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Novel traction systems for sustainable railway futures in LICs

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Abstract

This report presents the results of data gathering for several representative routes in low—income countries in Sub-Saharan Africa. It builds on the results of route mapping, and the development of a Single Train Simulator tool with a Graphical User Interface, which was used to establish energy and fuel requirements for each combination of route and vehicle. This will be used to inform the next stage of designing vehicle architecture.

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ABBREVIATIONS/ACRONYMS

GUI	**Graphical User Interface**
CO2e	**Carbon dioxide equivalent**
kWh	**Kilowatt Hours**

EXECUTIVE SUMMARY

This report is one of a series in a project that sets out to investigate the potential of introducing low carbon traction systems to low-income countries (LICs) in Sub-Saharan Africa (SSA). The previous report investigated traffic volumes, and detailed various practical implications for introducing new technology for railway traction. This report follows on from that initial study, and investigates suitable novel power sources for railways in SSA as well as determining the power and energy requirements for four different types of route – a short commuter railway, a medium distance passenger route, a long distance passenger service, and a long distance freight service. The routes were selected based on a number of factors including availability of data, and were as follows:

- Kampala – Namanve, which is a short commuter route in a crowded city;
- Dar es Salaam – Kigoma, which is a long-distance passenger route;
- Buchanan – Tokadeh, which is a heavy haul freight route.
- Abuja – Kaduna, a passenger service between two population centres

The team used a range of online sources to derive the parameters necessary to undertake analysis using the University of Birmingham's Single Train Simulator, a piece of code written in Matlab (a mathematics 'engine'). This was then used to calculate the traction energy required for a return journey, to which was then added an estimated hotel load to cover on-train services such as Heating Ventilation and Air Conditioning (HVAC) and lighting. The results are summarised in the following table:

Table showing the key results of power and energy required for the four selected routes

Route	Fuel Requirements and CO2 Emissions Produced
Kampala – Namanve (Short distance, lightweight commuter train)	--Daily Use-- Diesel only: 610 litres **(1633kg CO2)** Diesel hybrid: 535 litres **(1431kg CO2)** Hydrogen hybrid: 14 kg **(0-192kg CO2)** Battery only: 366 kWh **(0kg CO2)**
Dar es Salaam – Kigoma (Long distance, locomotive hauled passenger)	--Return trip: Dar es Salaam – Kigoma-- Diesel only: 12394 litres **(33214kg CO2)** Hydrogen hybrid: 1498 kg **(0-20508kg CO2)** Diesel hybrid: 12719 litres **(34084kg CO2)** --Return trip: Dar es Salaam – Mwanza-- Diesel only: 12233 litres **(32781kg CO2)** Hydrogen hybrid: 1485 kg **(0-20330kg CO2)** Diesel hybrid: 12521 litres**(33553kg CO2)**
Buchanan – Tokadeh (Medium distance, heavy locomotive hauled freight)	--Return trip-- Diesel only: 2814 litres **(7510kg CO2)** Hydrogen hybrid: 1941 kg **(19016kg CO2)** Diesel hybrid: 2470 litres **(5150kg CO2)**
Abuja – Kaduna (Medium distance, locomotive hauled passenger)	--Daily Use-- Diesel only: 2728 litres **(7311kg CO2)** Hydrogen hybrid: 345 kg **(4715kg CO2)** Diesel hybrid: 2717 litres **(7282kg CO2)**

It should be noted that only the traction types discovered to be capable of achieving the duty cycles investigated are listed in the table above. This is why the battery only option is only listed for the Kampala – Namanve route, as it was found that this technology was not suitable for the other routes.

A key metric for determining suitability of each traction type is the emissions produced. These can be assessed in two ways. Firstly, the Carbon Dioxide (CO2) emissions for each traction type for each route was analysed. Secondly, the potential for zero harmful emissions at point of use from each traction type can be assessed as the marker for whether a traction type for self-propelled trains is "novel". As such, it is considered that alternative diesel engines and conventional lineside electrification are not "novel" and fall outside the scope of this report.

While the result above are for four specific routes, the approach taken was to base the analysis on 'open source' data, with the desire to make it relatively easy to replicate for other lines. A methodology was developed using Google Earth Pro to derive data from routes and gradient profiles, and a generic method of calculating train resistance (a key factor in energy consumption) was developed that ought to be able to cover the full range of train types in operation on the continent. Additionally, a Graphical User Interface was developed specifically for this project to enable other routes to be evaluated without requiring the user to be familiar with using Matlab.

The conclusion of this analysis was that while there are a number of options for alternative power for the commuter route, the longer distance passenger and freight services require considerable quantities of energy to be carried by the train, with the freight service also requiring considerable installed power. This will help define the appropriate alternative low-carbon energy sources that could be used, which is to be explored further in the next stage of this project.

SECTION 1: INTRODUCTION

1.1 The Challenge

This project investigates the potential of introducing low carbon rail traction systems to low-income countries (LICs) in Sub-Saharan Africa (SSA). The first stage in developing potential solutions is to understand the key requirements in terms of power and energy. It was not possible to analyse all the routes in SSA – instead four typical routes were selected to assess a broad range of service types at the likely extremes of the requirements 'envelope'. These routes were then simulated to determine the likely power and energy requirements.

1.2 Route Selection

Given the difficulty in elaborating a systematic process to select case studies in the region for further research, the project team adopted an alternative qualitative approach based on stakeholder inputs and line characteristics. Following the key stakeholder workshop, experts were asked to submit their suggestions for case studies on an online form. The form contained the following questions:

- Name of the route
- Total length of the route (in km)
- Gauge of the route
- Number of stops
- Type of traction
- Type of traffic
- If freight, what type of load?
- Typical speed on the line (in km/h)
- Minimum headway between services operated (in minutes)
- Typical services per day
- Typical number of wagons/carriages per train
- Typical number of locomotives on a consist
- Are route data available (gradient, speed limits, and station stops)
- Are data available on the current traction systems used?
- Are running data available (GPS or Train monitoring systems)?

The main aim of using expert inputs for case study selection was to draw representative lines in the region, which would be used to explore the particularities of each category of railway service. For instance, urban rail lines, passenger intercity lines, mixed traffic lines, and dedicated heavy haul freight lines. Another aspiration was to encompass the various gauges encountered in the region (at least metre and Standard gauges). These would provide us with a clearer picture of the region to assess via case studies.

However, only tour suggestions were received for two lines: Kampala – Namanve in Uganda, and Addis Ababa – Djibouti linking Ethiopia to Djibouti. The former was given a high interest for its peculiar setting of a short commuter line in a region dominated by long-distance freight routes. Also, it highlights a distinct urban system to the newer and future lines found in Addis Ababa, Dakar, and Lagos which are (or will be) all electrified. The same reason of being already electrified was used to dismiss the Ethiopian line to the port of Djibouti.

Furthermore, the supporting role of the Nigerian Ministry for Transportation has highlighted the country's railways as a potential case study. In particular, the Abuja – Kaduna line stands as a representative of the new Standard Gauge Railways (SGRs) that some countries have built, or are planning to build. The 186 km line was planned to operate mixed traffic, yet government officials have mentioned that only passenger services are currently in operation. The Ministry has agreed to supply detailed information about rolling stock and traffic volumes, yet none has been formally received at the time of this report.

On top of that, the research team assessed a number of routes in the countries within the scope of the project. Lines were then chosen to represent different lengths and uses of routes, taking data availability into consideration. An interesting example for long distance passenger lines was found in Tanzania, linking Dar es Salaam to Kigoma on metre gauge tracks. However, the Tanzanian Standard Railway Gauge network includes a line parallel to the existing one.

The final representative line is the Buchanan – Tokadeh route operated by Acelor Mittal. The privately owned line stands as a case of dedicated heavy haul freight lines which have distinct operational requirements. That may include power and energy use, length of consists and number of locomotives, distinct turnaround times, etc.

Below is the resulting group of selected lines and their characteristics:

Routes considered	Route type	Gauge	Data availability
Kampala – Namanve (Uganda)	Commuter/ Urban	1,000mm	Train type – online reference sources available Train parameters – online reference sources available and / or data from UoB model library Alignment & gradient profile – available from Google Earth Pro Line speeds: Assumed based on published journey times
Buchanan – Tokadeh (Liberia)	Dedicated heavy haul freight	1,435mm	
Dar es Salaam – Kigoma (Tanzania)	Long distance passenger	1,000mm (new SGR to be built parallel to existing line)	
Abuja – Kaduna (Nigeria)	Standard Gauge Railway (designed for mixed traffic but currently only operating passenger services)	1,435mm	Data confimed by the Ministry, yet to be made available to refine initial models based on Google Earth information.

1.3 Aims & Objectives

While the key objective was to establish the range of energy and power requirements for alternative low-carbon traction, simulations to calculate energy and power are usually undertaken by engineers specialising in this field, using bespoke software such as the University of Birmingham's Single Train Simulator (STS). This work was conducted with the aim of suggesting emissions reducing options for Sub-Saharan Africa.

The reduction of harmful emissions is the ultimate aim of the project team and is the core of what is being attempted to be achieved. This can be achieved by several means, such as modal shift from other forms of transport, removal of harmful emissions from populated areas through use of the zero emission modes of hybrid traction systems and wholesale removal of harmful emissions from the transport system by using fuels that can be generated from completely sustainable energy sources.

A second key objective was therefore to develop a method and tool to enable stakeholders in the railway industry to quickly and easily undertake their own calculations. This was done by developing a Graphical User Interface (GUI) for the STS, and a methodology for obtaining input parameters that was based on online open-source data. This process was completed as deliverable 2.1 of this project.

SECTION 2: SINGLE TRAIN SIMULATOR GRAPHICAL USER INTERFACE TOOL

2.1 What is a Single Train Simulator (STS)?

The Single Train Simulator (STS) is a software simulation tool developed by researchers at the Birmingham Centre for Railway Research and Education (BCRRE) for evaluating the energy consumption of railway traction. It is based on the first-principle of longitudinal dynamics and the energy conservative principle [1]. The longitudinal dynamics are expressed in the form of mathematical formulae that when combined form a simulation model. The model is then used to predict the motion of a train under a set of conditions, namely gradient, train mass, friction and traction force applied.

STS first computes the traction force F_T required to fulfil a given acceleration profile α using the Davis equation formula:

$$m(1+\lambda)\alpha=F(T-(a+bv+cv\text{^}2+mg\theta))$$

Where m is train mass, $a + bv + cv^2$ is the summation of frictional forces, and $mg\theta$ is gravitational pull. The acceleration profile α is derived from a given velocity profile v.

After obtaining the traction force required to fulfil a trip, STS then computes the energy required by the respective traction system. STS uses powertrain efficiency curves that are custom to the selected traction technology in order to provide more accurate energy estimates. The energy required at each step is computed using the formula:

$$E = \frac{F_T \Delta}{\eta}$$

Δ is the distance for which a specific F_T is applied and η is the powertrain's efficiency. Total energy consumption is then computed by adding the consumption of all steps. The energy calculation only accounts for traction requirements and does not account for hotel loads.

The STS is highly flexible by allowing the user to specify the railway route and the parameters of the train simulated, and modular enough to accommodate various traction systems both conventional and hybrid. The state-of-charge ζ of the energy storage device of hybrid powertrains is modelled using the formula:

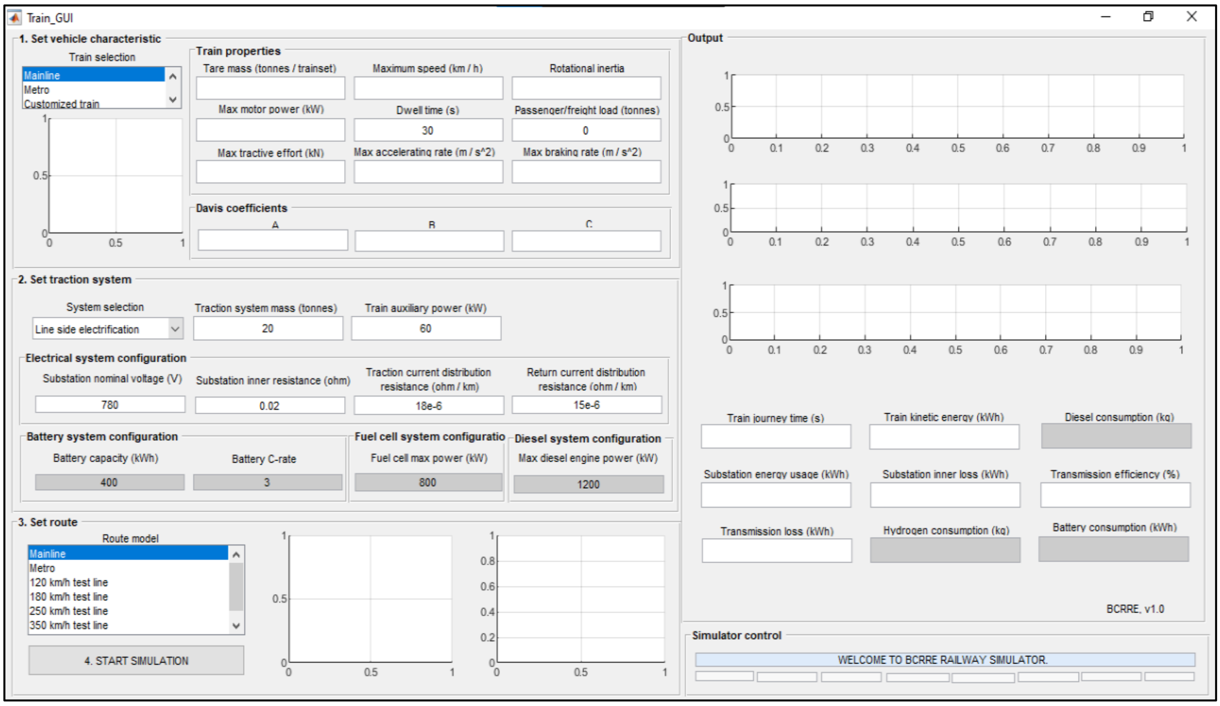
$$\frac{d\zeta}{dt} = \frac{-i}{3600.Q}$$

i is battery current and Q is battery capacity [2]. Battery current is computed using battery voltage and traction power.

2.2 The STS GUI

The STS was developed using MATLAB and relies on specialist knowledge to setup and operate. Therefore, a Graphical User Interface (GUI) was developed specially for this project – Figure 1 shows the developed STS GUI. The left part of the screen is dedicated to simulation settings and parameters, whereas the right part is reserved for plotting and displaying numerical results. This allows users to change routes and parameters without having to reprogramme the software, and presents key results in a clear to understand manner. It must be noted that, the STS only provides values relating to the kinetic energy required to move the train (i.e. it does not include factors such as hotel loads[1]).

Figure 1: Screenshot of STS GUI



Section 1 of the GUI concerns vehicle characteristics. There are several default options, or one can customise their own train, using the train properties in this section, including:

- Tare mass (tonnes/trainset). This is the mass of the train (in tonnes) without an engine or other traction system
- Maximum speed (km/h). The maximum speed the train is permitted to travel
- Rotational inertia. This figure describes the fact that when a train moves, it is not just a particle; within the bearings etc., components have to be turned to achieve movement. To correct for this, a factor is applied, usually around 0.08
- Max. motor power (kW). The maximum power (in kilowatts) that can be used to propel the train
- Dwell time (s). This is the time (in seconds) allowed at each station by the simulator
- Passenger/freight load (tonnes). The mass (in tonnes) of freight or passengers carried
- Max. tractive effort (kN). The maximum force that the train can develop to move it forward
- Max. accelerating rate (m/s^2). The maximum acceleration which the train is permitted to use

Max. braking rate (m/s^2). The maximum deceleration which the train is permitted to use.

Section 2 of the GUI concerns the traction system, the system which takes a fuel or electricity supply, and turns it into power to the wheels in order to drive the train.

There are several types of traction system to choose from, including:

- **Line side electrification**. This is a system of supplying electricity to a train using lineside infrastructure. When selected, the user may select a voltage for the substations, and the resistance of both the traction current distribution and the return current distribution (that is, the resistance of the circuit between the substation and the train, and back to the substation respectively)
- **Diesel**. This simulates a diesel engine. When selected, the user may select the maximum power of said diesel engine

[1] Hotel loads describes the electrical power needed for things like lights, air conditioning, heating, and other passenger facilities

- **Hydrogen hybrid**. This simulates a system made up of a hydrogen fuel cell and a battery. When selected, the user may input the power of the fuel cell stack (in kW), the capacity of the battery, and its C rate (more on this in Section 3)
- **Diesel hybrid**. This is very similar to the hydrogen hybrid, but with a diesel engine in place of the fuel cell stack
- **Hydrogen only**. This simulates a system made up of a hydrogen fuel cell only. When selected, the user may input the power of the fuel cell stack
- **Battery only**. This simulates a train powered exclusively by a battery. One may input the capacity and C rate of the battery

It should be noted that, while in theory any of these can be simulated, some are not included in certain cases. For example, battery powered trains are not appropriate for larger energy requirements due to the energy storage limitations of current battery technology [3].

The Single Train Simulator (STS) does not model mechanical or hydraulic transmissions. While it might be possible to configure the simulator to model these transmission types, these are not considered appropriate because converting a diesel electric locomotive (which already has electric motors and control equipment which can be fed by a fuel cell or battery for example) would be considerably simpler than completely replacing the entire transmission of a locomotive.

The diesel performance as modelled should be considered to be that of the base train and is to be used as a baseline. It has been considered that the selection of retrofitting more modern diesel engines is not a “novel” form of traction technology and therefore is outside the scope of this report. Whilst this option would reduce emissions and fuel consumption, it does not provide the opportunity for the emissions free operation which is a key attribute of novel traction systems through the provision of energy storages, zero emissions producing prime movers or both.

Section 3 concerns the route data. There are several test routes to choose from, and a customised route option; this is entered externally in a spreadsheet provided with the STS. More information is found in the manual in Appendix B.

The outputs consist of three diagrams:

- A running diagram, with velocity on the y axis, and time on the x axis
- A power diagram, showing the power used by both the traction system and the brakes during the run
- An energy diagram, showing the cumulative energy use over the simulation run

There are also several number outputs. For all cases, the journey time is listed, as is the kinetic energy required. The other outputs concern the energy and fuel consumption, whether that be in terms of kilowatt hours (kWh) for batteries, or diesel or hydrogen consumption.

SECTION 3: TRACTION SYSTEM PARAMETERS

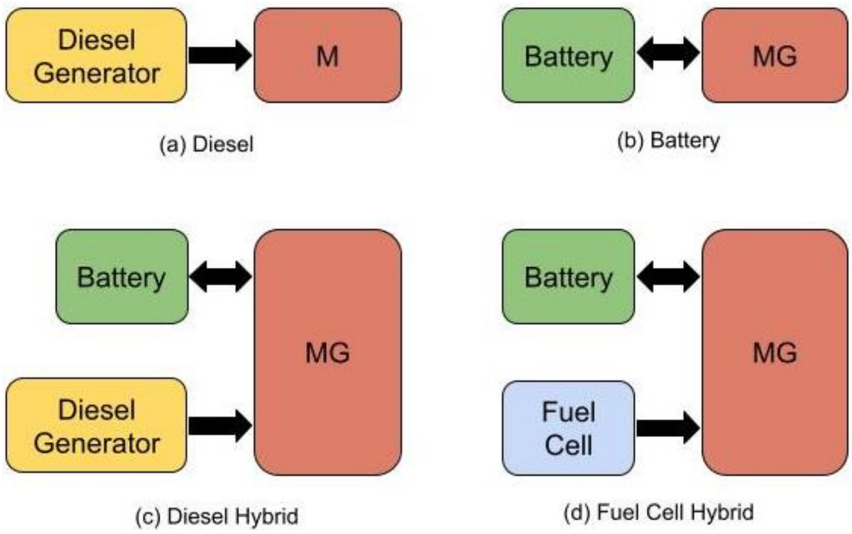
Before discussing powertrains, we must first define the “traction system”. In this document, the “traction system” is defined as the system which converts energy stored on board, or supplied to the train, to kinetic energy to move the train.

Other systems will be analysed where they are immediately relevant and where such analyses are simple to perform; it is acknowledged that electrical transmission efficiency will reduce the amount of power available and thus have an impact on the final energy use, however, the analysis of an electricity grid is complicated and outside the scope of this system.

The project investigates a range of alternative powertrains that could potentially be used to reduce carbon emissions, and Figure 2 depicts the powertrain architectures covered in this study.

BCRRE has experience of using electric energy storage technologies on trains, including the traction batteries used on HydroFlex and the supercapacitors used on the Hydrogen Hero prototype locomotive. These technologies use electric motors to both harvest kinetic energy and to propel the train. As such, the Single Train Simulator is configured to model electric traction systems. This is a suitable choice for transmission technology as motors are reliable, robust, and facilitate usage of a range of primary energy sources. It was therefore assumed for the purposes of this study that electric traction motors would be employed.

Figure 2: Powertrain architectures. M stands for electric Motor, MG stands for electric Motor-Generator



Each of the architectures shown either uses a fuel to generate electricity, and/or has an on-board store of electricity (i.e. a battery) to power or help power the train. In the case of Figure(a), the electric motor is used to purely power the train, but in the case of Figure(b), (c) and (d) the electric motor can also be used as a generator to help slow the train down while generating electricity that can then be stored using on-board batteries for later reuse (i.e. a ‘Motor Generator’).

Whilst other transmission technologies are available such as hydraulic and mechanical transmissions these are not considered as the Single Train Simulator is not configured to model these options. It should be noted that it is possible to combine electric energy storage with hydraulic and mechanical transmissions, however these options are not specifically modelled as this would greatly increase the amount of simulation, analysis and reporting that would have to be detailed in this report to present multiple versions of the same analysis which would bear very similar results to one another.

A survey was undertaken to identify appropriate commercially available diesel engines, batteries and fuel-cells for use in subsequent modelling activities, summarised in the following paragraphs of this sections.

3.1 Diesel Powertrain

The diesel-only architecture is powered solely by a diesel generator sized big enough to support all on-board power needs. This configuration has been and remains by far the most common architecture for diesel-powered locomotives, but is considered to perform the poorest in terms of emissions at point-of-use. One litre of diesel combusted releases 2.68 kg CO_2e of greenhouse gas emissions [4].

