realizing this option, a minimal viable product (MVP) has been proposed to demonstrate the proof of concept. This MVP will serve as a foundation to validate the feasibility of the approach, proving its ability to optimize power distribution. Once the concept is proven, AI tools can then be integrated to enhance decision making, scalability, and automation, allowing the full potential of AI-driven power distribution systems.

Despite several promising options available in this high-level research proposal, it is important to recognize the risks associated with each method. These risks whether technological, operational, safety, environmental or financial, must be thoroughly investigated to ensure the most appropriate and effective solutions are implemented for the diverse types of railways within Australia.

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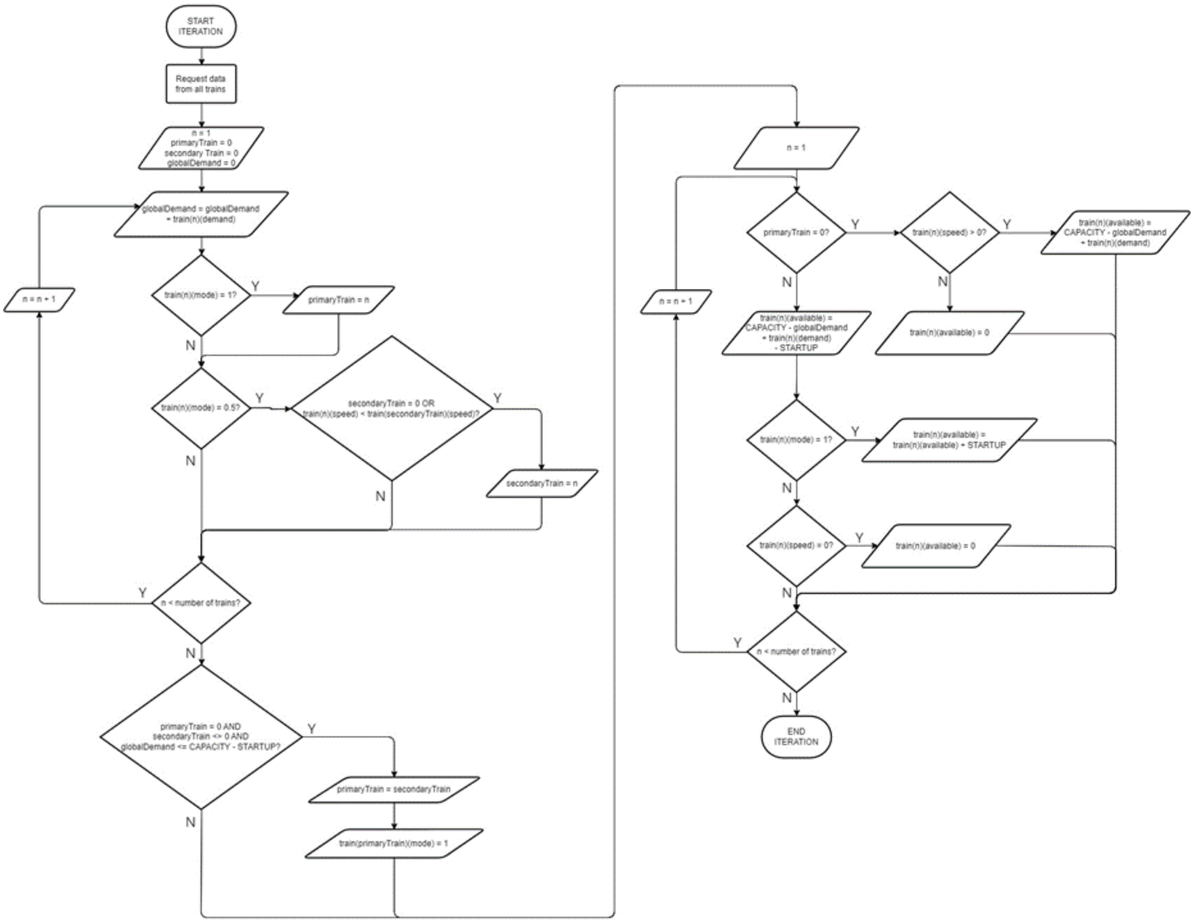
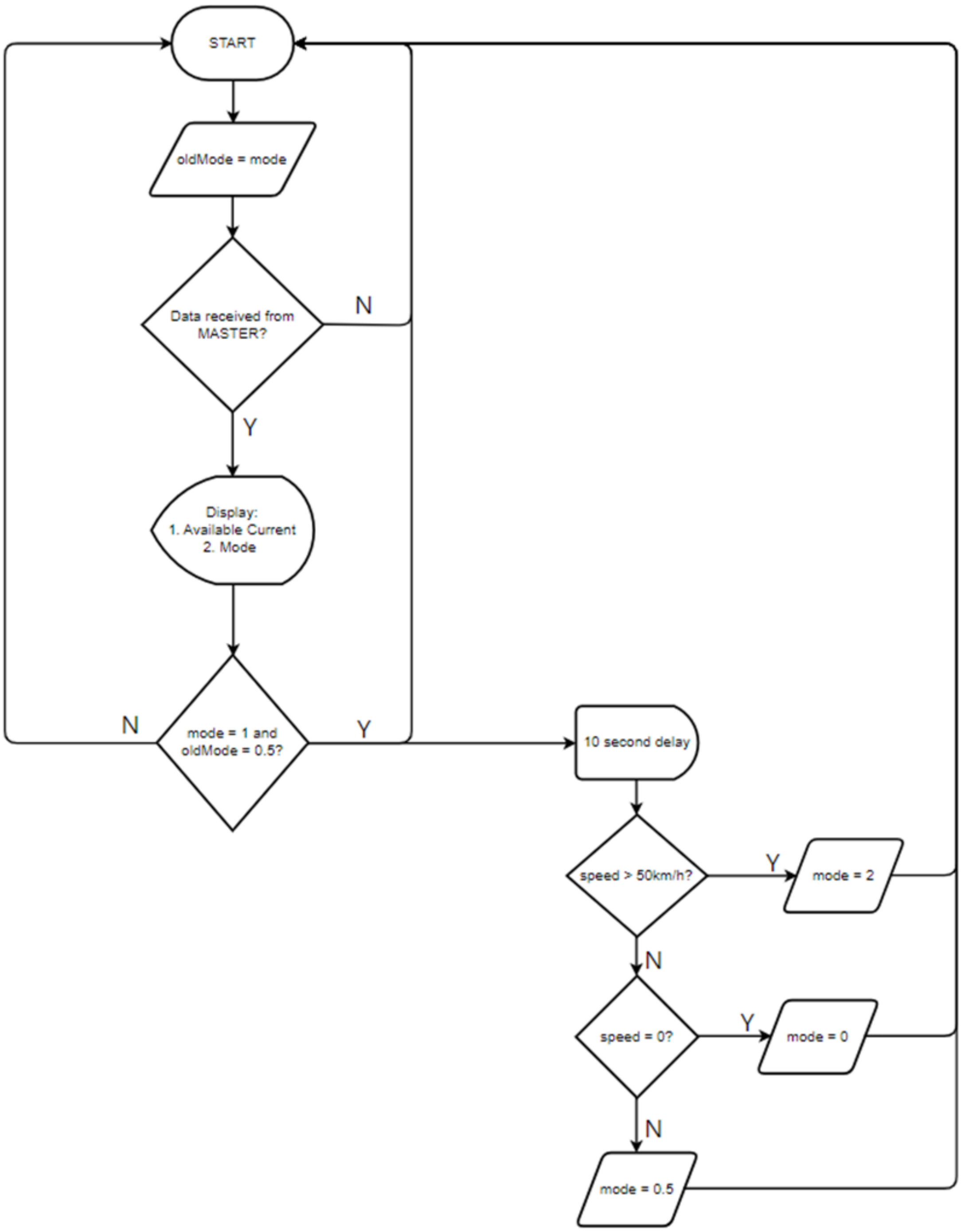
Appendices