This report models the base prime mover of each of the base trains. As such it should be considered as the benchmark to assess the rest of the simulations against. Whilst it would be theoretically possible to model a range of diesel options including more modern diesels, this cannot be considered to be a “novel” traction technology, as although this would reduce emissions and fuel consumption, this would not provide the option for emissions free running, a tenet of what this report considers to be “novel”. Therefore, this analysis falls outside the scope of this report.

3.2 Battery Powertrain

Battery-powered trains are similar to electric cars in their sole reliance on batteries for propulsion. This means they do not release greenhouse gas emissions at point-of-use, but rather at the electric grid’s power sources should they not be from renewable sources.

Battery-powered trains have historically been limited to niche applications due to the inferior energy density of batteries in comparison to diesel fossil fuel. More recently, several train manufacturers have announced plans for short-haul battery trains [6-8] partly due to the improvement in battery energy density, and partly due to the political will for transport decarbonisation.

The most vital parameters to consider when designing a battery pack are energy capacity and C-rate. Energy capacity determines how much energy a battery can store, and hence mandates the train’s operating range. C-rate determines how quickly a battery can discharge a set amount of its energy capacity. Designing a battery pack in a high C-rate configuration reduces the amount of batteries required, but negatively impacts lifetime. Since the batteries in a battery-powered train are heavily utilised, it is good practice to design low C-rate battery packs to maximise lifetime.

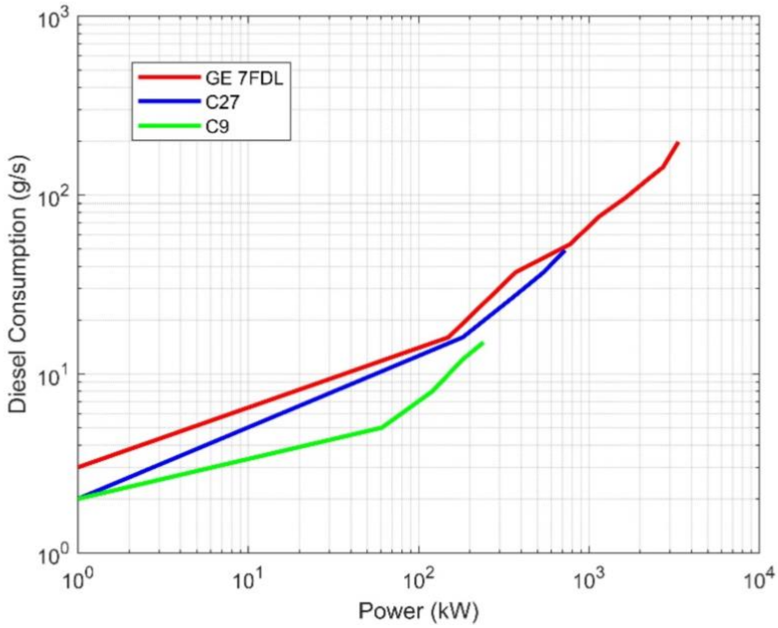
A lithium-ion NMC battery chemistry was selected for this study due to its high energy density. This battery can operate up to 7,000 cycles at a C-rate of 1C [9].

3.3 Diesel Hybrid Powertrain

The diesel hybrid architecture relies on a diesel generator as well as a battery. In comparison to diesel-only powertrains, the diesel engine in a hybrid arrangement can be downsized leading to potential fuel savings and reduced emissions. The battery is used to supplement the smaller diesel generator during acceleration phases, and can store regenerative braking energy for later use.

The Caterpillar CAT C9 (240kW) and CAT C27 (700kW) were selected as reference designs for downsized diesel generators [10, 11]. Figure 3 shows the fuel consumption of these two engines by comparison with the larger GE engine referred to earlier (i.e. GE 7FDL). This demonstrates how smaller engines consume less fuel when operating at lower power levels.

Figure 3: Diesel consumption figures. Power ratings: GE 7FDL 3,300kW; C27 700kW; C9 240kW



Since the battery serves as a supplementary role in a hybrid train, it can be specified with a high C-rate configuration. The high-power lithium-titanate-oxide battery type was selected for this application. This has a lower energy density than NMC batteries, but a higher C-rate rating. The Toshiba SCiB battery was selected as a reference battery due to its long lifetime of up to 20,000 cycles at a high C-rate of 3C [12].

3.4 Fuel Cell Hybrid Powertrain

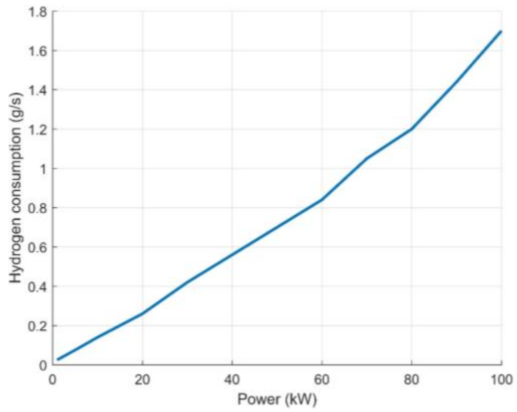
Fuel cells are electrochemical devices that convert fuel directly into electricity [13]. Polymer Electrolyte Membrane Fuel Cells (PEMFC) are currently the most relevant fuel cell technology for transport applications as they (i) allow for frequent change in electric output, (ii) exhibit short start-up times, and (iii) operate at relatively low temperatures.

Hydrogen is currently the most promising fuel to use with PEMFCs, with water vapour being the only by-product at point-of-use. The greenhouse gas emissions entailed from using hydrogen depends on the means of producing it. Hydrogen produced by electrolysis using renewable energy is considered emissions free. However, industrial hydrogen is mainly produced by steam methane reforming which emits 13.7kg CO2e per kg hydrogen [14]. We use the latter emissions figure in our analysis in order to reflect the worst case scenario in terms of emissions, but it should be noted that in many of the countries studied, electrolysis from solar panels would be a viable zero-emission option.

Heavy-duty applications such as rail typically store hydrogen in gas tanks at a pressure of 350 bar. For various technical reasons fuel cells are best deployed in a hybrid vehicle configuration alongside a traction battery [15].

The Ballard HD100 100kW was selected as the reference design for a PEMFC [16]. The HD100 has been specifically designed for heavy-duty transport applications. Figure 4 shows hydrogen consumption figures for a fuel cell typical of the HD100. The same Toshiba SCiB battery was selected as a reference design for the supporting battery.

Figure 4: Fuel cell hydrogen consumption. Data reference [16]



3.5 Scope on traction systems analysis

According to Hoffrichter [17] the efficiency of the electric transmission of a modern locomotive (including the motors, transmission and motor auxiliaries) is around 86.5%. The simulator takes account of this using an 85% factor to account for transmission losses (this allows for some variation in components).

As has been stated, the replacement of legacy diesel engines with more modern types is not considered to be novel, therefore has not been considered. An analysis of the application of multiple types of diesel engine would dilute the useful findings of this report about the applicability of truly novel traction systems.

In addition to this, lineside electrification has not been considered. Railway electrification is an established technology and as such cannot be considered to be novel either.

SECTION 4: ENERGY GENERATION IN SELECTED LIC ANALYSIS

Background research was undertaken on all four of the example routes to be modelled, including the route, traffic types, current traction and type of rolling stock operated, in addition to the modelling conducted. This chapter discusses the sources of data and the energy generation for each country which assisted in our findings.

4.1 Energy Generation in Selected LICs of Sub-Saharan Africa

The general production and availability of centrally generated electricity in Sub-Saharan Africa is limited when compared to other regions. According to the World Bank [19], only about 48% of the Sub-Saharan Africa population have access to electricity. In rural regions, less than one in ten inhabitants have such access whereas those with access are faced with the challenge of its reliability [20].

This is highly relevant because many of the solutions that might be considered, for example battery-powered trains, will rely on access to electricity which might be scarce. If electricity is not available, this will limit the decarbonisation options available.

The four countries studied here were selected because each contains a line which is representative of a particular kind of duty cycle (see Section 5: Route Reports), and its electricity supply investigated to inform which type of traction might be most suitable for reducing emissions produced by each line.

Equivalent figures for carbon emissions are difficult to find for the countries in question; therefore the information provided below is for background only.

4.1.1 Uganda

According to the Ugandan Electricity Regulatory Authority [21], the electricity supply industry is divided into three independent segments:

- Generation – Government of Uganda owned power plants in collaboration with Independent Power Producers (IPPs) and Public-Private Partnerships (PPPs)
- Transmission – wholly owned by the government of Uganda
- Distribution – liberalized and has private players as well as government owned distribution company (Uganda Electricity Distribution Company Ltd.)

The country’s power generation is mainly diversified across four different sources (hydropower, thermal, cogeneration and grid-connected solar) with a total generation capacity of 1237.49 MW as of October 2020. Transmission is managed by the Uganda Electricity Transmission Company Ltd. This is a single operator of the transmission system responsible for directly executing Power Purchase Agreements with IPPs and manages the scheduling and actual dispatching of Power Plants.

Currently, 51% of the population have access to electricity due to the improvement in electricity distribution as a result of the conducive regulatory environment created by the ERA.

4.1.2 Tanzania

Tanzania is the 6th most populous country in sub-Saharan Africa and has only 32.8% of households connected to electricity by 2016 [22] [23]. Approximately 58% of the country’s electricity is generated from natural gas. Previously, the country relied on hydropower, expensive thermal and emergency generation sources that utilise diesel, heavy fuel oil and jet fuel.

The source of Tanzania's main grid system is a hydrothermal mix which has an installed generation capacity of about 1,501 MW. In addition, the country has an isolated grid with an installed capacity of 55MW. The Ministry of Energy anticipates further diversification of its electric power fuel sources toward (in order of priority) natural gas, coal, hydro, geothermal and renewables especially solar and wind.

The main challenges faced by the sector are poor sector governance, lack of credit worthy off-taker and the lack of cost reflective tariffs [22].

4.1.3 Liberia

Following from the war, the Liberian government is working with development partners to undertake measures to rebuild the country's electricity infrastructure (w6). Liberia has one of the lowest electricity access rates (approximately 12%) in the world with only 8% of households connected to the national grid [24][25].

The country has an installed generation capacity of 126MW. High tariffs on electricity ($o.35/kWh) makes it the single largest component of operational expenses in Liberia for businesses. This in conjunction with the lack of reliable electricity and poor road networks are the binding constraints to the country's growth (International Trade Administration, no date). Many businesses rely on privately-owned generators for their operations.

In July 2017, the rehabilitated Mount Coffee Hydroelectric Plant became fully functional and completely took over from the diesel power plants the Liberia Electricity Corporation had relied on for many years. The hydro plant currently generates 88 MW of power with the capacity to expand to 126 MW. Its current constraint is the distribution of the power generated.

According to US AID [25], the major challenges faced by the sector include:

- Weak and underdeveloped enabling environment
- Weak public utility that isn't commercially viable with high tariff and high commercial losses
- Delayed expansion of transmission and distribution network to evaluate existing generating capacity
- Nascent off-grid sector

4.1.4 Nigeria

Nigeria has the largest economy in sub-Saharan Africa and is endowed with large amounts of oil, gas, hydro and solar resources [26]. Electricity generation in Nigeria is largely dependent on hydropower (12.5%) and fossil (gas) thermal (87.5%) power sources [27]. There are 25 grid-connected power generating plants with an installed capacity of 12,500MW. However, only 3,500MW to 5,000MW are available for transmission to the final consumer.

The power plants are faced with the frequent occurrence of technical and non-technical issues resulting in insufficient power supply. Therefore, majority of consumers, especially businesses, rely on the use of standby generators for their operations. Factors attributed to the insufficient supply of electricity include insufficient gas processing and pipeline infrastructure, lack of investment in gas-processing facilities, failure to complete already funded projects and regular vandalism of existing pipeline infrastructure by militants.

Interestingly, off-grid electrification initiatives are emerging. For example, in 2017 the Nigerian government launched an initiative to distribute 20,000 solar powered lighting systems to rural communities. Also, there are ongoing plans to add 13 GW of off grid solar power by 2030.

4.1.5 Summary of Power Generation in the Selected Countries

Table 2: Comparison of electrical power in Liberia, Nigeria, Tanzania and Uganda

Country	Installed Capacity	Generation	Transmission & Distribution	Access to Electricity
Liberia	126 MW	Diesel & HFO – 38 MW Hydro – 88 MW	Distribution constraints	12% access rate (3% rural, 16% urban) 832000 households are without electricity.
Nigeria	12500 MW (16384 MW according to w8)	25 grid-connected generation plants: Hydro – 2062 MW Gas – 11972 MW Wind – 10 MW Solar – 7 MW Other/Diesel/HFO – 2333 MW	Only 3500 – 5000 MW are available for transmission to the final consumer. The network comprises 159 substations and 15022 km of transmission lines. The distribution grid operates mainly on 33 kV and 11 kV (medium and low voltage respectively).	60% access rate (34% rural, 86% urban)
Tanzania	1513 MW (Isolated grid – 55 MW)	Hydrothermal mix: Hydro – 568 MW Thermal (natural gas) – 925 MW Other renewables – 82.4 MW	50 substations and 5 off-grid substations are interconnected by: 670 km of 400 kV, 3610.7 km of 220 kV, 1662.47 km of 132 kV, and 543 km of 66 kV transmission lines.	32.8% of households have access to electricity (by 2016). 7.7 million households are without electricity.
Uganda	1237.49 MW	40 generation plants: Hydro – 1023.59 MW Thermal – 100 MW Cogeneration – 63.9 MW Grid-connected solar – 60 MW	Managed by a single operator, the Uganda Electricity Transmission Company Ltd. Conducive regulatory environment led to improvement in the distribution of electricity.	51% access rate

4.1.6 Summary of Suitability of Electricity Generation to Support Novel Traction Systems

As can be seen in Table 2, all four countries analysed have low levels of electricity access when compared with other, more developed countries where access to electricity is almost complete and can largely be taken for granted. As such, access to grid electricity cannot be assured in any of these countries for the purpose of charging batteries or producing hydrogen by process of electrolysis.

That being said, it is outside the scope of this report to analyse the specific availability of electricity to support the specific location of the routes in each of the specific case studies shown. Instead, this analysis has been included to allow a more general assessment of the capability of novel traction systems to be supported in each of the assessed LICs.

It should be noted that sustainable electricity is available in each of the LICs, thus meaning that battery and hydrogen trains could use this energy to produce hydrogen fuel and charge batteries with completely no emissions from point of energy generation. Specifically in the case of hydro-electric power, both of the ingredients needed for sustainable hydrogen – electricity and water – are present at source. This could allow for hydrogen to be generated in situ. Transport of the generated hydrogen could be conducted by pipeline or by rail or road in tube trailers.

However, it should be noted that even if electrolysis is not available, hydrogen can also be formed by other technologies such as Steam Methane Reforming (SMR). Figures for CO2 emissions from this are included with the case studies.

As has been discussed in section 3.5, lineside electrification is considered outside the scope of this project and as such the suitability of electrical grids for provision of electricity for this technology has not been considered.

It is impossible to rule out, from an electricity supply point of view, the use of electrolysed hydrogen or battery trains in each country. A possible scenario could see the adoption of hydrogen or battery powered vehicles linked with a drive to increase electricity generation or distribution within each country. As such, the use of hydrogen or battery powered trains will not be ruled out on this basis in this report. Instead, traction technologies will be ruled out on the basis of whether they are capable of satisfying each duty cycle as this is a capability analysis report.

SECTION 5: ROUTE REPORTS

Background research was undertaken on all four of the example routes to be modelled, including the route, traffic types, current traction and type of rolling stock operated.

Note that for the hydrogen options, 0 kg of emissions for electrolysed hydrogen is stated; this is an ambition based upon the idea that new electricity generation may be required given the low access to electricity in the region.

Note also that for many hybrid options, battery charging is considered. This is because on some of the moves, some of the energy in the battery at the start of the run is used up; in order to return to the same energy in the battery, this energy lost must be put back into the battery by charging it. If this was not the case, the battery would slowly lose energy with each run and eventually run out.

5.1 Kampala – Namanve Route

5.1.1 Route

This route serves the suburbs of Kampala, the Ugandan capital, with 4 stops along the 12 km route before terminating in Namanve (see Figure 5).

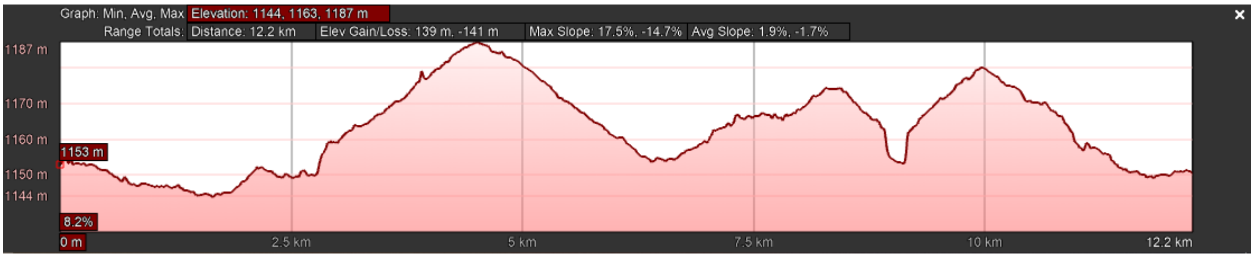
Figure 5: Kampala to Namanve route, showing station stop locations [28]

In order to get a more accurate picture of the route in question, the route was mapped using Google Earth Pro (see Figure 6).

Figure 6: The Kampala – Namanve route shown in Google Earth

The route mapping enabled gradient information to be generated for the simulation, as shown in Figure 7.

Figure 7: Kampala - Namanve gradient profile from Google Earth, with Kampala on the left and Namanve on the right

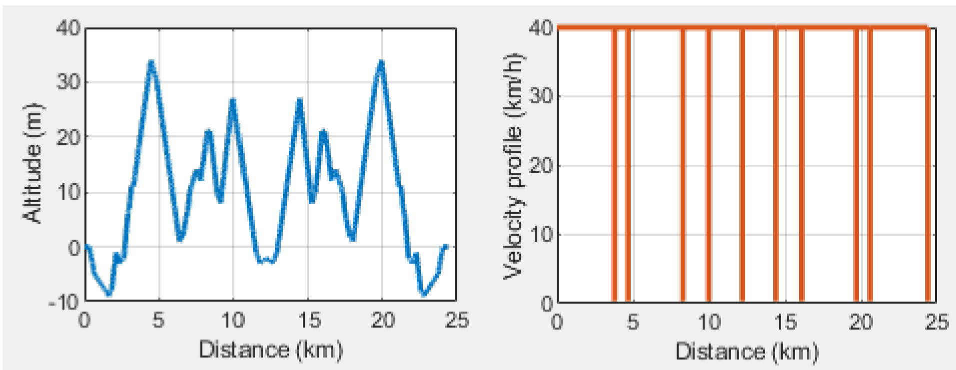


It should be noted that the gradient data from Google Earth Pro is imperfect as it tends to select road elevations rather than rail ones wherever the two meet. It also provides ground elevation values which can misrepresent tunnels and bridges. For example in **Error! Reference source not found.** 7 there is a significant dip in the graph between 7.5 and 10 km. This does not represent reality; the Google Earth map confirms that the line enters an embankment here (see **Error! Reference source not found.**) rather than dropping away dramatically.

Figure 8: Section of embankment on the Kampala – Namanve route

However, it was also necessary to translate the data to a form suitable for the STS modelling. This involved taking the elevation at key points and calculating the gradient between them, and then modifying the format used. This process effectively 'smoothed out' the gradient data, thereby removing problematic features such as that highlighted above. This produced the simplified route profile in Figure 9 (note that this is symmetrical because in this case a round trip starting and finishing in Kampala was studied).

Figure 9: Route profile for the Kampala – Namanve route in the Single Train Simulator



According to local sources [29], the service transports around 2,000 people each day. Given there are 2 round trips per day [29], this equates to roughly 500 people per trip, or 100 per coach for a 5 coach train.

In the absence of more accurate data, a line speed of 25 mph has been assumed for the model. The reason for the relatively slow speed is that the line is mainly open with no boundary fence, so there is a significant risk of collisions with pedestrians. It is also the case that most stations have no platforms or expected waiting areas, and people commonly gather around the track. The assumed speed is also supported by the timetable which allows 45 minutes [30] for a journey of just 12.2 km, a start-stop average of just 10.1 mph.

5.1.2 Rolling Stock

The rolling stock used on the route currently consists of a small diesel locomotive and 5 carriages (see Figure 10)[31].

Figure 10: Kampala – Namanve train, viewed from the rear [31]

It is assumed that the rolling stock consists of an 80 tonne locomotive (a typical weight for a locomotive of this size), hauling 5 conventional coaches of 35 tonnes each. This give a total of 255 tonne for the train.

The train resistance was calculated based on converting values from a seminal publication by Canadian National formula [32] into the following Davis Equation parameters, as necessary for STS modelling (further detail on this is contained in Appendix A):

$$R=3.7+0.11V+0.007V^2$$

The output for a locomotive of this type would typically be around 1000 kW for traction with 50 kW for auxiliary loads.

However, an alternative modern solution would be to use an Ultra-Light Rail (ULR) vehicle, as shown in Figure 11. This particular vehicle is manufactured in the UK by Severn Lamb, and is a hybrid configuration with a diesel engine and hybrid battery [33].

Figure 11: Ultra-Light Rail (ULR) vehicle [33]

The configuration in Table 3 has been derived using data from [33].

Table 3: Basic characteristics of the ULR-based train proposed

Characteristic	Value
No. of vehicles in consist	5
Passenger capacity (crush load)	600
Mass (tare)	110 tonnes
Mass (crush load) (used for simulation)	160 tonnes
Traction power	840 kW (Based on ~ 140 kW prime mover, plus 20%
Auxiliary power	50 kW (10 kW per car; this is assumed)

Note that, even fully loaded, this is far lighter than the current conventional train.

The Davis Equation parameters were again generated using the Canadian National formula [32], and for this configuration, the following Davis Equation was arrived at (see Appendix A for further information):

$$R=2.8+0.04V+0.0034V^2$$

It should be noted that the Severn Lamb ULR is a hybrid. This usually consists of a diesel generator feeding a series hybrid system, but a hydrogen fuel cell module could reasonably be fitted in place of the diesel generator. Both configurations were simulated with the characteristics shown in Table 4.

Table 4: Characteristics of the hybrid power plants tested on the Kampala – Namanve route

Characteristic	Value
Prime mover power	700 kW
Hybrid battery capacity	220 kWh
Hybrid battery C rate	0.64

5.1.3 Simulation Results

Figure 12 shows the simulator outputs for the conventional diesel train.

Figure 12: Simulation output for the Kampala – Namanve route, using the hydrogen hybrid ULR-based train

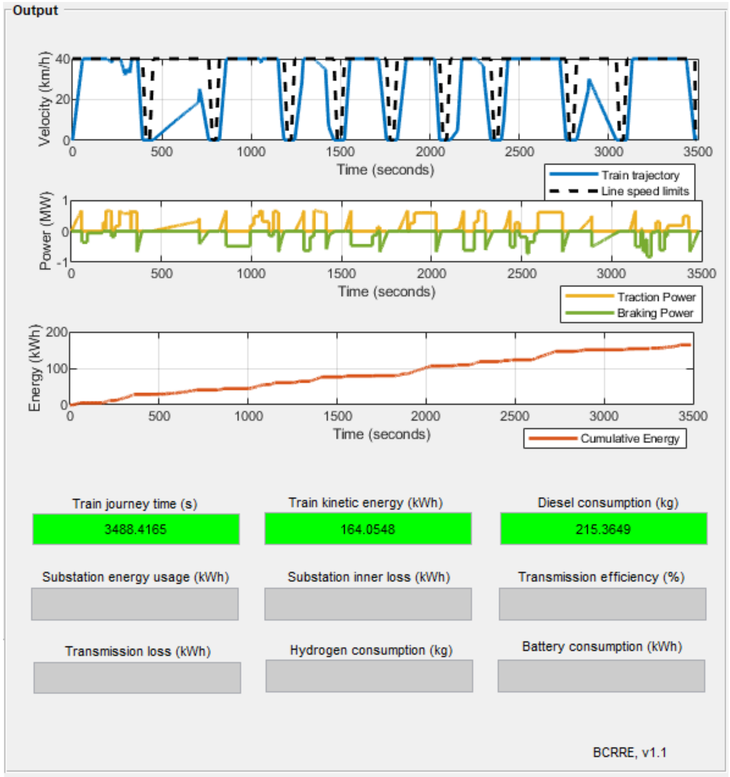


Figure 13 and Figure 14 below show the simulator outputs for hydrogen and diesel ULR options respectively.

Figure 13: Simulation output for the Kampala Namanve route, using the hydrogen hybrid ULR-based train

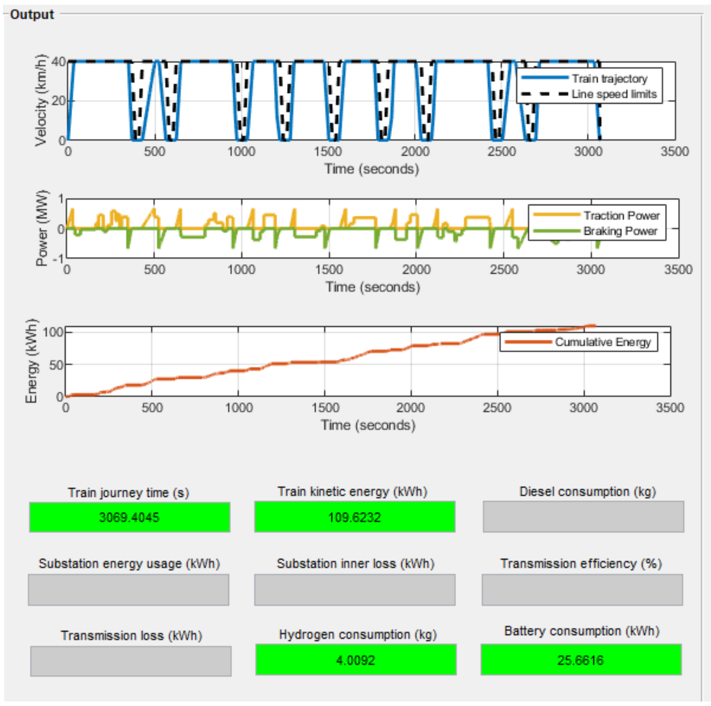
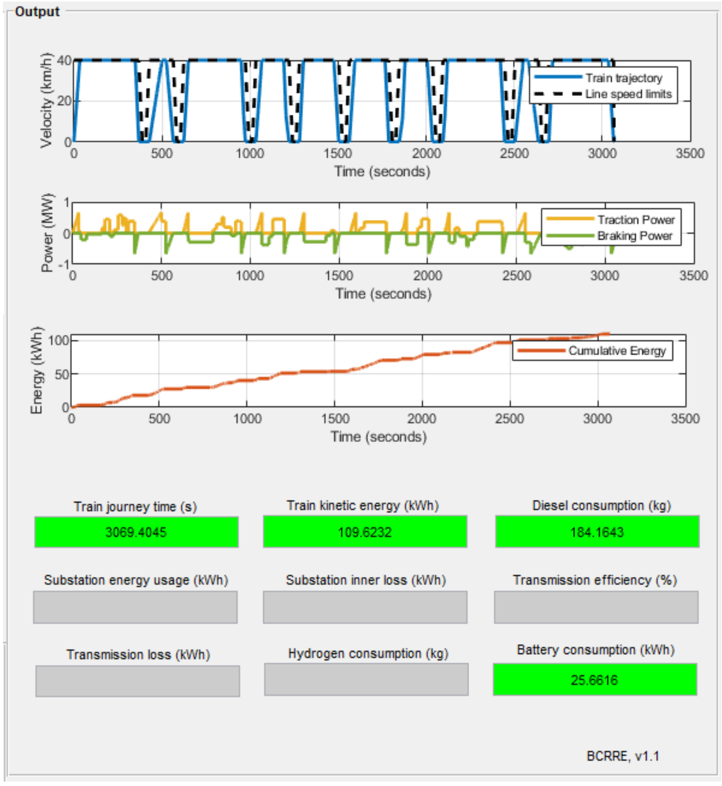


Figure 14: Simulation output for the Kampala – Namanve route, using the diesel hybrid ULR-based train

Figure 14: Simulation output for the Kampala – Namanve route, using the diesel hybrid ULR-based train

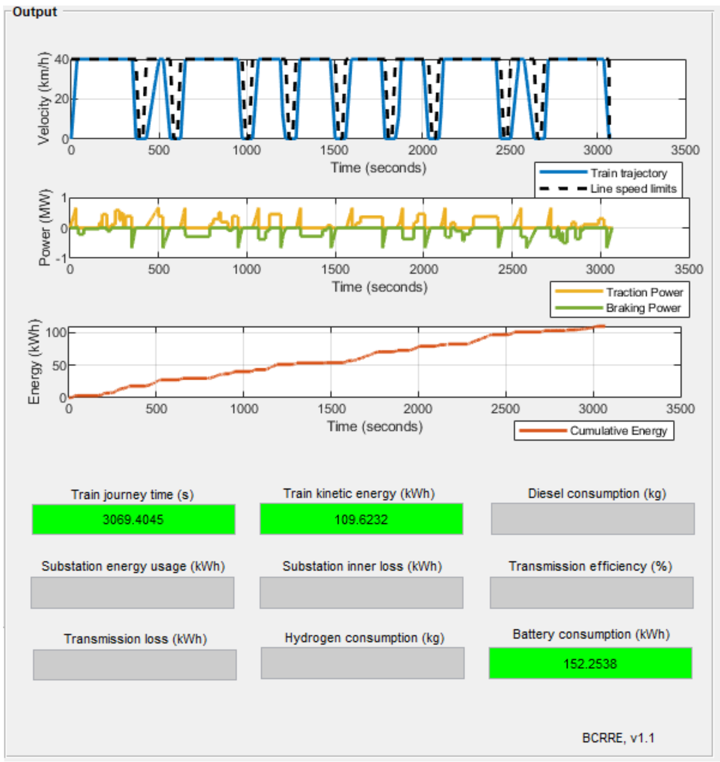
Figure 14: Simulation output for the Kampala – Namanve route, using the diesel hybrid ULR-based train

Figure 14: Simulation output for the Kampala – Namanve route, using the diesel hybrid ULR-based train



In addition, a battery-only ULR option was modelled assuming a 100 kWh battery per vehicle, to give a total of 500 kWh of storage and the same total power output of 840 kW. Figure 15 shows the results for this battery train.

Figure 15: Simulation output for the Kampala – Namanve route, using the battery only ULR-based train



It should be noted that in both of the hybrid cases, the battery state of charge declined by 12% at the end of the route, necessitating some battery charging at the end. In addition, some energy will also need to be expended in order to cover for the auxiliary load when the train is dwelling for extended periods. A 12%

battery state of charge equates to 26.4 kWh. At around 50% overall efficiency, this equates to 52.8 kWh or around 1.6 kg of additional hydrogen, or around 5.4 kg of diesel.

The fuel and energy requirements are summarised in Table 5 below. Two round trips are listed as there are two trains a day [28].

Table 5: Fuel requirements for each type of train

	Diesel hybrid	Hydrogen hybrid	Battery only	Diesel only (conventional)
Basic requirement	216.66 l	4.01 kg	152.25 kWh	253.38 l
(inc. battery charging)	222.07 l	5.61 kg	-	-
(+ 20% for eventualities)	267.06 l	7 kg	183 kWh	304.7 l
2 round trips	**534.2 l**	**14 kg**	**366 kWh**	**609.4 l**

The source of the 20% for operational eventualities is based upon the authors' experience with projects such as HydroFLEX. It is an included margin for safety that is included within all calculations conducted by the team in order to ensure that enough fuel is stored even in a worst-case scenario.

Table 6 below shows the entailed emissions. It is observed that the hydrogen scenario emits significantly less greenhouse gases than diesel due to the higher efficiency of fuel cells. The battery only and electrolysed hydrogen scenarios are shown as emitting no greenhouse gases. This has been assessed to be the case as Uganda's electric grid is primarily powered by renewable hydropower [34]. Whilst it is possible that in some cases electricity will be produced by fossil fuels, the vast majority of the time this is unlikely to be the case. In this case study, there is an emissions saving from using a diesel hybrid train, but there is a far greater saving to overall emissions from using either a hydrogen hybrid or battery powertrain.

Table 6: Equivalent carbon dioxide emissions for each train type

<table>
<tr><th></th><th>Diesel hybrid</th><th>Hydrogen hybrid</th><th>Battery only</th><th>Diesel only (conventional)</th></tr>
<tr><td rowspan="2">Equivalent carbon dioxide emissions (CO2e)</td><td rowspan="2">1431 kg</td><td>SMR: 192 kg</td><td rowspan="2">0 kg</td><td rowspan="2">1633 kg</td></tr>
<tr><td>Electrolysis: 0 kg</td></tr>
</table>

5.1.4 Findings

The key conclusions from the simulations detailed above are as follows:

- All the ULR-based options complete the journey in a shorter time than the conventional train;
- The ULR-based hybrid, even when the diesel efficiency is kept the same (as done in the simulation above), uses 76 l less diesel than the conventional diesel engine, thus reducing operational expenses and carbon emissions;
- The hydrogen hybrid consumes relatively little hydrogen (the consumption in the simulations above is less than the hydrogen storage capacity on board the University's recent HydroFLEX demonstrator). However, a supply chain for this hydrogen would have to be sought;
- Modelling suggests that a 500 kWh battery would be sufficient to meet the current timetable requirements. However, the charging arrangements may be difficult given the relatively limited access to electricity in Uganda; it is highly unlikely that such a scheme would be prioritised over street lighting, for example;

- Both hydrogen and battery solutions curtail significant amounts of greenhouse emissions in comparison to diesel;
- There is potential for zero-emission battery charging or hydrogen production, due to the bulk of the Ugandan energy mix being zero emission (see section 4), however, with electricity access not universal, transmission losses may be a problem and local generation (for example a small scale solar plant) may have to be considered

5.2 Buchanan - Tokadeh Route

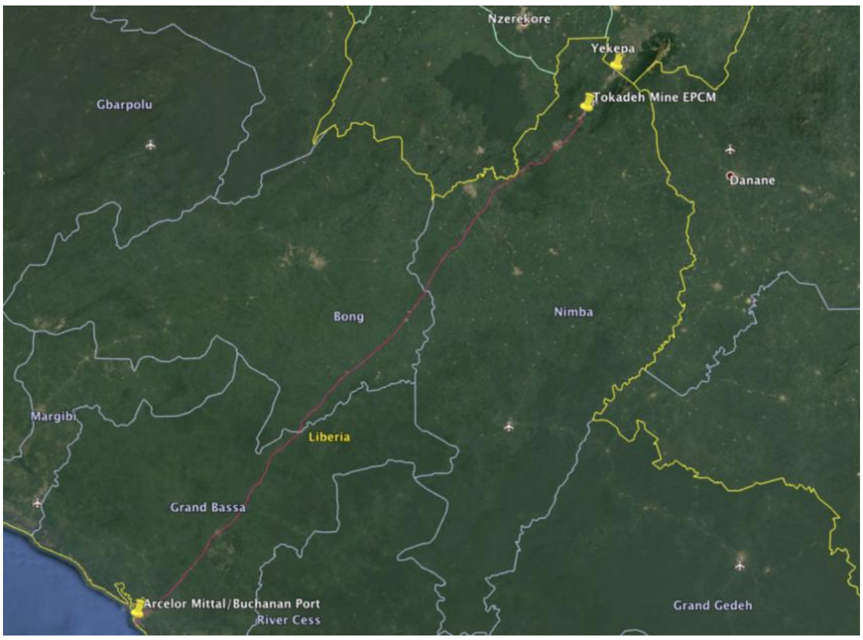
5.2.1 Route

The Buchanan to Yekepa railway line is one of 3 lines constructed between the 1960s and 1980s for the transportation of iron ore (see Figure 16) [35]. The line was closed in the 1990s due to the civil war in Liberia. In 2006, Mittal Steel – now part of ArcelorMittal – was granted permission to rehabilitate the line for the transportation of ore from the Tokadeh mine (about 20km from Yekepa) to the coast.

Figure 16: Transportation of iron ore on the Buchanan – Tokadeh route [35]

This route was modelled in Google Earth in a similar way to the Kampala route (see Figure 17 and Figure 18).

Figure 17: The Buchanan - Tokadeh route shown in Google Earth

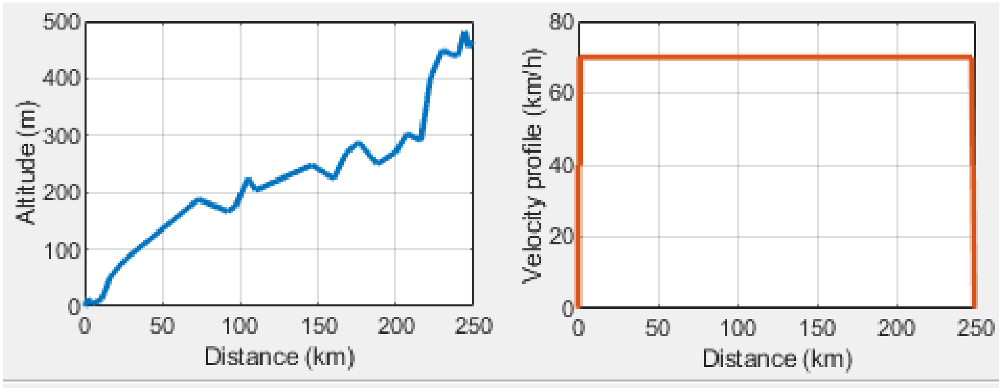


The corresponding elevation profile from Google Earth Pro is shown in **Error! Reference source not found.** 18. Note the considerable change in altitude from Buchanan at sea level to Tokadeh.

Figure 18: Buchanan - Tokadeh gradient profile from Google Earth, with Buchanan on the left and Tokadeh on the right

As this route is far longer than the Kampala line, it was not modelled in a great level of detail; with altitude assessed at roughly 2 km intervals to give the route profile shown in Figure 19.

Figure 19: Route profile for the Buchanan - Tokadeh route in the Single Train Simulator



5.2.2 Rolling Stock

The railway is equipped with General Electric AC4400 evolution locomotives rated at 4400 hp. These are used for moving trains formed of up to 75 wagons. It is understood that each wagon has a payload of 90 tonnes of ore and the empty wagon was assumed to weigh 30 tonnes which is typical for a wagon of this type. The key characteristics are shown in Table 7, derived using data from CIT [36].

Table 7: Basic characteristics of the freight train tested

Characteristic	Value
No. of vehicles in consist	78 (3x AC4400CW locomotives + 75 wagons)
Mass (empty)	2830 tonnes
Mass (loaded)	9580 tonnes
Traction power	9780 kW
Auxiliary power	120 kW

The Davis equations for these configurations were generated using the Canadian National formula [31], which gave the following Davis Equations Parameters (further information is proved in Appendix A):

R=45.5+0.98V+0.01V^2 (empty train)

R=95+3.2V+0.009V^2 (loaded train)

For the hybrid options, the configuration in Table 8 was modelled based on assumed values for a locomotive of this type.

Table 8: Characteristics of the hybrid power plants tested on the Buchanan - Tokadeh route

Characteristic	Value
Prime mover power	6000 kW
Hybrid battery capacity	1300 kWh
Hybrid battery C rate	3

5.2.3 Simulation Results

The return journey was modelled as two separate journeys as the mass of the train changes substantially in each direction. That is, when empty and running between Buchanan - Tokadeh, the train has a mass of 2830 tonnes, whereas when loaded and running between Tokadeh - Buchanan, the train has a mass of 9580 tonnes.

While this might not seem significant at first, the change in mass has a significant impact on both performance and energy consumption (see Figure 20 and Figure 21).

Figure 20: Simulation output for the Buchanan – Tokadeh route, using the empty diesel train

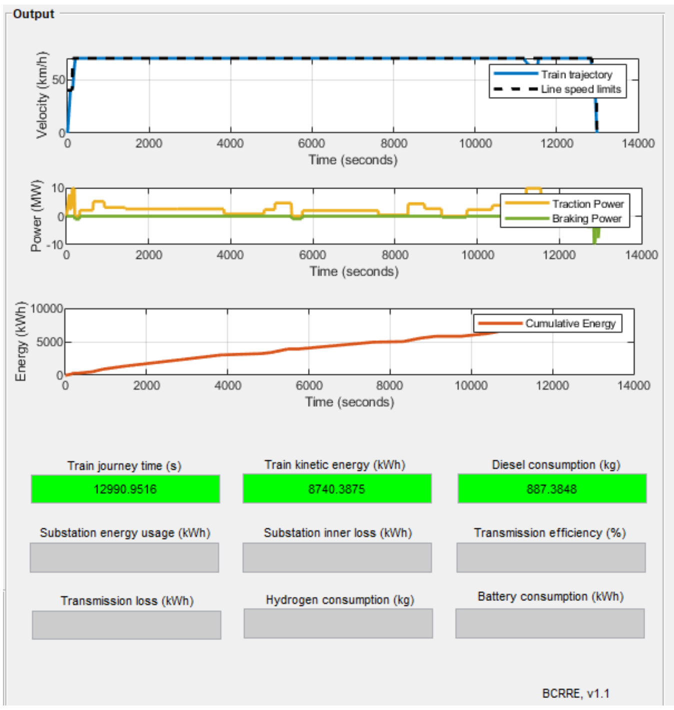
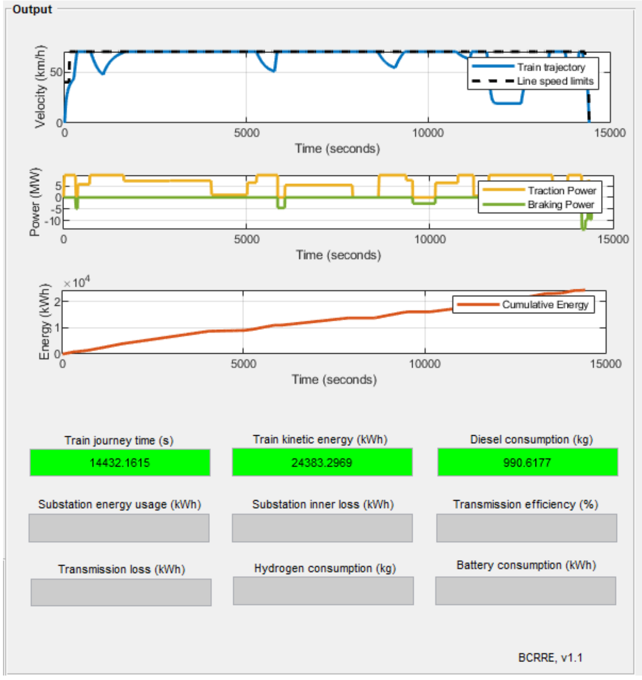


Figure 21: Simulation output for the Buchanan – Tokadeh route, using the loaded diesel train

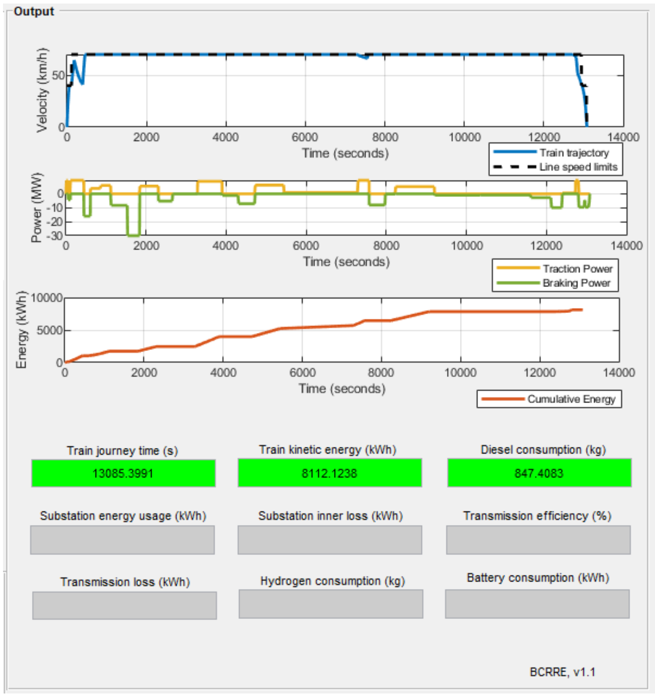


As can be seen in the figures above (i.e. Figure 20 and Figure 21), not only does the loaded train use 121.4 l more diesel than the empty one, but it also takes 1441 seconds (24.02 minutes) longer to complete the journey. Therefore, we can conclude that the train mass has a significant impact.