Appendix A: Detailed Logic Diagram of Opportunity Solution

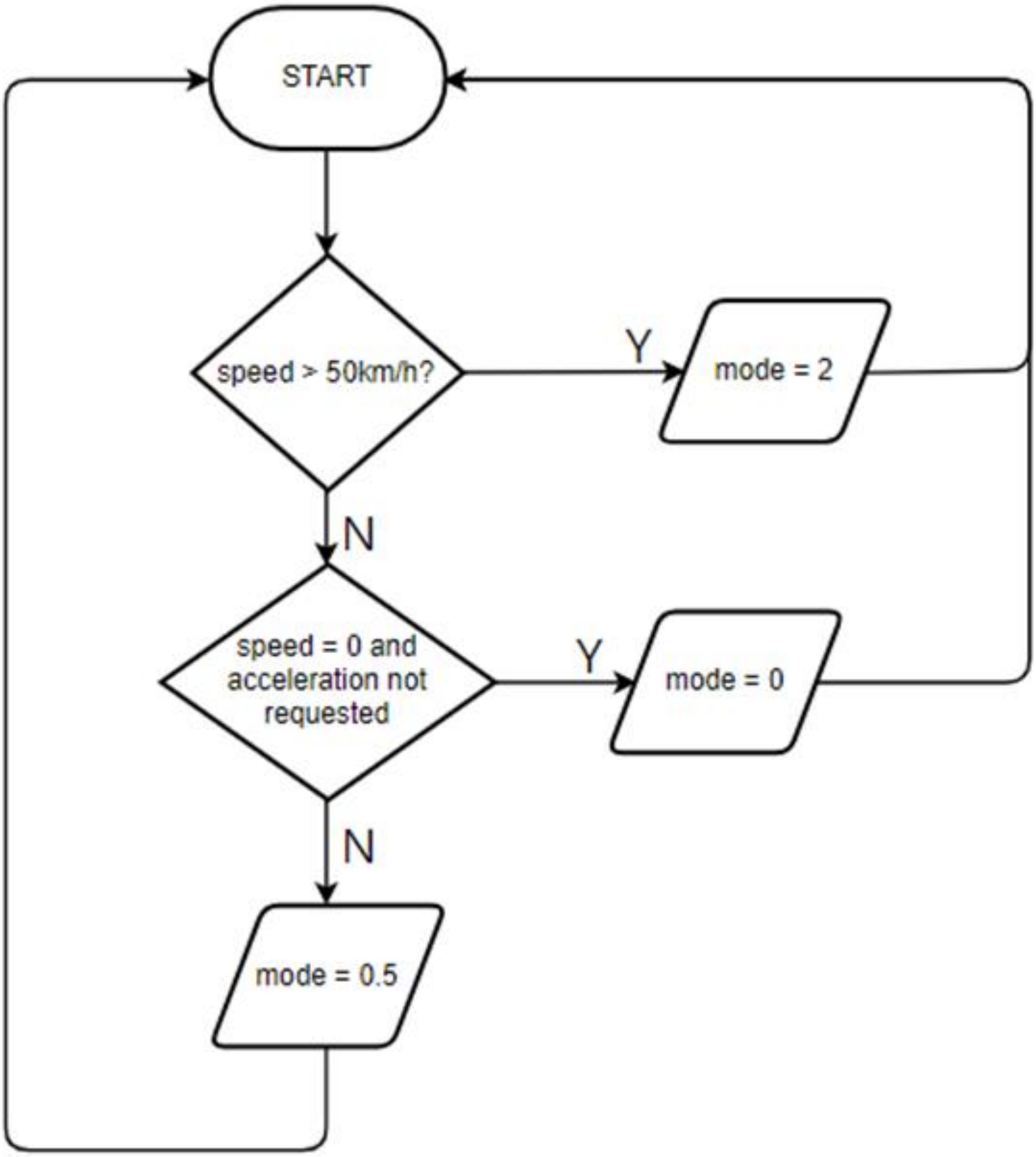
Basic Solution Algorithm



On-train data receiving logic



On-train mode determination logic



On-train data submission logic