The following figures 33 to 37 show the results of the simulations included in the report.

Figure 22 shows the simulator outputs for a loaded diesel train from Tokadeh - Buchanan. The empty train in the other direction has already been shown in Figure 20.

Figure 22: Simulation output for the Tokadeh - Buchanan route, using the loaded diesel train



Error! Reference source not found. shows the simulator outputs for an empty hydrogen-hybrid train from Buchanan - Tokadeh.

Figure 23: Simulation output for the Buchanan – Tokadeh route, using the empty hydrogen hybrid train

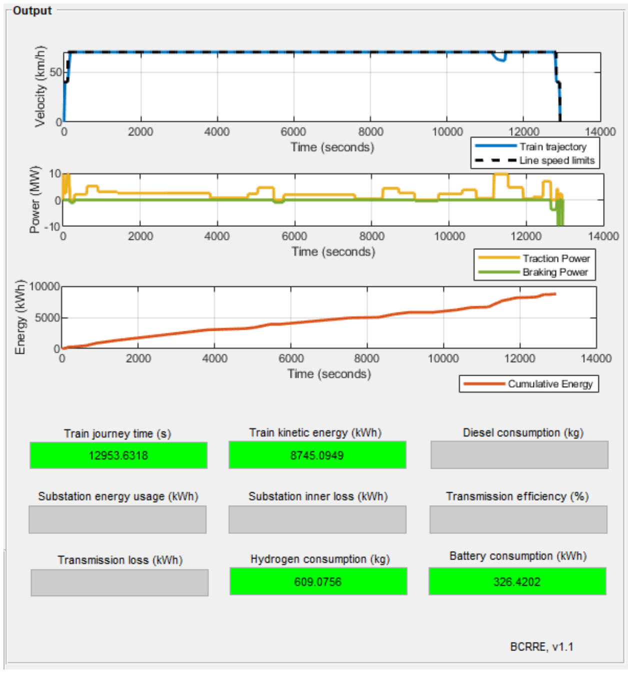


Figure 24 shows the simulator outputs for a loaded hydrogen-hybrid train from Tokadeh -Buchanan.

Figure 24: Simulation output for the Tokadeh – Buchanan route, using the loaded hydrogen hybrid train

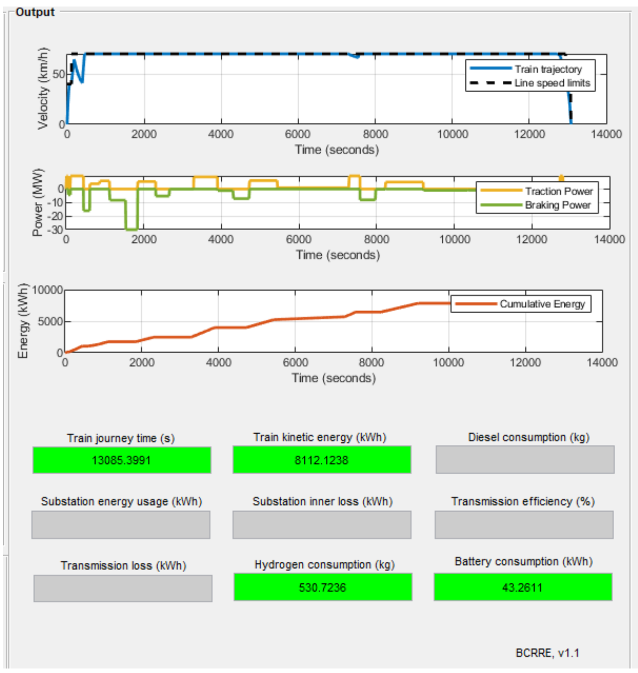


Figure 25 shows the simulator outputs for an empty diesel-hybrid train from Buchanan – Tokadeh.

Figure 25: Simulation output for the Buchanan – Tokadeh route, using the empty diesel hybrid train

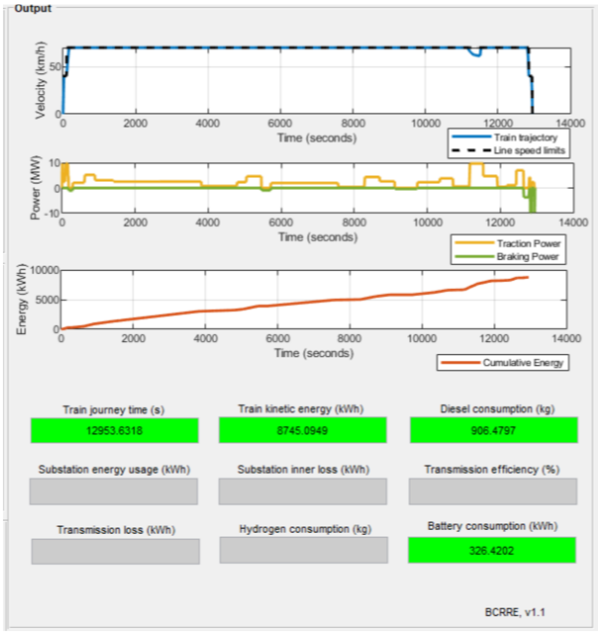
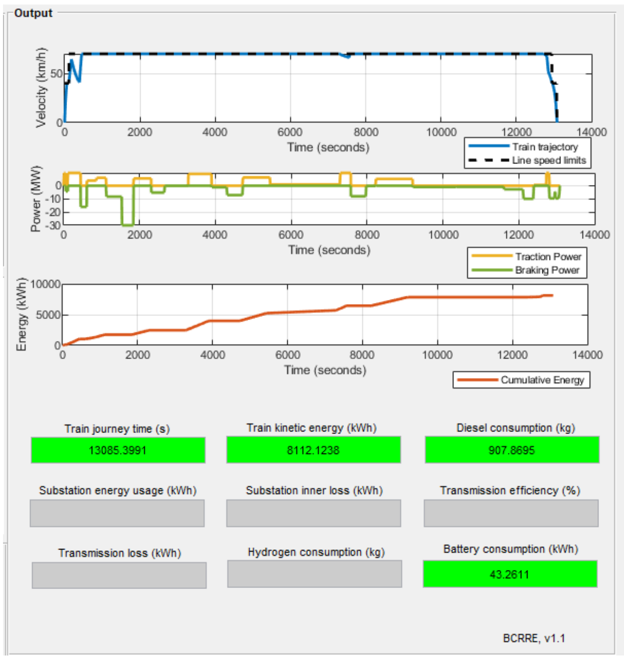


Figure 26 shows the simulator outputs for a loaded diesel-hybrid train from Tokadeh -Buchanan.

Figure 26: Simulation output for the Tokadeh - Buchanan route, using the loaded diesel hybrid train



It should be noted that in the Buchanan - Tokadeh cases, the battery state of charge declines, whereas for the Tokadeh - Buchanan cases, the battery state of charge overall actually increases due to the downhill gradient.

In the hydrogen hybrid, the overall efficiency of charging the battery is assumed to be 50%, whereas for the diesel hybrid, it is assumed to be 20%. This is on the basis of the relative known efficiencies of prime mover, transmission and bus losses [44].

Results for Buchanan - Tokadeh are shown in Table 9, results for Tokadeh - Buchanan are shown in Table 10, and the overall requirements in Table 11.

Table 9: Fuel requirements for each type of train from Buchanan – Tokadeh

	Diesel hybrid	Hydrogen hybrid	Diesel only
Basic requirement	1067 l	610 kg	1041 l
(inc. battery charging)	1242 l	621 kg	-
(+20% for eventualities)	**1491 l**	**746 kg**	**1250 l**

Table 10: Fuel requirements for each type of train from Tokadeh – Buchanan

	Diesel hybrid	Hydrogen hybrid	Diesel only
Basic requirement	1069 l	531 kg	1166 l
(inc. battery charging)	1092 l	535 kg	-
(+20% for eventualities)	**1311 l**	**642 kg**	**1398 l**

Table 11: Fuel requirements for each type of train for a round trip on the Buchanan – Tokadeh route

	Diesel hybrid	Hydrogen hybrid	Diesel only
Total Requirement	**2802 l**	**1388 kg**	**2648 l**

Table 12 below shows the entailed emissions for a round trip on the Buchanan – Tokadeh route. It is observed that in this case, there is potentially no overall benefit to introducing hydrogen-powered trains; although the emissions at the point of use would be zero (hydrogen fuel cells do not produce harmful emissions), the emissions produced in the production of that hydrogen from natural gas are more than twice those from diesel-powered trains. However, policy makers should not ignore the possibility of zero emissions if the hydrogen is produced by electrolysis using renewable electricity.

Table 12: Equivalent carbon dioxide emissions for each train type on the Buchanan – Tokadeh route

	Diesel hybrid	Hydrogen hybrid	Diesel only
Equivalent carbon dioxide emissions (CO2e)	**7510 kg**	**SMR: 19016 kg** **Electrolysis: 0 kg**	**7097 kg**

5.2.4 Findings

- Although the total round trip hydrogen requirement seems onerous, it would be far more likely that if a hydrogen-hybrid option were pursued, refuelling would be performed at each end of the line rather than just fuelling the train once for the entire trip. It should be noted that this is still likely to be far in excess of any existing hydrogen-powered train;
- There is no benefit to hybridisation here in terms of overall CO2 emissions; in fact the diesel hybrid produces worse fuel consumption than the diesel only option. This is due to the constant speed nature of this route which presents few opportunities for regenerative braking

- However, it might be the case that it is considered worthwhile to hybridise a diesel locomotive to allow for the battery to power the train in emissions sensitive areas. This can be considered beneficial by removing hazards to human health from populated areas. These hazards include particulates, noxious gases, noise and vibration. This option would provide a discernible benefit whilst utilising the existing diesel supply infrastructure
- Hydrogen from methane does not offer an emissions advantage in this case study. However, hydrogen might have an overall carbon emissions advantage if the hydrogen was produced using renewable energy.
- The exceedingly high SMR hydrogen emissions figure is assessed to be due to the fuel cells in the locomotives having to operate in an inefficient regime for a protracted period of time (i.e. the fuel cell stack is being asked to operate near its maximum power where it is less efficient, compared with a diesel engine which is most efficient at maximum power). This is combined with the inherently high carbon emissions of SMR hydrogen production to produce an exceedingly high emissions figure.
- Given the extremely limited supply of electricity in Liberia (see 11.5, Section 4) there is little prospect of zero-emission hydrogen production, unless a new power source, for example a solar power station, was constructed
- It should be noted that despite the potential carbon disadvantage hydrogen brings with it other advantages, particularly as there are no emissions at the point of use and much reduced noise compared with diesel; these advantages should be considered rather than just the headline figures

5.3 Dar es Salaam – Kigoma Route

5.3.1 Route

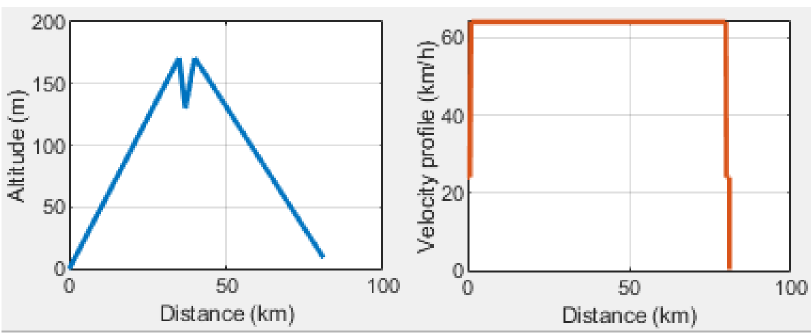
This route traverses Tanzania from Dar es Salaam on the Indian Ocean coast to Kigoma on the shore of Lake Tanganyika. The 1000mm narrow gauge line was built by the Germans starting at Dar es Salaam in 1905 [37], reaching Kigoma in 1914 [38].

The line to either end destination is just over 1200km in length, and there are significant elevation gains along the route. For instance, the line climbs to over 1300m on its way to Tabora (1200m elevation) before either dropping down to Kigoma (770m elevation), or remaining at a similar elevation all the way to Mwanza (1140 elevation).

As this is an extremely long route, it was split into several sections:

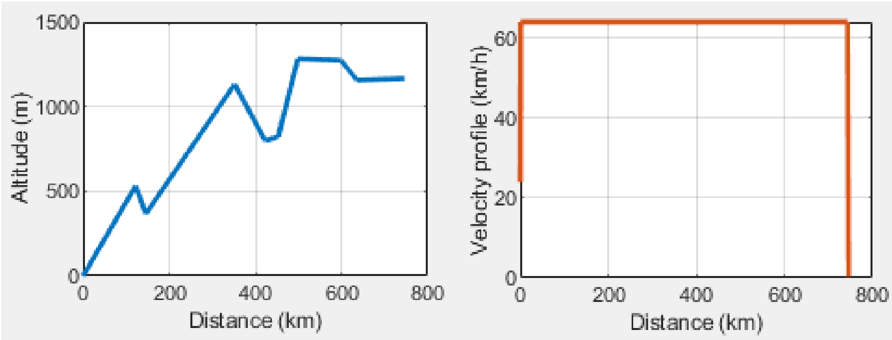
- Dar es Salaam - Mahundi Jn. The route profile inside the STS is shown in Figure 27.

Figure 27: Route profile for Dar es Salaam – Mahundi Jn. The return trip was also simulated



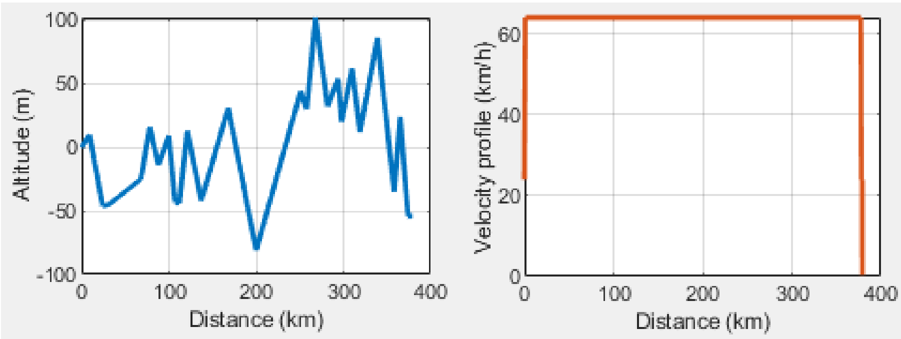
- Mahundi Jn. – Tabora. The route profile inside the STS is shown in Figure 28.

Figure 28: Route profile for Mahundi Jn. – Tabora. The return trip was also simulated



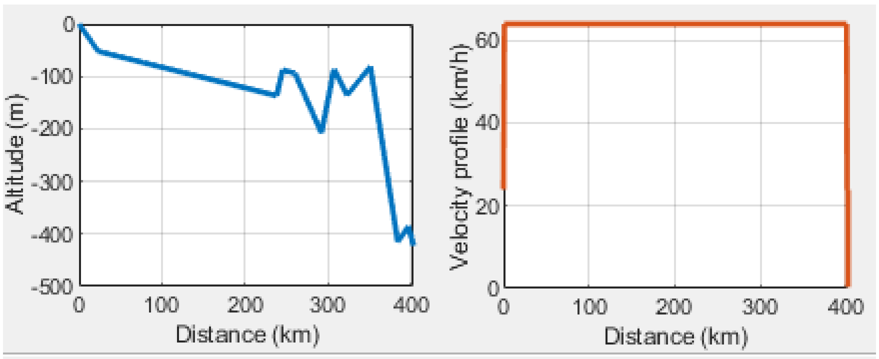
- Tabora – Mwanza. The route profile inside the STS is shown in Figure 29.

Figure 29: Route profile for Tabora - Mwanza. The return trip was also simulated



- Tabora - Kigoma (either Mwanza or Kigoma can be reached from Tabora). The route profile inside the STS is shown in Figure 30.

Figure 30: Route profile for Tabora - Kigoma. The return trip was also simulated



5.3.2 Rolling Stock

The train is locomotive hauled, with both sleeping and seated coaches (see Figure 31 and Figure 32).

Figure 31: The new Dar es Salaam to Kigoma Train [38]

Figure 32: The new Deluxe Train [39]

The journey from Dar es Salaam to Tabora takes around 21.5 hours, and a further 10.5 hours to travel onward to Kigoma or 12.5 hours onward to Mwanza. This suggests that the average speed is around 39kph to Kigoma or 36kph to Mwanza.

Basic characteristics of the studied train are shown in Table 13. It is assumed that each coach requires 20 kW of auxiliary power; this may not allow for air conditioning. Further, although there may be benefits in switching to a multiple unit, only the locomotive power plant is being studied here; whether it be hydrogen hybrid, diesel hybrid, or the current case of diesel.

Table 13: Basic characteristics of the train studied

Characteristic	Value
No. of vehicles in consist	11 (1 locomotive, 10 coaches)
Mass (crush load) (used for simulation)	500 tonnes
Maximum power plant power	2000 kW
Traction power	1800 kW
Auxiliary power	200 kW

Note these characteristics remain the same in all cases.

The Davis equation for this was generated using the Canadian National formula [32], and this gave the Davis Equation parameters as follows (more information is provided in Appendix A):

$$R = 7.15 + 0.155V + 0.01V^2$$

For the hybrid options, the characteristics of the power plant were also kept the same, and these are shown in Table 14. The conventional diesel is assumed to just have a maximum power of 2000 kW.

Table 14: Characteristics of the hybrid power plants tested

Characteristic	Value
Prime mover power	1400 kW
Hybrid battery capacity	220 kWh
Hybrid battery C rate	2.73

5.3.3 Simulation Results

Due to the large number of simulations performed, representative simulation results will be given here (figures 44 – 51), with additional graphs available in Appendix B.

Figure 33: Simulation output for the Dar es Salaam – Mahundi Jn. section, using the diesel only train

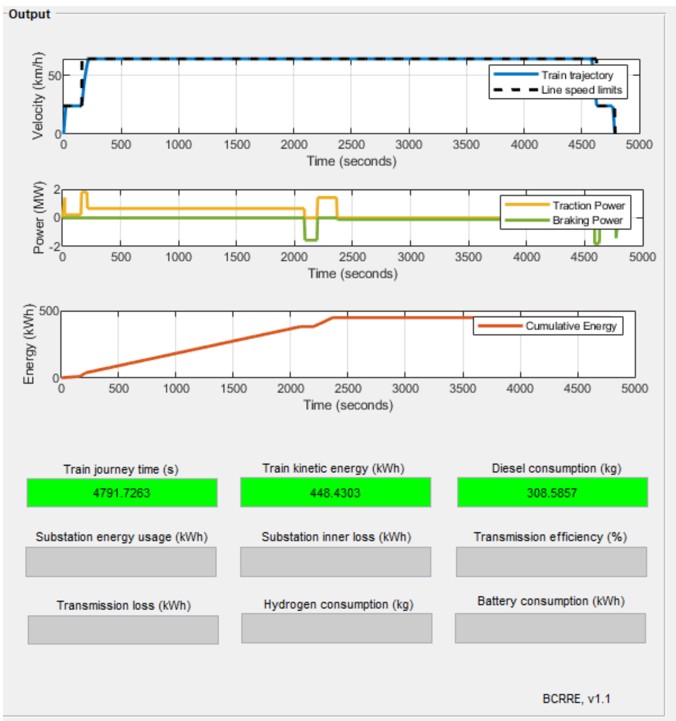
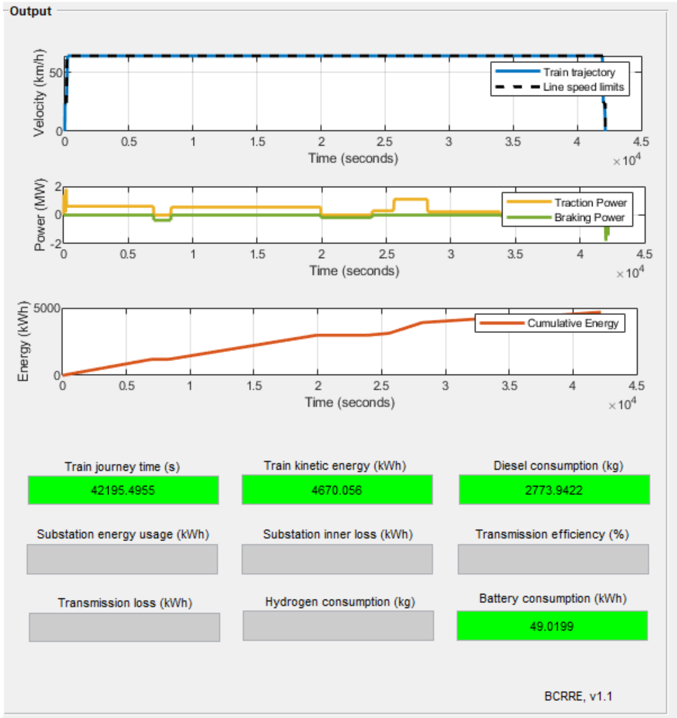
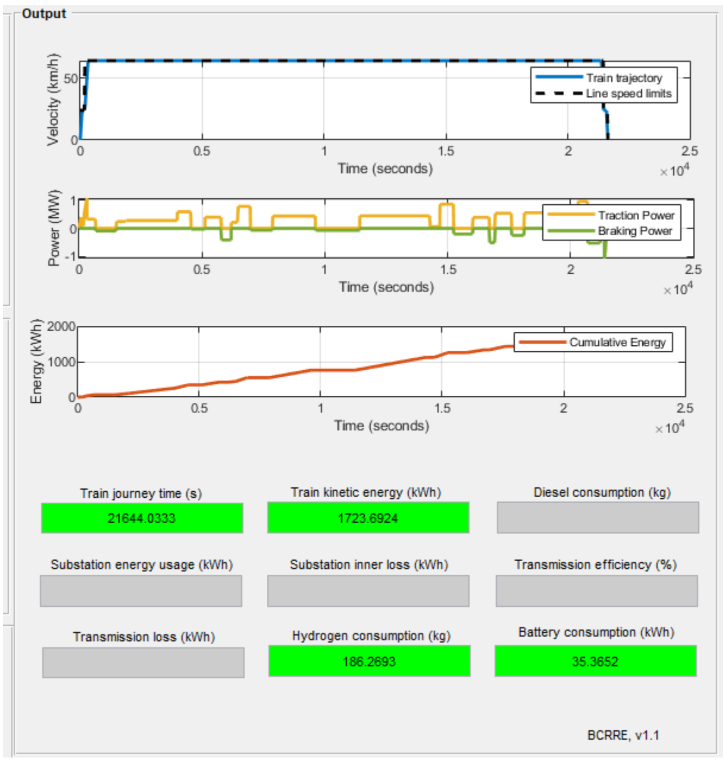


Figure 34: Simulation output for the Mahundi Jn. – Tabora section, using the diesel hybrid train



Note that the hybrid battery charge declines by 23% in Figure 34.

Figure 35: Simulation output for the Tabora – Mwanza section, using the hydrogen hybrid train



Note that the hybrid battery charge declines by 17% in Figure 35.

Figure 36: Simulation output for the Tabora – Kigoma section, using the diesel only train

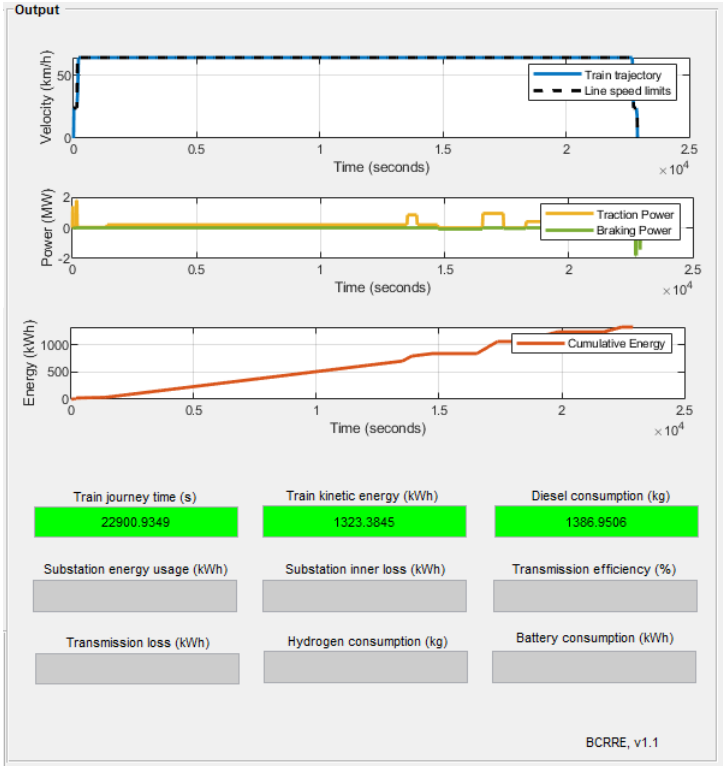
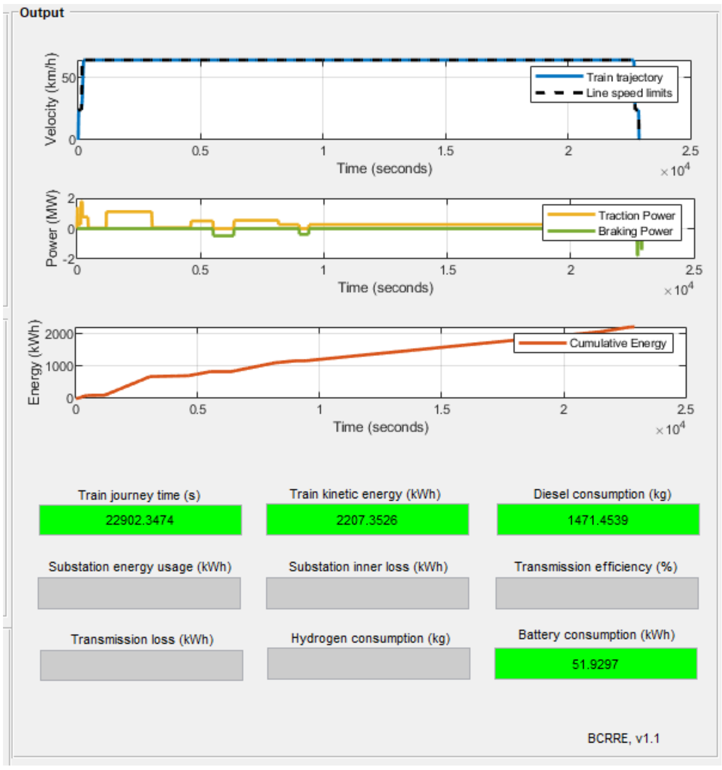


Figure 37: Simulation output for the Kigoma – Tabora section, using the diesel hybrid train

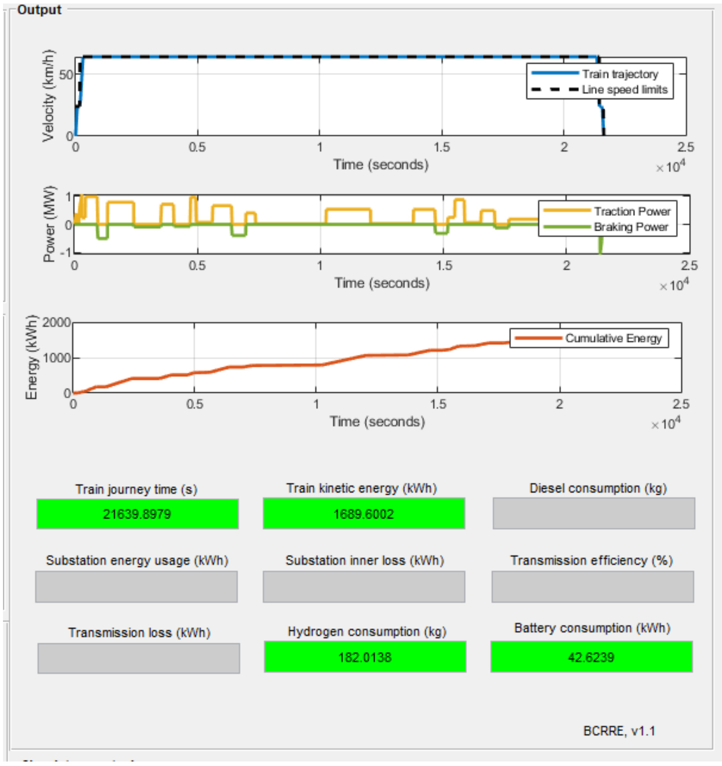


Note that the hybrid battery charge declines by 24% in Figure 37.

Figure 38: Simulation output for the Mwanza – Tabora section, using the hydrogen hybrid train

Figure 38: Simulation output for the Mwanza – Tabora section, using the hydrogen hybrid train

Figure 38: Simulation output for the Mwanza – Tabora section, using the hydrogen hybrid train



Note that the hybrid battery charge declines by 21% in Figure 38.

Figure 39: Simulation output for the Tabora – Mahundi Jn. section, using the diesel only train

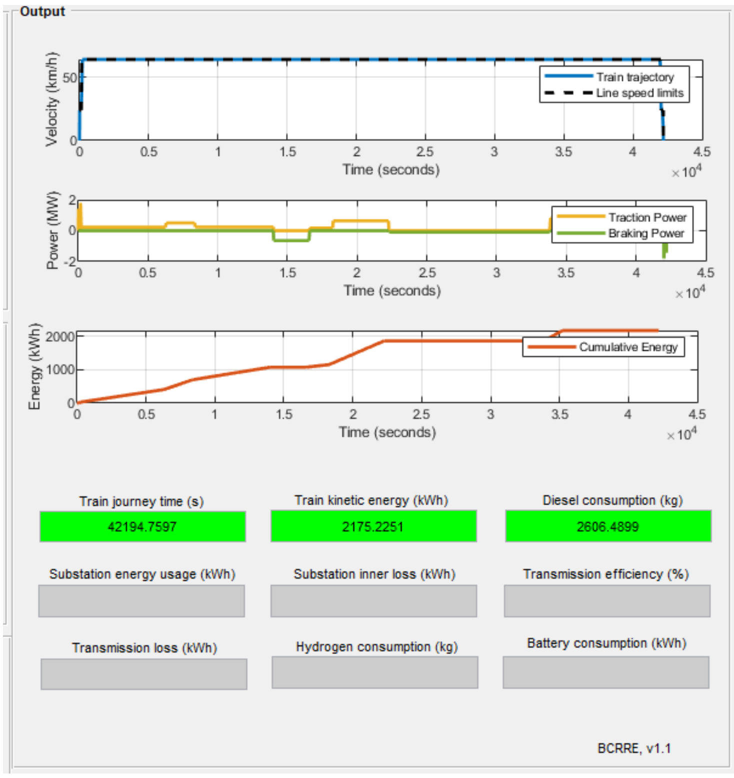
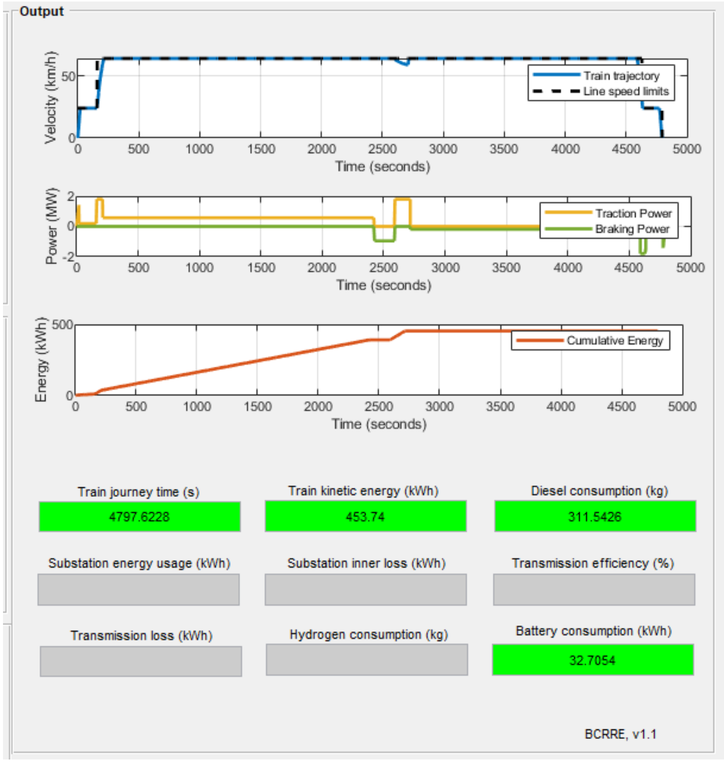


Figure 40: Simulation output for the Mahundi Jn. – Dar es Salaam section, using the diesel hybrid train



Note that the hybrid battery charge declines by 15% in Figure 40.

Table 15 summarises the fuel requirements for a diesel only train.

Table 16 summarises the fuel requirements for a hydrogen hybrid train. It should be noted that in **Error! Reference source not found.**, battery charging is assumed to have 50% overall efficiency.

Table 17 summarises the fuel requirements for the diesel hybrid case. It should be noted that in **Error! Reference source not found.** 17 a 20% battery charging efficiency is assumed.

Table 15: Diesel requirements for the diesel only train

	Basic requirement	(+20% for eventualities)
Dar es Salaam – Mahundi Jn.	364 l	436 l
Mahundi Jn. – Tabora	3226 l	3871 l
Tabora – Kigoma	1632 l	1959 l
Tabora – Mwanza	1567 l	1881 l
Mwanza – Tabora	1364 l	1926 l
Kigoma – Tabora	1674 l	2009 l
Tabora – Mahundi Jn.	3067 l	3680 l
Mahundi Jn. – Dar es Salaam	367 l	441 l
Dar es Salaam – Kigoma Round Trip		**12394 l**
Dar es Salaam – Tabora Round Trip		**12233 l**

Table 16: Fuel requirements for the hydrogen hybrid train

	Basic requirement	Inc. battery charging	(+20% for eventualities)
Dar es Salaam – Mahundi Jn.	47 kg	49 kg	58 kg
Mahundi Jn. – Tabora	484 kg	487 kg	585 kg
Tabora – Kigoma	155 kg	157 kg	188 kg
Tabora – Mwanza	187 kg	189 kg	227 kg
Mwanza – Tabora	183 kg	185 kg	222 kg
Kigoma – Tabora	225 kg	228 kg	274 kg
Tabora – Mahundi Jn.	282 kg	284 kg	340 kg
Mahundi Jn. – Dar es Salaam	44 kg	46 kg	55 kg
Dar es Salaam – Kigoma Round Trip			**1498 kg**
Dar es Salaam – Tabora Round Trip			**1485 kg**

Table 17: Fuel requirements for the diesel hybrid train

	Basic requirement	Inc. battery charging	(+20% for eventualities)
Dar es Salaam – Mahundi Jn.	364 l	379 l	455 l
Mahundi Jn. – Tabora	3264 l	3286 l	3944 l
Tabora – Kigoma	1665 l	1686 l	2023 l
Tabora – Mwanza	1623 l	1642 l	1970 l
Mwanza – Tabora	1614 l	1635 l	1062 l
Kigoma – Tabora	1732 l	1756 l	2107 l
Tabora – Mahundi Jn.	3097 l	3112 l	3734 l
Mahundi Jn. – Dar es Salaam	367 l	382 l	459 l
Dar es Salaam – Kigoma Round Trip			**12719 l**
Dar es Salaam – Tabora Round Trip			**12521 l**

Table 18 below shows the entailed emissions for a round trip on the Buchanan – Tokadeh route. It is observed that the most environmentally friendly option is hydrogen hybrid, but also that there is a slight environmental disadvantage to the diesel hybrid train. This may be because the train does not have to brake very often on its journey, and there is thus little advantage to recovering this energy through regenerative braking. Further, the engine must charge the battery, which will lose more energy than using the electricity to power the traction motors.

Table 18: Equivalent carbon dioxide emissions for each train type on the Dar es Salaam route

Equivalent carbon dioxide emissions (CO2e)	Diesel only	Hydrogen hybrid	Diesel hybrid
Dar es Salaam – Kigoma Round Trip	**33214 kg**	**SMR: 20508 kg** **Electrolysis: 0 kg**	**34084 kg**
Dar es Salaam – Tabora Round Trip	**32781 kg**	**SMR: 20330 kg** **Electrolysis: 0 kg**	**33553 kg**

5.3.4 Findings

- The hydrogen hybrid requires considerable hydrogen storage, particularly if there is no intention to refuel it at stops or at each end of the route. This is not an insurmountable problem but is far in excess of all existing hydrogen-powered trains;
- In this case, there is no advantage to hybridising the diesel locomotive; in fact it uses slightly more diesel than the diesel only option because of the necessity of charging the battery;
- However, this may change if the route were to be changed; for example, if there were more stops, this would increase the braking energy which can be recovered by a hybrid system, and change the outcome of the simulation;
- Hydrogen from methane provides a 33% reduction of greenhouse gases in comparison to diesel. Hydrogen sourced from renewable energy sources are bound to provide a more substantial reduction due to their lower carbon footprint;
- Tanzania has relatively low access to electricity but has many micro-grids (see 11.5, Section 4), and therefore while mains electricity may not be available to produce hydrogen, the use of small-scale generation (for example using solar) may be considered.

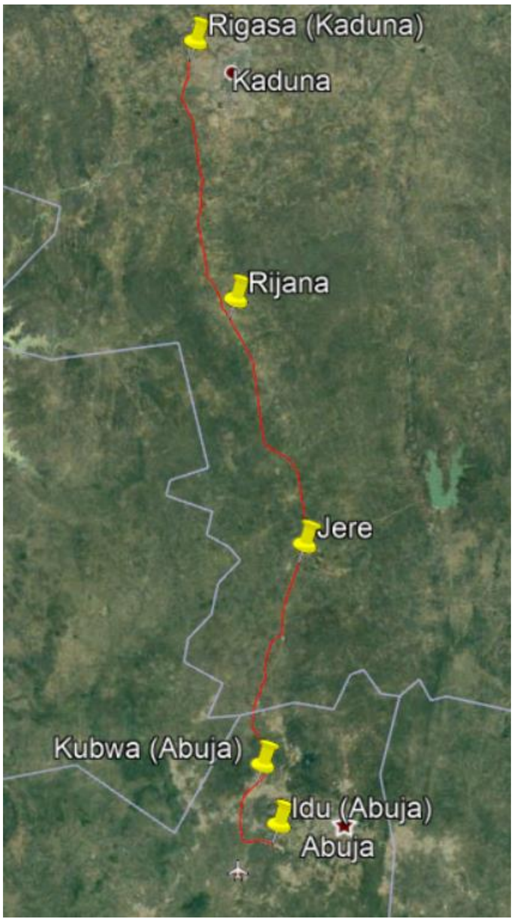
5.4 Abuja – Kaduna Route

5.4.1 Route

This route runs around 185 km from the Nigerian capital Abuja to the city of Kaduna. The line was constructed between February 2011 and December 2014 by the China Civil and Engineering Construction Company, and is among the first modern standard gauge lines in Nigeria [40]. Currently, passenger trains on the route reach a maximum speed of 100 km/h, taking just over 2 hours in each direction [41].

As with the other routes, Google Earth was used to map out the topography (see Figure 41 and Figure 42).

Figure 41: The Abuja – Kaduna route shown in Google Earth

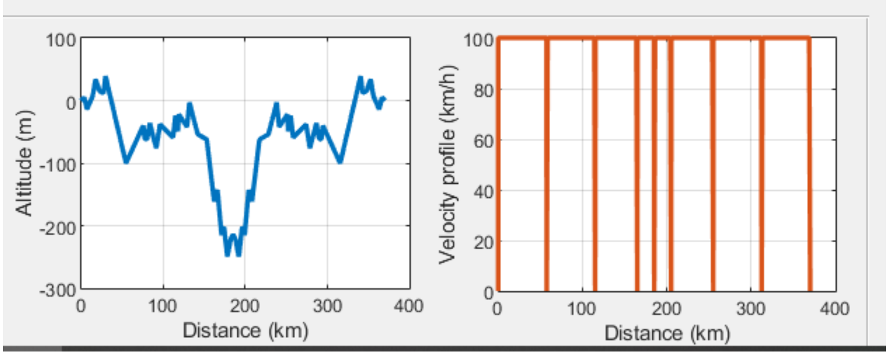


The corresponding elevation profile from Google Earth is shown in Figure 42.

Figure 42: Kaduna – Abuja gradient profile from Google Earth, with Kaduna on the left and Abuja on the right. Note the considerable change in elevation

This is a relatively long route by comparison with the Kampala route and therefore altitude measurements were taken approximately every 2 – 5 km rather than at every change. Great care had to be taken to avoid errors due to the large number of bridges on the route. This gives the route profile shown in Figure 43.

Figure 43: Route profile for the Kaduna - Abuja route in the Single Train Simulator. Note that it is symmetrical as it represents a round trip, with Kaduna at the outside and Abuja in the middle



5.4.2 Rolling Stock

The aim was to simulate a typical passenger train on this route (see Figure 44). Given a lack of specific information, the following characteristics were assumed for the rolling stock (see table 19).

Figure 44: Typical Passenger train on the Abuja – Kaduna route [42]

Table 19: Basic characteristics of the train tested

Characteristic	Value
No. of vehicles in consist	7 (1x locomotive, 6x coaches)
Mass (locomotive)	100 tonnes
Mass (coaches)	240 tonnes (40 tonnes each)
Traction power	1500 kW
Auxiliary power	120 kW (20 kW each)

Three basic types of locomotive were simulated, including diesel, diesel hybrid and hydrogen hybrid. The characteristics of the hybrid system are outlined in table 20.

Note that in this case, the prime mover could either be a diesel engine or hydrogen fuel cell stack. It is possible in either case that the locomotive would be heavier; however, for the purposes of this investigation, all three locomotive types are considered to have equal mass.

Table 20: Characteristics of the hybrid power plants tested on the Abuja – Kaduna route

Characteristic	Value
Prime mover power	940 kW
Hybrid battery capacity	220 kWh
Hybrid battery C rate	3

The Davis equations for these configurations were generated using the Canadian National formula [32], which gave the following Davis Equations Parameters (further information is proved in Appendix A):

R=3.3+0.11V+0.0095V^2

5.4.3 Simulation Results

Figure 45 shows the simulator outputs for the conventional diesel train.

Figure 45: Simulation output for the Abuja – Kaduna route, using the conventional diesel train

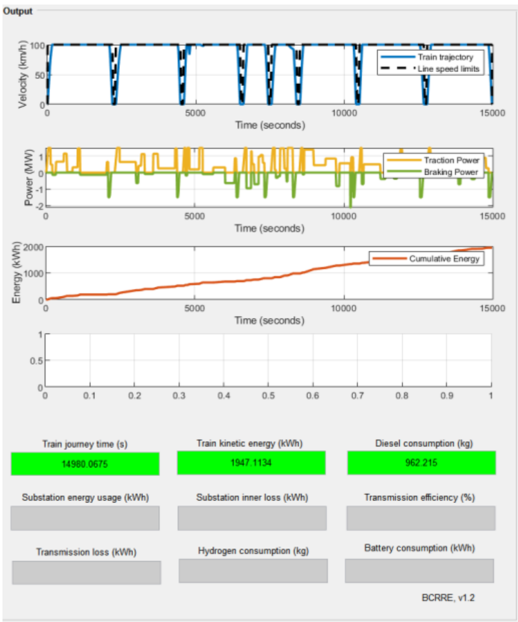


Figure 46 shows the simulator outputs for the hydrogen hybrid train.

Figure 46: Simulation output for the Abuja – Kaduna route, using the hydrogen hybrid train

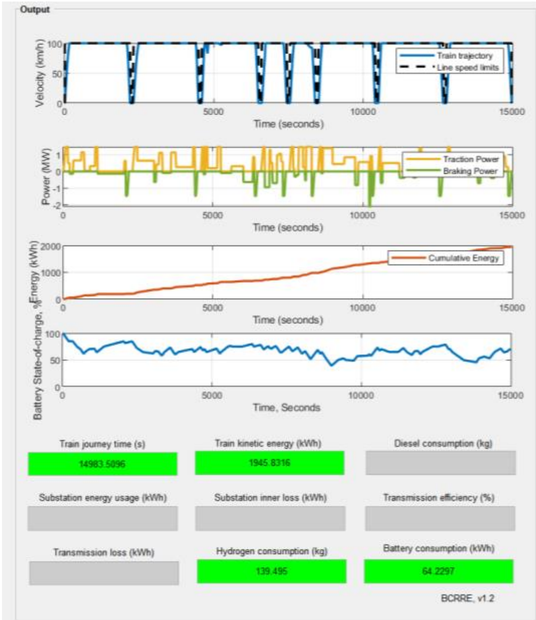


Figure 47 shows the simulator outputs for the diesel hybrid train.

Figure 47: Simulation output for the Abuja – Kaduna route, using the diesel hybrid train

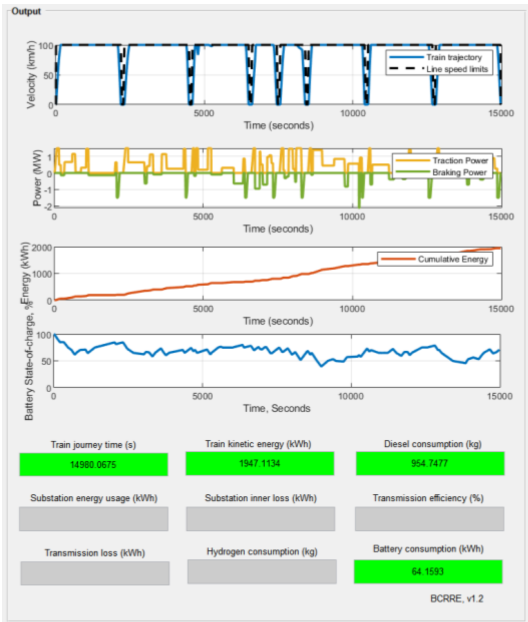


Table 21 shows the fuel requirements for the various trains. It should be noted that the timetable in [41] suggests 2 round trips a day, hence this value is being considered.

Note that in both of the hybrid cases, the battery state of charge declines. Some energy will also need to be expended to cover for auxiliary loads and shunting movements not considered here. Therefore allowances must be made.

At around 50% overall efficiency, the battery consumption of around 64.2 kWh equates to 3.9 kg of hydrogen or 13.3 l of diesel.

Table 21: Fuel requirements for each type of train on the Abuja – Kaduna route

	Diesel hybrid	Hydrogen hybrid	Diesel only (conventional)
Basic requirement	1123.24 l	139.50 kg	1132.02 l
(inc. battery charging)	1136.54 l	143.40 kg	-
(+ 20% for eventualities)	1363.85 l	172.08 kg	1358.43 l
2 round trips	**2727.7 l**	**344.16 kg**	**2716.9 l**

Table 22 below shows the emissions produced from these fuels. It is observed there is no benefit, and in fact a slight environmental disadvantage, to the diesel hybrid. It should be noted that the hydrogen emissions are calculated based upon Steam Methane Reforming (SMR) to produce hydrogen; it may be possible to considerably reduce these emissions by using electrolysis, fed with renewable electricity, to produce the hydrogen.

Table 22: Equivalent carbon dioxide emissions for each train type

	Diesel hybrid	Hydrogen hybrid (SMR Hydrogen)	Diesel only (conventional)
Equivalent carbon dioxide emissions (CO2e)	**7311 kg**	**4715 kg**	**7282**

5.4.4 Findings

The key conclusions from the simulations detailed above are as follows:

- There is no carbon benefit to a diesel hybrid over a conventional diesel train. This may be because of the infrequent stops on the route, which limits the energy that can be recovered in regenerative braking;
- There would be a tangible benefit to emissions if a hydrogen hybrid locomotive were used in place of the existing conventional diesel. This benefit could be increased if electrolysis were used, but Nigeria has considerable reserves (5.4 trillion cubic metres) of the natural gas needed to produce hydrogen by SMR [43]
- The hydrogen consumption is significant at 344.16 kg (compared, for example, with the 20 kg of storage on board the University of Birmingham's HydroFLEX demonstrator). An infrastructure to supply the several hundred kilograms per day required would need to be set up;
- Access to electricity is relatively high in Nigeria, particularly in urban areas (see 11.5, Section 4), and so there is a prospect of reducing emissions by electrolysing hydrogen

SECTION 6: CONCLUSION

Four typical routes have been modelled based on online 'open source' data using the GUI version of the University's STS software developed specifically for this project. A methodology was developed that enabled alignments and gradients to be derived from Google Earth Pro, and a means of deriving the all-important train resistance values was developed that can be adapted to any train type.

Table 23 provides a summary of the fuel requirements derived from the four routes, using the factors discussed above in the STS.

Table 23: Summary of fuel requirements for each route studied

Route	Fuel Requirements and CO2 Emissions
Kampala – Namanve (Short distance, lightweight commuter train)	--Daily Use-- Diesel only: 610 litres **(1633kg CO2)** Diesel hybrid: 535 litres **(1431kg CO2)** Hydrogen hybrid: 14 kg **(0-192kg CO2)** Battery only: 366 kWh **(0kg CO2)**
Dar es Salaam – Kigoma (Long distance, locomotive hauled passenger)	--Return trip: Dar es Salaam – Kigoma-- Diesel only: 12394 litres **(33214kg CO2)** Hydrogen hybrid: 1498 kg **(0-20508kg CO2)** Diesel hybrid: 12719 litres **(34084kg CO2)** --Return trip: Dar es Salaam – Mwanza-- Diesel only: 12233 litres **(32781kg CO2)** Hydrogen hybrid: 1485 kg **(0-20330kg CO2)** Diesel hybrid: 12521 litres**(33553kg CO2)**
Buchanan – Tokadeh (Medium distance, heavy locomotive hauled freight)	--Return trip-- Diesel only: 2814 litres **(7510kg CO2)** Hydrogen hybrid: 1941 kg **(19016kg CO2)** Diesel hybrid: 2470 litres **(5150kg CO2)**
Abuja – Kaduna (Medium distance, locomotive hauled passenger)	--Daily Use-- Diesel only: 2728 litres **(7311kg CO2)** Hydrogen hybrid: 345 kg **(4715kg CO2)** Diesel hybrid: 2717 litres **(7282kg CO2)**

The simulations provided a range of power and energy requirements that will be taken forward to the next stage of this project, but the key overarching findings were as follows:

- The shorter commuting route could be operated using a number of different types of traction including hybrid drives, hydrogen and operated using ULRs rather than conventional rolling stock;
- However, the longer passenger and freight routes require a considerable quantity of energy to be stored on-board, which restricts the number of alternative traction options that would be suitable;

- The freight route also requires a high-level of installed power which further restricts the suitable range of traction types.
- Battery and hydrogen powertrains provide a clear emissions reduction in comparison to diesel for commuter and long-distance routes

It might be suggested on the basis of these findings that a better course of action than introducing novel traction systems to these use cases would be to retrofit more modern diesel prime movers instead. Indeed, this is an approach that has been taken with the conversion of Class 47 and Class 56 locos into Class 57 and Class 69 locos respectively in the UK. However, it is a naive view that such a conversion process would be simple or indeed cheap. The authors of this report can state from experience with the HydroFLEX project that whilst retrofitting legacy trains might seem like an easy, simple way to achieve a quick win in terms of reducing carbon emissions by improving fuel economy and efficiency, it is in practice exceedingly hard to make modern prime movers interface with decades old locomotives and multiple units. This difficulty has most recently been shown by the delays incurred to the diesel FLEX project.

As such, it cannot simply be assumed that the retrofit of a more modern and efficient but not “novel” diesel prime mover would give a significant capital expenditure (CAPEX) reduction compared to retrofitting a “novel” prime mover or hybrid traction technology that can actually offer zero-emissions operation. Given that operators in low income countries are likely to be more sensitive to CAPEX than operators in higher income countries, it is not likely that conducting such a program of replacing dated but functional diesel prime movers with slightly more efficient modern diesel engines for the reason of emissions reduction (an unpriced negative externality) and for slightly reduced operating expenditure (OPEX) will be a more attractive option than adopting a novel traction technology. Instead, it is likely that an operator in a low income country would prefer to sweat a diesel powered asset and run to end of life in the absence of any external factors.

As alluded to, the decision to retrofit or procure a novel or sustaining traction technology will likely be driven by external factors. These might include government subsidy, taxation of emissions or regulation preventing or charging for emissions in sensitive populated areas or external investment into a LIC by a developed country. As such, these external factors might determine that developments of traction in said LICs are driven down the path of “novel” technologies such as those investigated.

To surmise, this report has determined that a range of novel traction options are suitable for low speed, lightweight, passenger railway operations. As speeds and weights increase, the available options are reduced and the amounts of energy and power required increase. It is likely at the present time that for the most demanding duty cycles, hybridisation of diesel locomotives might be the only option that gives the option for zero emissions running within sensitive areas within the duty cycle, by discharging a battery that is charged during normal operation, but it should be noted that due to increased interest, investment and implementation the capabilities of technologies such as batteries, fuel cells and hydrogen storage are improving rapidly and may soon become viable for all of the modelled duty cycles.

The next stage of the project will be to build on the modelling undertaken at this stage to further develop the suitable traction options for each type of route.

SECTION 7: REFERENCES

[1]H. Douglas, P. Weston, D. Kirkwood, S. Hillmansen, and C. Roberts, 2016. Method for validating the trainmotion equations used for passenger rail vehicle simulation. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 231, no. 4, pp. 455-469, 2016, doi: 10.1177/0954409716631784.

[2] L. Guzzella and A. Sciarretta, *Vehicle Propulsion Systems: Introduction to Modeling and Optimization*, 3rd ed. Springer-Verlag Berlin Heidelberg, 2013

[3] Turnbull-Neep J., 2021. DECARB: Battery Powered Trains: Route to Enter into Service. *Rail Safety and Standards Board* p. 11

[4] Gov.UK. "Greenhouse gas reporting: conversion factors 2020." https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020

[6] Siemens Mobility Solutions, 2020. Mireo Plus decarbonises Europe's railways. *mobility.siemens.com* [online] Available at: https://www.mobility.siemens.com/global/en/company/newsroom/specialist-articles/mireo-plus-decarbonises-europes-railways.html (accessed 2021)

[7]Railway Technology, 2021. Bombardier Talent 3 Battery Train. *railway-technology.com* [online] Available at: https://www.railway-technology.com/projects/bombardier-talent-3-battery-train/ (accessed. 2021)

[8]Alstom, 2020. Alstom signs first contract for battery-electric regional trains in Germany. *alstom.com* [online] Available at: https://www.alstom.com/press-releases-news/2020/2/alstom-signs-first-contract-battery-electric-regional-trains-germany (accessed 2021)

[9] AKASOL, 2021. 15 AKM 46 POC. *akasol.com* [online] Available at: https://www.akasol.com/library/Downloads/Datenbl%C3%A4tter/01-02-2021/AK_Datenblatt_15%20AKM%2046%20POC_2020.pdf (accessed 2021).

[10] Caterpillar, 2016. Caterpillar C9 Datasheet. *myrak.com* [online] Available at: http://www.myrak.com/wp-content/uploads/2016/11/DE300.pdf (accessed 2021).

[11] Caterpillar, 2019. Caterpillar C27 Datasheet.*s7d2.scene7.com* [online] Available at: https://s7d2.scene7.com/is/content/Caterpillar/CM20170815-11465-45410 (accessed 2021).

[12] Toshiba, 2019 .Toshiba SCiB Datasheet. *global.toshiba.com* [online] Available at: https://www.global.toshiba/content/dam/toshiba/ww/products-solutions/battery/scib/pdf/ToshibaRechargeableBattery-en.pdf (accessed 2021).

[13] J. Larminie and A. Dicks, 2003. Fuel cell systems explained. 2nd ed. Chichester, West Sussex: J. Wiley, 2003, pp. xxii, 406

[14] N. Muradov and T. Vezirolu, "From hydrocarbon to hydrogen?carbon to hydrogen economy," *International Journal of Hydrogen Energy,* vol. 30, no. 3, pp. 225-237, 2005, doi: 10.1016/j.ijhydene.2004.03.033.

[15]J. T. Pukrushpan, A. G. Stefanopoulou, and H. Peng, 2004. Control of Fuel Cell Breathing. *IEE Control Systems Magazine*. Vol.24 Issue. 2

[16] Ballard, 2021. Ballard HD100 Datasheet. *ballard.com* [online] Available at: https://www.ballard.com/docs/default-source/spec-sheets/fcvelocity-hd.pdf?sfvrsn=2debc380_4 (accessed 2021).

[17] Hoffrichter A., 2013. Hydrogen as an Energy Carrier for Railway Traction. PhD Thesis. University of Birmingham, Birmingham, England p. 101

[18] Waterman Burrow Crocker, 2003. Auto*Rail*™ 5 mile Line Diagrams.

[19] World Bank, 2018. Database : Access to electricity (% of population) – Sub-Saharan Africa. World Bank, Sustainable Energy for all (SE4ALL) database from the SE4ALL Global Tracking Framework led jointly by the World Bank, International Energy Agency, and the Energy Sector Management Assisteant Program. Available at https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZG (accessed 2021)

[20] Blimpo, M.P. and Cosgrove-Davies, M., 2019. *Electricity access in Sub-Saharan Africa: Uptake, reliability, and complementary factors for economic impact*. The World Bank.

[21] Electricity Regulatory Authority. 2020. Uganda's Electricity Sector Overview. Published on 11/11/2020. *era.go.ug* [online] Available at https://www.era.go.ug/index.php/sector-overview/uganda-electricity-sector (accessed 2021)

[22] USAID, 2020a. Tanzania. Power Africa Fact Sheet. Updated 21/07/2020. *usaid.gov* [online] Available at https://www.usaid.gov/powerafrica/tanzania (accessed 2021)

[23] International Trade Administration. 2021. Tanzania. Country Commercial Guide. U.S. Department of Commerce. Published 09/03/2021. *trade.*gov [online] Available at https://www.trade.gov/country-commercial-guides/tanzania-energy (accessed 2021)

[24] International Trade Administration. Liberia – Energy. U.S. Department of Commerce. *privacyshield.gov* [online] Available at https://www.privacyshield.gov/article?id=Liberia-Energy (accessed 2021)

[25] USAID, 2020b. Liberia. Power Africa Fact Sheet. Updated 16/04/2020. *usaid.gov* [online] Available at https://www.usaid.gov/powerafrica/liberia (accessed 2021)

[26] USAID, 2021. Nigeria. Power Africa Fact Sheet. Updated 04/03/2021. *usaid.gov* [online] Available at https://www.usaid.gov/powerafrica/nigeria (accessed 2021)

[27] GET.invest. Nigeria Energy Sector. *get-invest.*eu [online] Available at https://www.get-invest.eu/market-information/nigeria/energy-sector/ (accessed 2021)

[28] Pill Travel, 2019. We took Uganda's only passenger train | Uganda has a train PART2. *youtube.com* [online] Available at:

https://www.youtube.com/watch?v=X1Ph6HHd8Zk&t=283s (accessed 2021)

[29] Daily Monitor, 2019. Inside Uganda's passenger train service. *monitor.co.ug* [online] Available at:https://www.monitor.co.ug/uganda/news/national/inside-uganda-s-passenger-train-service-1848308 (accessed 2021)

[30] Uganda Railways Corporation, 2021. Commuter train. *Urc.go.ug* [online] Available at: http://urc.go.ug/pts.html (accessed 2021)

[31] Diary of a Muzungu, 2015. On the right track: my first Ugandan train ride. *muzungubloguganda.com*

[online] Available at: https://www.muzungubloguganda.com/adventure/rift-valley-railways-kampala-train/ (accessed 2021)

[32] AREMA, 1999. Section 2.1: RESISTANCE TO MOVEMENT: *AREMA Manual for Railway Engineering 1999*. Lanham, Maryland, USA: American Railway Engineering and Maintenance-of-Way Association

[33] Severn Lamb, 2015. ULR: Express: Technical Specification. Alcester: Severn Lamb.

[34] Reuters, 2019. Uganda says its power generation capacity will jump 55% by year-end. *reuters.com* [online] Available at: https://www.reuters.com/article/uganda-electricity-idUSL5N2684KP (accessed 2021)

[35] Williams, 2019. Railways in Liberia. *sinfin.net* [online] Available at: https://www.sinfin.net/railways/world/liberia.html (accessed 2021)

[36] CIT, 2019. AC4400CW specifications. *cms-assets.cit.com* [online] Available at: https://cms-assets.cit.com/9j7wv5nnfw5f/3oRYloUQ8CTkDj9x753Fgq/6119ade515a1977d14df5fe628e4f5e7/Locomotive-Spec-AC4400CW.pdf (accessed 2021)

[37] Vourlias C., 2011. Rail travel: Africa's own Central Line. *theguardian.com* [online] Available at: https://www.theguardian.com/travel/2011/jul/03/train-railway-tanzania-central-line (accessed 2021)

[38] Tanzania Railways Limited, 2016. Railways Network*. trl.co.tz* [online] Available at: https://web.archive.org/web/20161006104508/http://www.trl.co.tz/?page_id=37 (accessed 2021)

[39] The Man in Seat 61, 2021. A guide to train travel in Tanzania & Zambia. *Seat61.com* [online] Available at: https://www.seat61.com/Zambia.htm#dar-es-salaam-to-moshi-kigoma-mwanza (access 2021)

[40] Railway Technology, 2021. Abuja – Kaduna Rail Line [online] Available at: Abuja-Kaduna Rail Line, Nigeria (railway-technology.com) [accessed 2021]

[41] Nigeria Railway Corporation, 2021. E-Ticketing App: Timetable [online] Available at: Nigeria Railway Cooperation E-Ticketing App (tps.ng) [accessed 2021]

[42] Malumfashi S., 2020. Nigeria's railway people: Life alongside a high-speed rail link [online] Available at: Nigeria's railway people: Life alongside a high-speed rail link | Poverty and Development | Al Jazeera (accessed 2021)

[43] BP, 2020. Statistical Review of World Energy [online] Available at: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf (accessed 20/11/20)

[44] William W. Hay, Railway Engineering, Editor(s): Robert A. Meyers, Encyclopedia of Physical Science and Technology (Third Edition), Academic Press, 2003, Pages 807-844, ISBN 9780122274107, Available at: https://doi.org/10.1016/B0-12-227410-5/00650-5.

APPENDIX A: DAVIS EQUATION CALCULATIONS

Kampala – Namanve

Conventional Train

The first step in calculating the Davis equation is to enter the characteristics of the conventional train in the spreadsheet. This is shown in Fig.A.1.

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	80,000	175,000	255,000	kg
		88.0	192.5	281	tons
N	Number of axles	4	20	24	
V	Velocity	30	30		mph
C	Streamlining value*	19	3.5		
a	Cross sectional area*	160.0	130.0		square feet
R	Resistance	556.8	863.0	1,420	lb
		2477.8	3840.1	6318	N
		2.5	3.8	**6.3**	**kN**

Figure A.1: Key characteristics of the conventional Kampala – Namanve train entered into the Davis calculation spreadsheet

For comparison purposes, this spreadsheet calculates the resistance at 30 mph.

The streamlining values and cross sectional areas are taken as those for a leading passenger locomotive and conventional passenger coaches in [31]

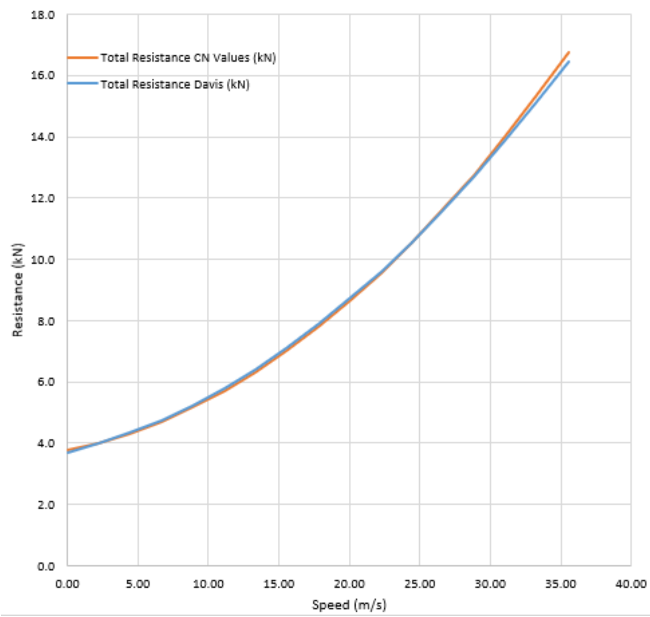
The following fig. A.2 shows the comparison of an approximated resistance curve with equation

$$\boldsymbol{R = 3.7 + 0.11V + 0.007V^2} \text{ (Equation A.1)}$$

to the curve generated by calculating the resistance using the Canadian National equation from [31].

Although the match is not perfect, this was felt to be a reasonable approximation.

Figure A.2: Comparison of estimated Davis equation curve (blue) with actual calculated values (orange) for the conventional Kampala – Namanve train



ULR

The first step in calculating the Davis equation is to enter the characteristics of the ULR in the spreadsheet. This is shown in Fig.A.3.

Figure A.3: Key characteristics of the ULR-based Kampala – Namanve train entered into the Davis calculation spreadsheet

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	32,000	128,000	160,000	kg
		35.2	140.8	176	tons
N	Number of axles	4	16	20	
V	Velocity	30	30		mph
C	Streamlining value*	10	2		
a	Cross sectional area*	110.0	110.0		square feet
R	Resistance	255.5	645.7	901	lb
		1136.9	2873.5	4010	N
		1.1	2.9	**4.0**	**kN**

In this case, the “loco” is taken as the leading vehicle of the train. All weights are for a loaded train.

The streamlining value, C, is taken as Med 6 (10.0) [22], as this is an intermediate value, but closer to a high speed passenger train than a “conventional” passenger train. The rest of the train is taken as lightweight passenger equipment.

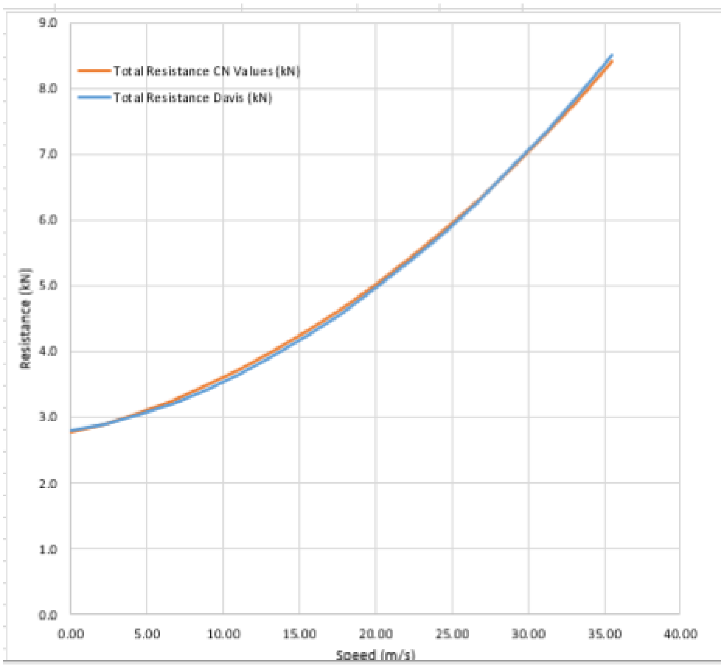
The following fig. A.4 shows the comparison of an approximated resistance curve with equation

$$\boldsymbol{R = 2.8 + 0.04V + 0.0034}V^2 \text{ (Equation A.2)}$$

to the curve generated by calculating the resistance using the Canadian National equation from [31].

Although the match is not perfect, this was felt to be a reasonable approximation.#

Figure A.4: Comparison of estimated Davis equation curve (blue) with actual calculated values (orange) for the ULR-based Kampala – Namanve train



Buchanan - Tokadeh (Empty)

The first step in calculating the Davis equation is to enter the characteristics of the empty freight train in the spreadsheet. This is shown in Fig.A.5.

Figure A.5: Key characteristics of the empty Buchanan – Tokadeh train entered into the Davis calculation spreadsheet

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	Coaches	Total	Units
W	Weight	579,960	2,250,000	2,829,960	kg
		638.0	2475.0	3,113	tons
N	Number of axles	9	300	309	
V	Velocity	30	30		mph
C	Streamlining value*	24	12		
a	Cross sectional area*	160.0	105.0		square feet
R	Resistance	2038.7	11453.4	13,492	lb
		9072.2	50967.6	60040	N
		9.1	51.0	**60.0**	**kN**

In this case, the "loco" is actually made up of three AC4400CW locomotives. The 75 wagons are assumed to be similar to the coal gondola described in the Canadian National equation.

Therefore, the streamlining values are:

For the locomotive: 24 (This corresponds to a leading freight locomotive in [31])

For the wagons: 12 (This corresponds to an empty coal gondola in [31])

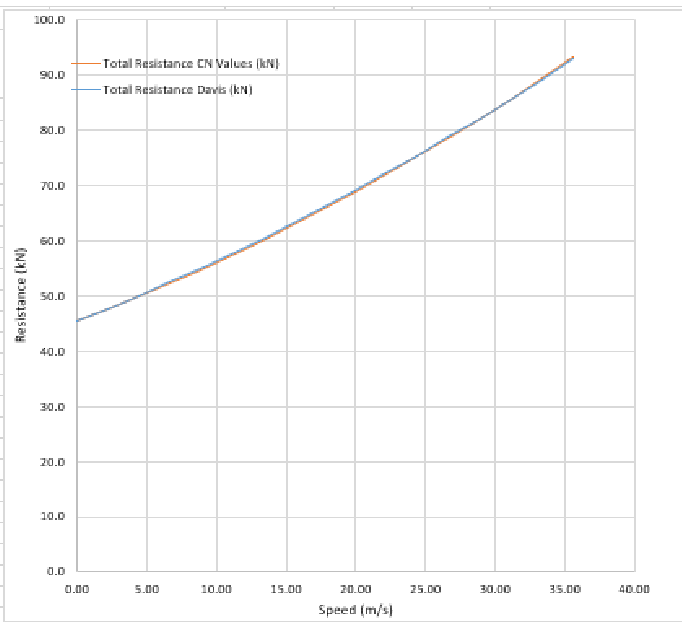
The following fig. A.6 shows the comparison of an approximated resistance curve with equation

$$\boldsymbol{R = 45.5 + 0.98V + 0.01V^2} \text{ (Equation A.3)}$$

to the curve generated by calculating the resistance using the Canadian National equation from [31]

This was felt to be the closest match that could reasonably be achieved.

Figure A.6: Comparison of estimated Davis equation curve (blue) with actual calculated values (orange) for the empty Buchanan - Tokadeh train



Tokadeh - Buchanan (Loaded)

The process was repeated for the loaded train (see fig A.7). The only differences between the empty and loaded configurations is that the loaded train has considerably greater mass, and the streamlining value, which has been changed to that for a loaded coal gondola rather than an empty one (i.e. from 12 to 4.2) [31].

Figure A.7: Key characteristics of the loaded Namanve – Kampala train entered into the Davis calculation spreadsheet

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	Coaches	Total	Units
W	Weight	579,960	9,000,000	9,579,960	kg
		638.0	9900.0	10,538	tons
N	Number of axles	9	300	309	
V	Velocity	30	30		mph
C	Streamlining value*	24	4.2		
a	Cross sectional area*	160.0	105.0		square feet
R	Resistance	2038.7	29199.7	31,238	lb
		9072.2	129938.6	139011	N
		9.1	129.9	**139.0**	**kN**

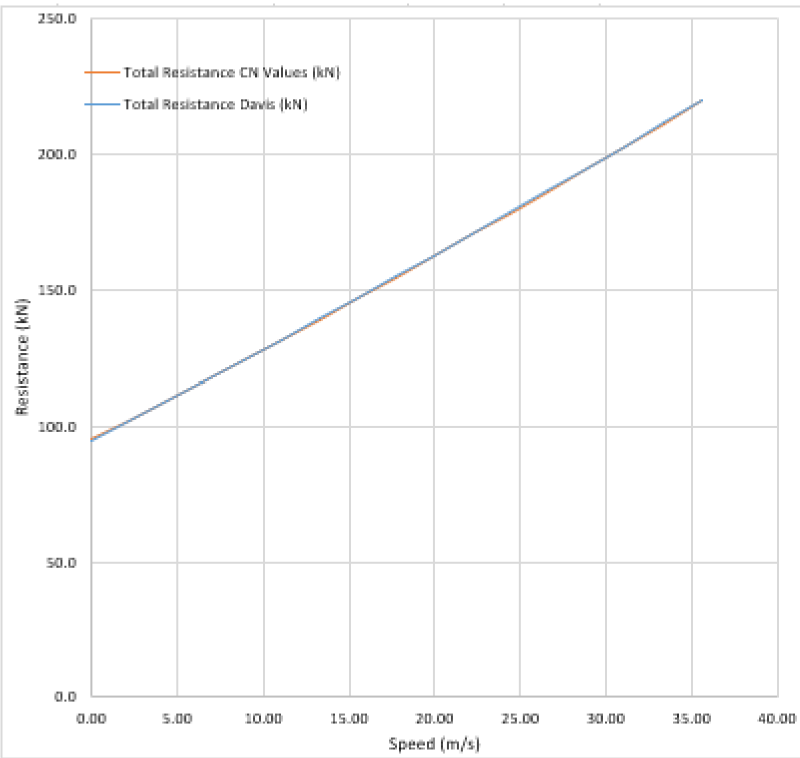
The following fig. A.8 shows the comparison of an approximated resistance curve with equation

$$R = 95 + 3.2V + 0.009V^2 \text{ (Equation A.4)}$$

to the curve generated by calculating the resistance using the Canadian National equation from [31].

This was felt to be the closest match that could reasonably be achieved.

Figure A.8: Comparison of estimated Davis equation curve (blue) with actual calculated values (orange) for the loaded Buchanan - Tokadeh train



Dar es Salaam - Kigoma Train

The first step in calculating the Davis equation is to enter the characteristics of the Dar es Salaam – Kigoma train in the spreadsheet. This is shown in Fig.A.9.

Figure A.9: Key characteristics of the Dar es Salaam – Kigoma train entered into the Davis calculation spreadsheet

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	100,000	400,000	500,000	kg
		110.0	440.0	550	tons
N	Number of axles	4	40	44	
V	Velocity	30	30		mph
C	Streamlining value*	24	3.5		
a	Cross sectional area*	160.0	105.0		square feet
R	Resistance	681.6	1809.1	2,491	lb
		3033.1	8050.4	11084	N
		3.0	8.1	**11.1**	**kN**

In this case, the locomotive is assumed to weigh around 100 tonnes and have 4 axles. The coaches are assumed to be similar to the "Conventional Passenger Coach" mentioned in [31] and thus have a streamlining value of 3.5.

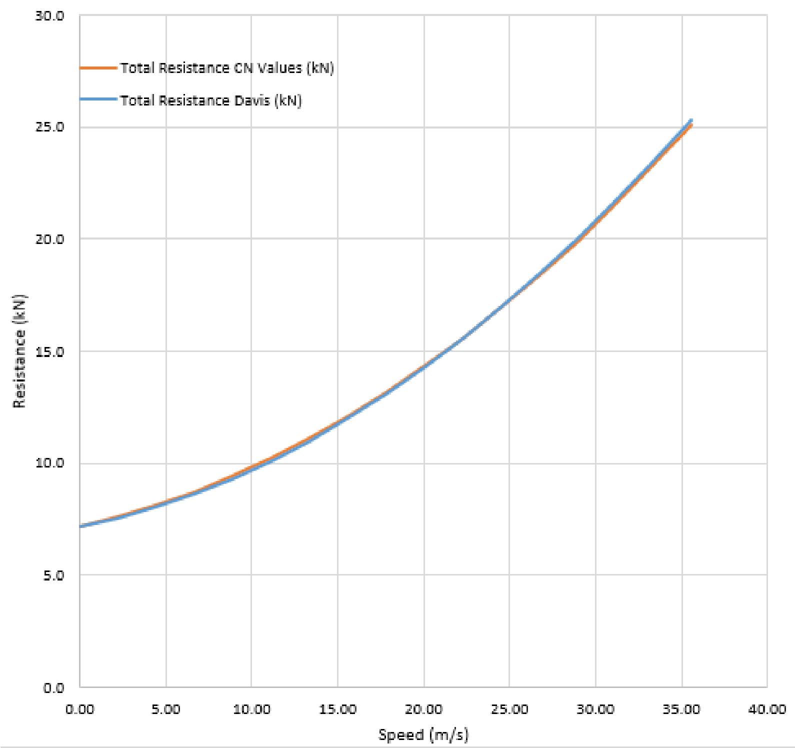
The following fig. A.10 shows the comparison of an approximated resistance curve with equation

$$\boldsymbol{R = 7.15 + 0.155V} + 0.01V^2 \text{ (Equation A.5)}$$

to the curve generated by calculating the resistance using the Canadian National equation from [31].

This was felt to be the closest match that could reasonably be achieved.

Figure A.10: Comparison of estimated Davis equation curve (blue) with actual calculated values (orange) for the empty Dar es Salaam – Kigoma train



Abuja – Kaduna

The first step in calculating the Davis equation is to enter the characteristics of the train in the spreadsheet, as shown in Fig.A.11.

Figure A.11: Key characteristics of the Abuja – Kaduna train entered into the Davis calculation spreadsheet

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	100,000	240,000	340,000	kg
		110.0	264.0	374	tons
N	Number of axles	6	4	10	
V	Velocity	30	30		mph
C	Streamlining value*	24	3.5		
a	Cross sectional area*	160.0	105.0		square feet
R	Resistance	717.6	738.7	1,456	lb
		3193.3	3287.1	6480	N
		3.2	3.3	**6.5**	**kN**

For comparison purposes, this spreadsheet calculates the resistance at 30 mph.

The streamlining values and cross sectional areas are taken as those for a leading passenger locomotive and conventional passenger coaches in [31]

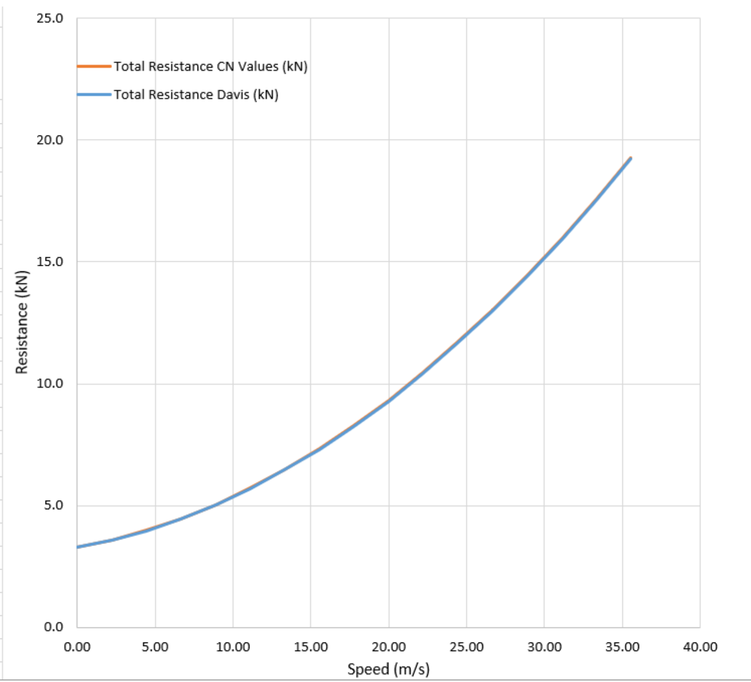
The following fig. A.12 shows the comparison of an approximated resistance curve with equation

$$R = 3.3 + 0.11V + 0.0095V^2 \text{ (Equation A.6)}$$

to the curve generated by calculating the resistance using the Canadian National equation from [31].

Although the match is not perfect, this was felt to be a reasonable approximation.

Figure A.12: Comparison of estimated Davis equation curve (blue) with actual calculated values (orange) for the Abuja – Kaduna train



APPENDIX B: RESULTS FOR DAR ES SALAAM – KIGOMA

Diesel Only

Figure B.1: Simulation output for the Mahundi Jn. – Dar es Salaam section, using the diesel only train

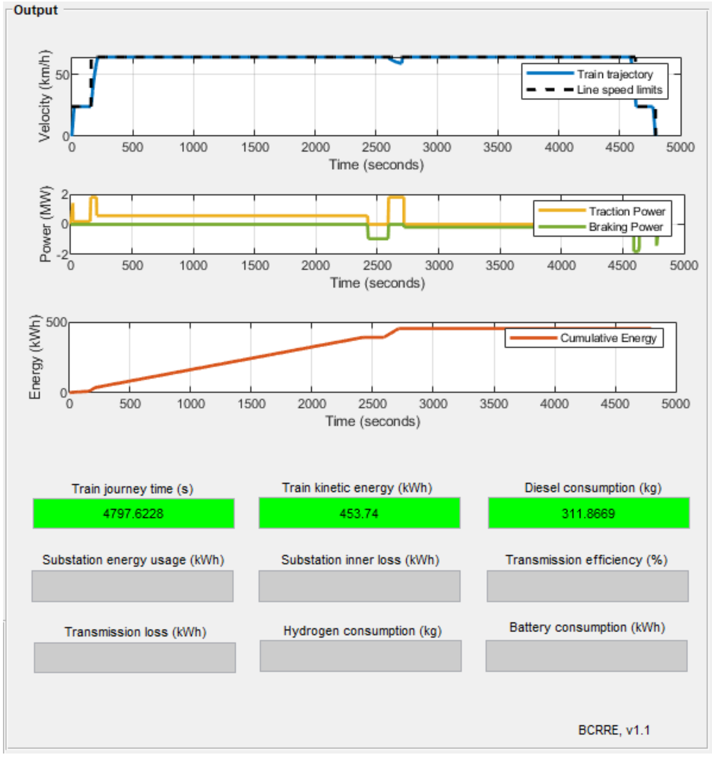


Figure B.2: Simulation output for the Mahundi Jn. – Tabora section, using the diesel only train

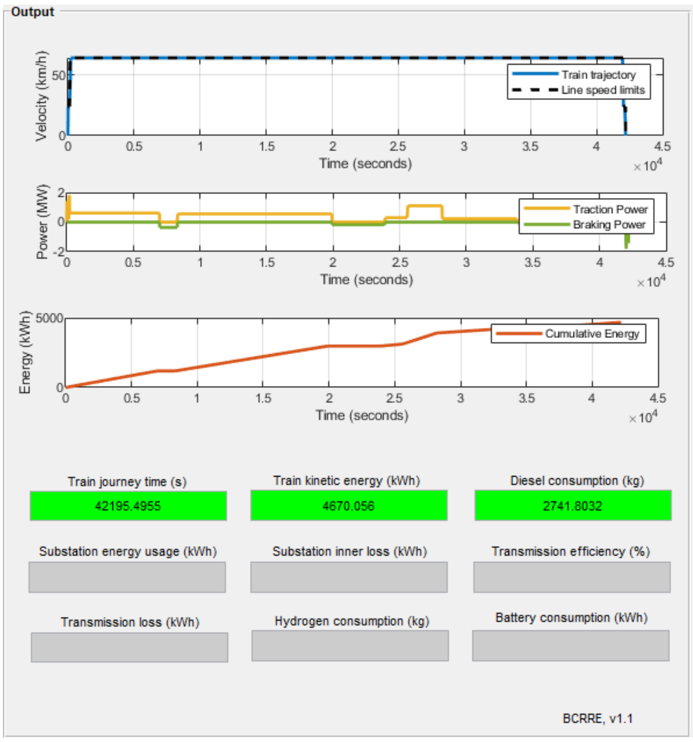


Figure B.3: Simulation output for the Kigoma – Tabora section, using the diesel only train

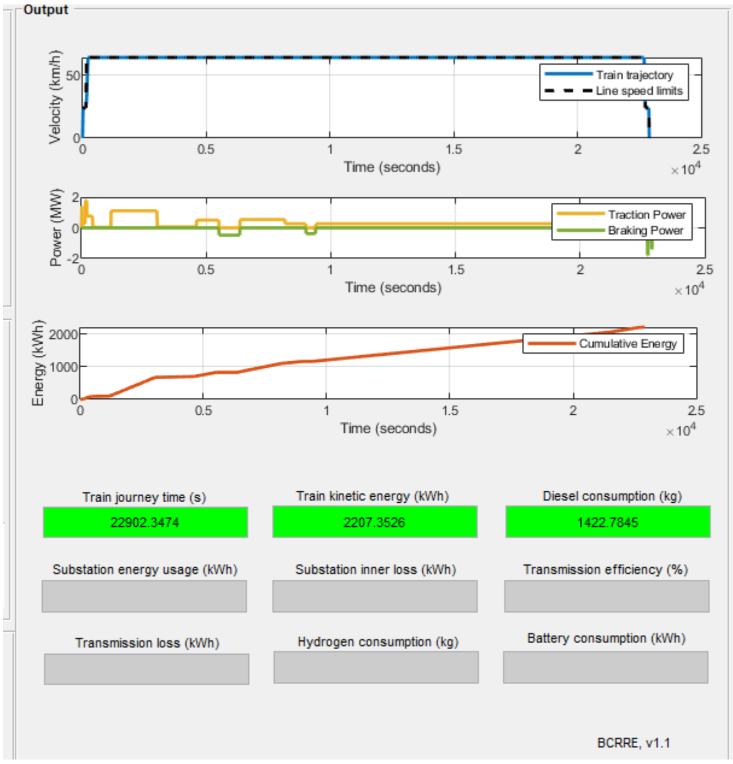


Figure B.4: Simulation output for the Tabora – Mwanza section, using the diesel only train

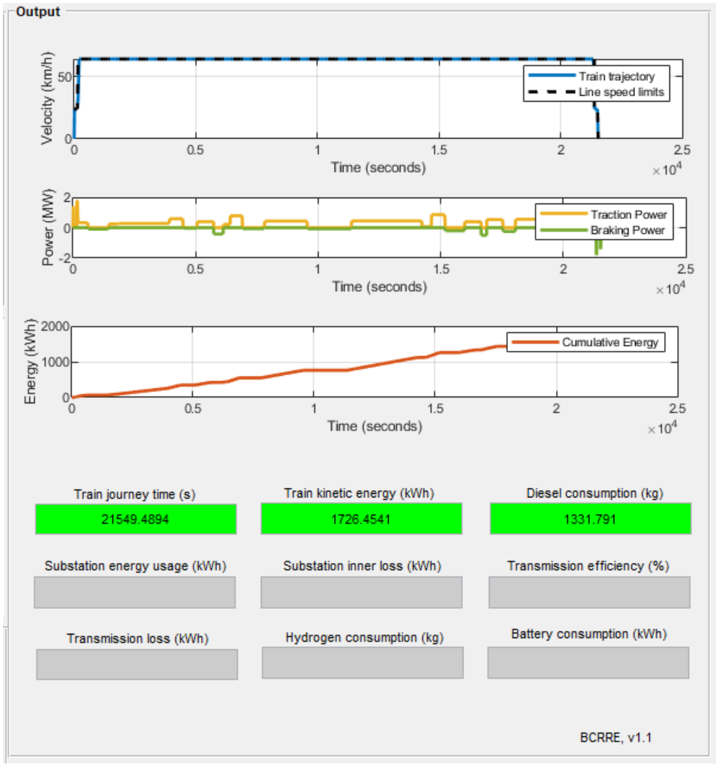
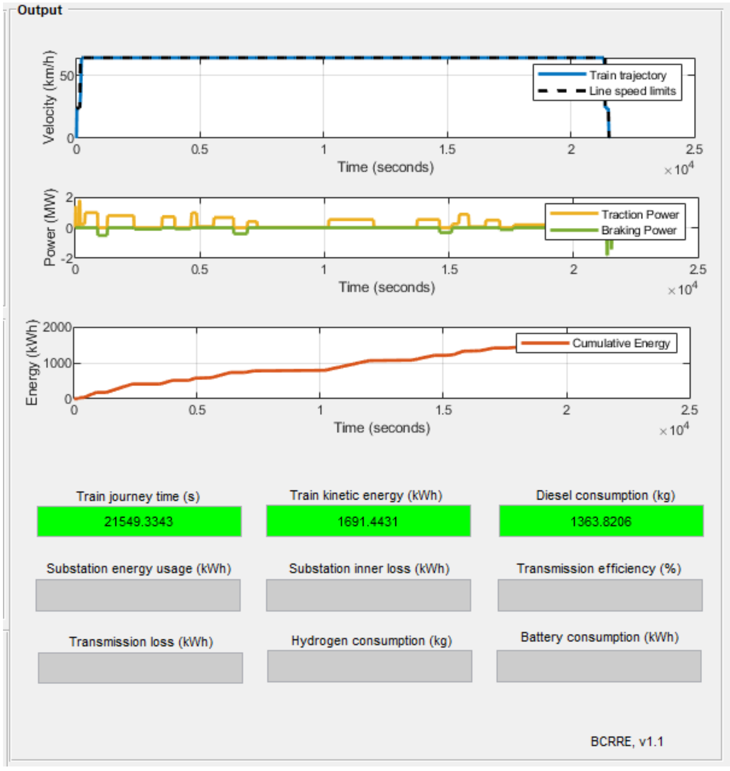
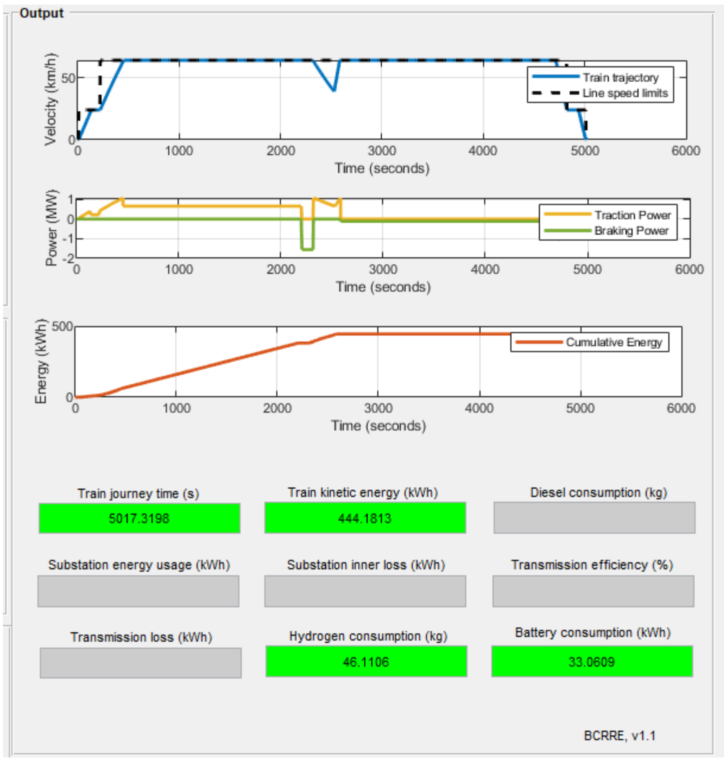


Figure B.5: Simulation output for the Mwanza – Tabora section, using the diesel only train



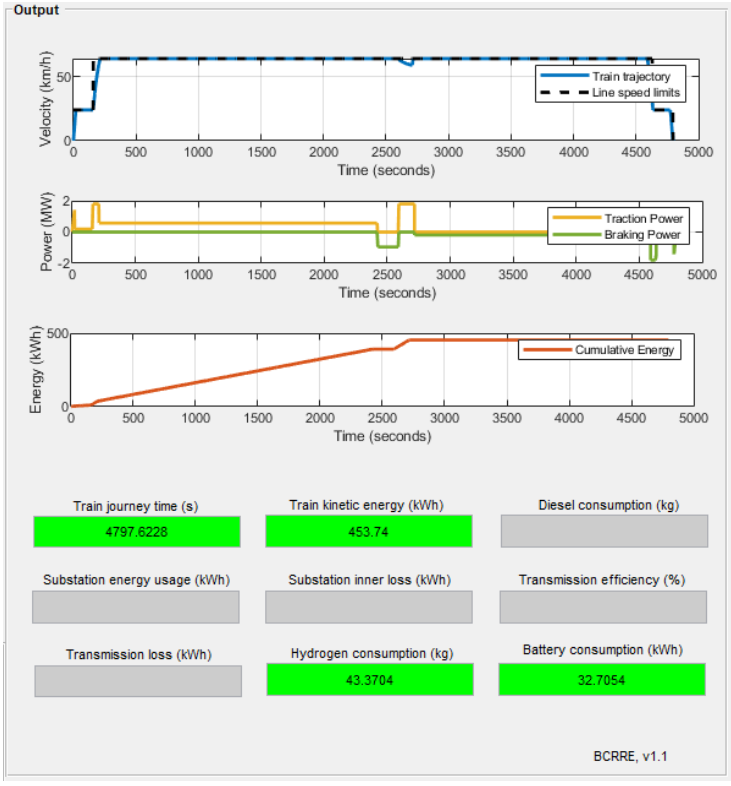
Hydrogen Hybrid

Figure B.6: Simulation output for the Dar es Salaam – Mahundi Jn. section, using the hydrogen hybrid train



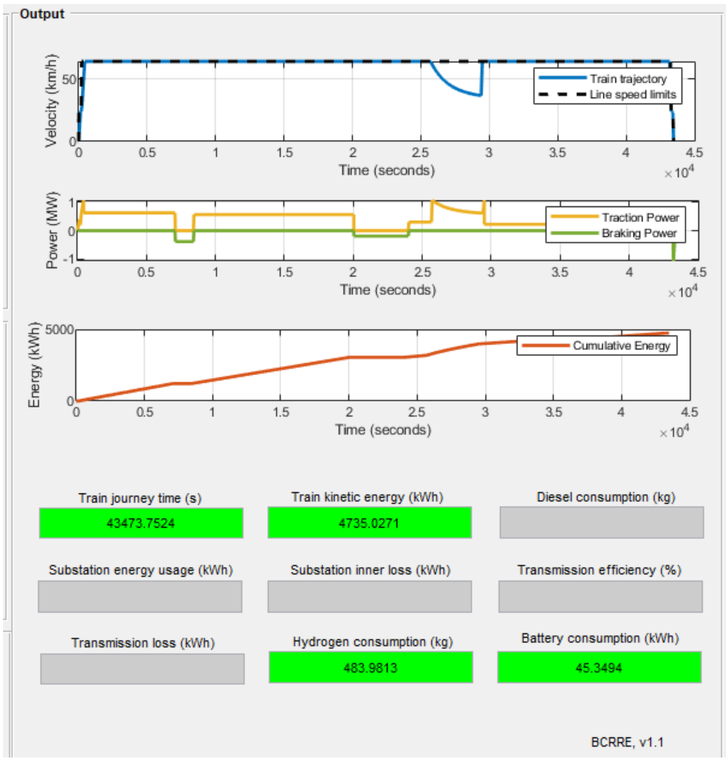
Note that the hybrid battery charge declines by 16% in Figure B.6.

Figure B.7: Simulation output for the Mahundi Jn. – Dar es Salaam section, using the hydrogen hybrid train



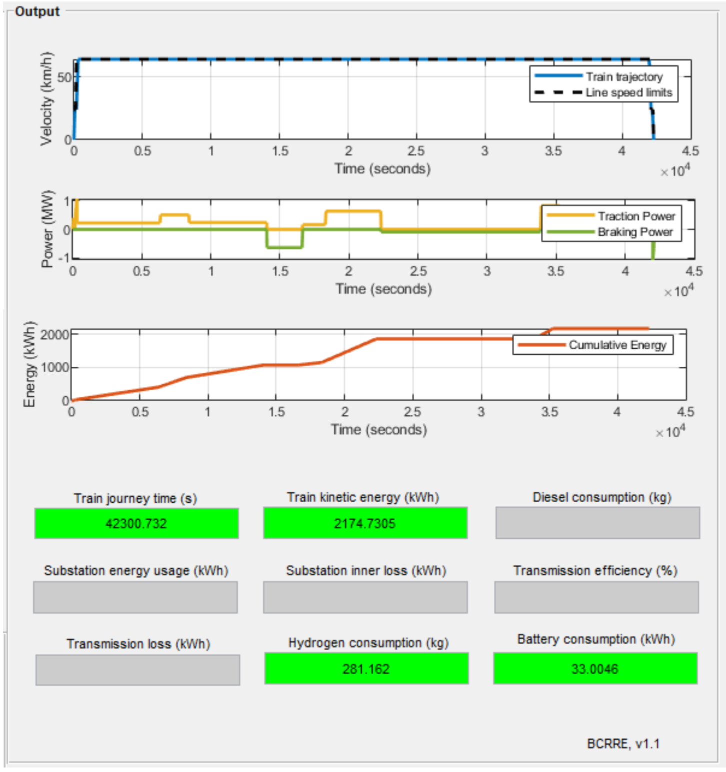
Note that the hybrid battery charge declines by 15% in Figure B.7.

Figure B.8: Simulation output for the Mahundi Jn. – Tabora section, using the hydrogen hybrid train



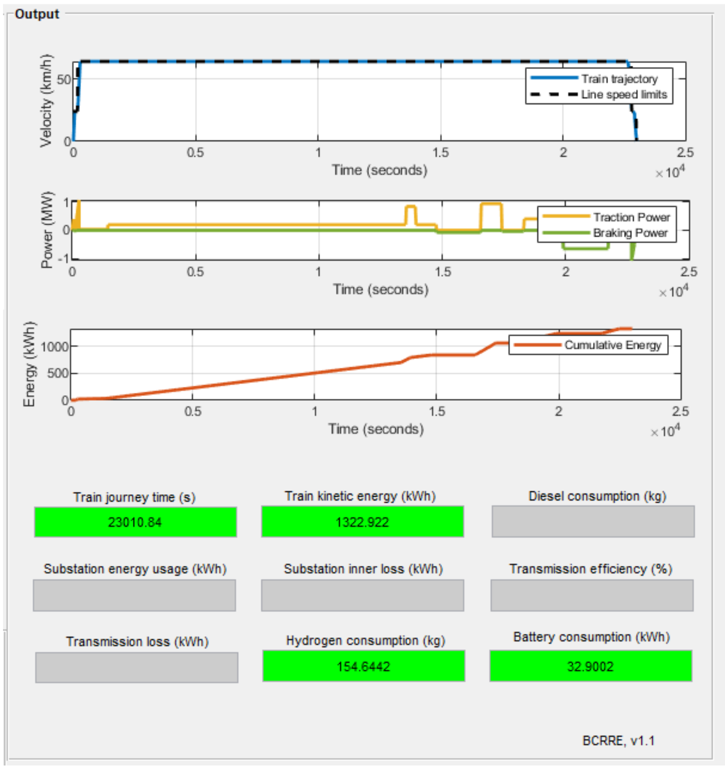
Note that the hybrid battery charge declines by 21% in Figure B.8.

Figure B.9: Simulation output for the Tabora – Mahundi Jn. section, using the hydrogen hybrid train



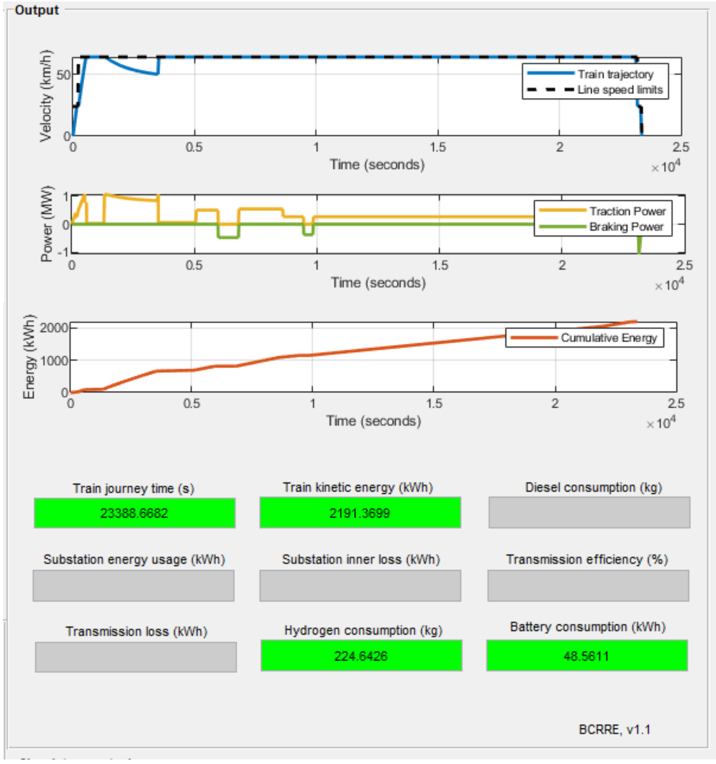
Note that the hybrid battery charge declines by 15% in Figure B.9.

Figure B.10: Simulation output for the Tabora – Kigoma section, using the hydrogen hybrid train



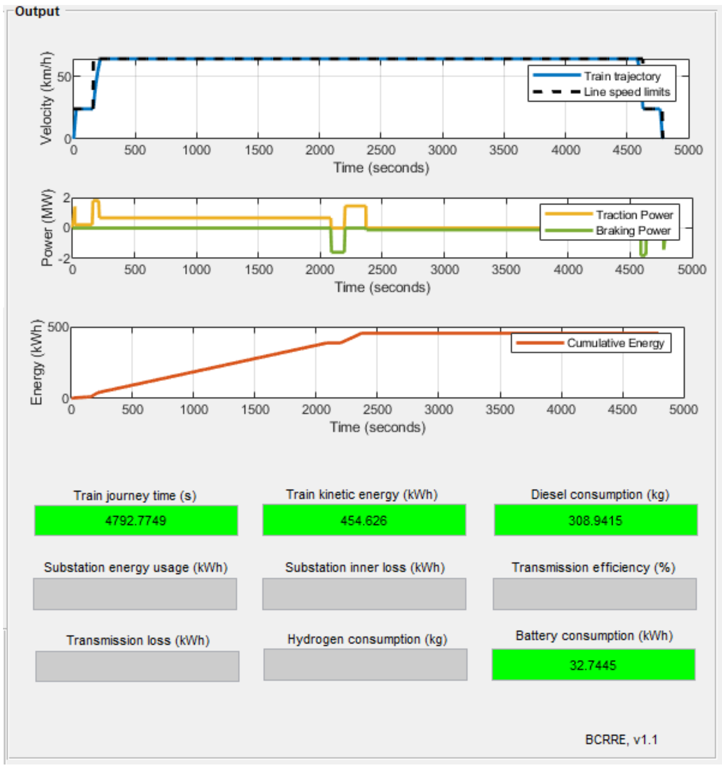
Note that the hybrid battery charge declines by 15% in Figure B.10.

Figure B.11: Simulation output for the Kigoma – Tabora section, using the hydrogen hybrid train



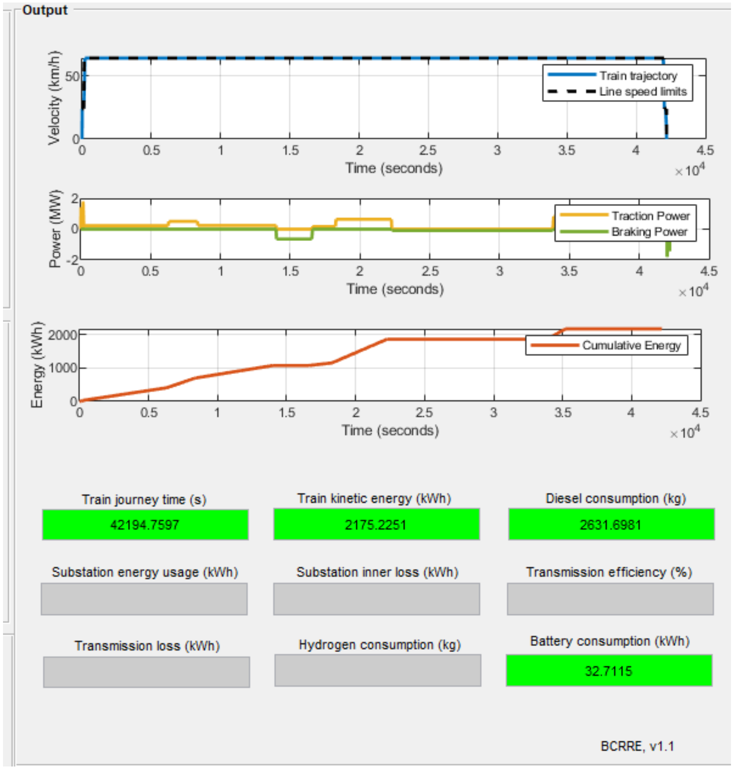
Note that the hybrid battery charge declines by 23% in Figure B.11.

Figure B.12: Simulation output for the Dar es Salaam – Mahundi Jn. section, using the diesel hybrid train



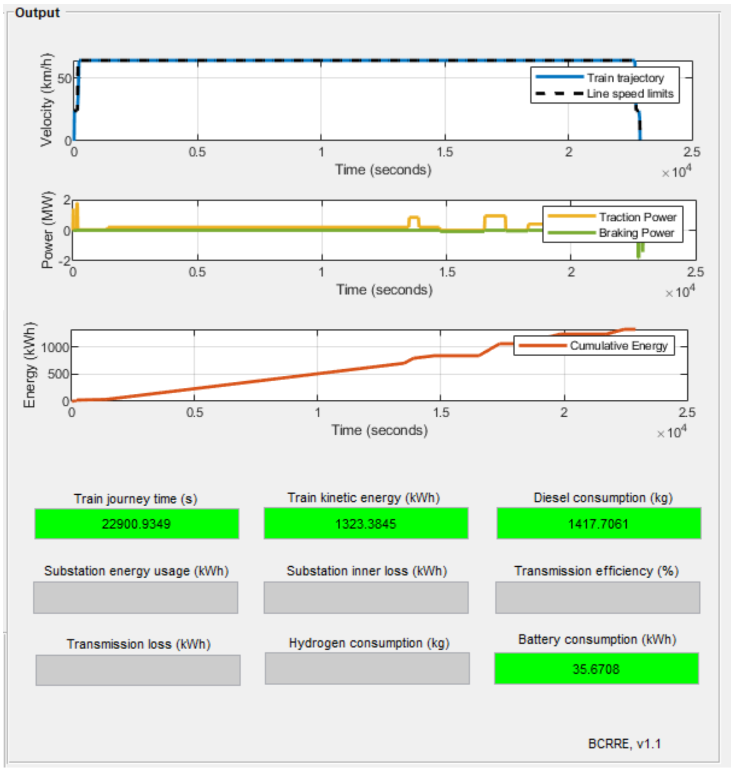
Note that the hybrid battery charge declines by 15% in Figure B.12.

Figure B.13: Simulation output for the Tabora – Mahundi Jn. section, using the diesel hybrid train



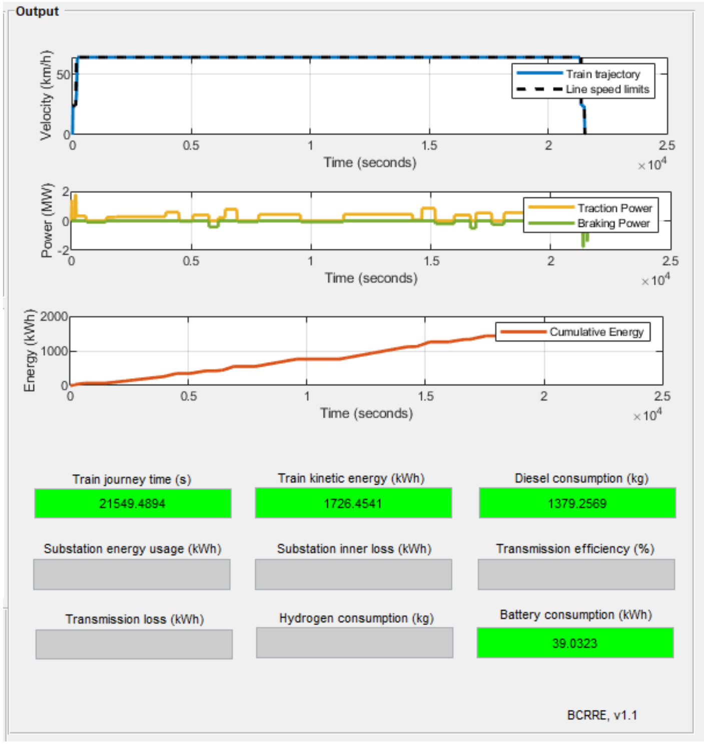
Note that the hybrid battery charge declines by 15% in Figure B.13.

Figure B.14: Simulation output for the Tabora – Kigoma section, using the diesel hybrid train



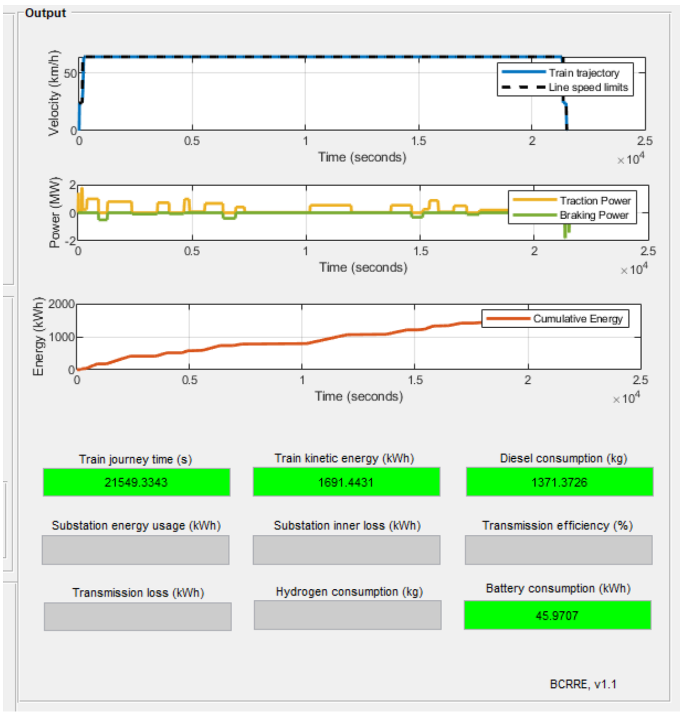
Note that the hybrid battery charge declines by 17% in Figure B.14.

Figure B.15: Simulation output for the Tabora – Mwanza section, using the diesel hybrid train



Note that the hybrid battery declines by 18% in Figure B.15.

Figure B.16: Simulation output for the Tabora – Mwanza section, using the diesel hybrid train



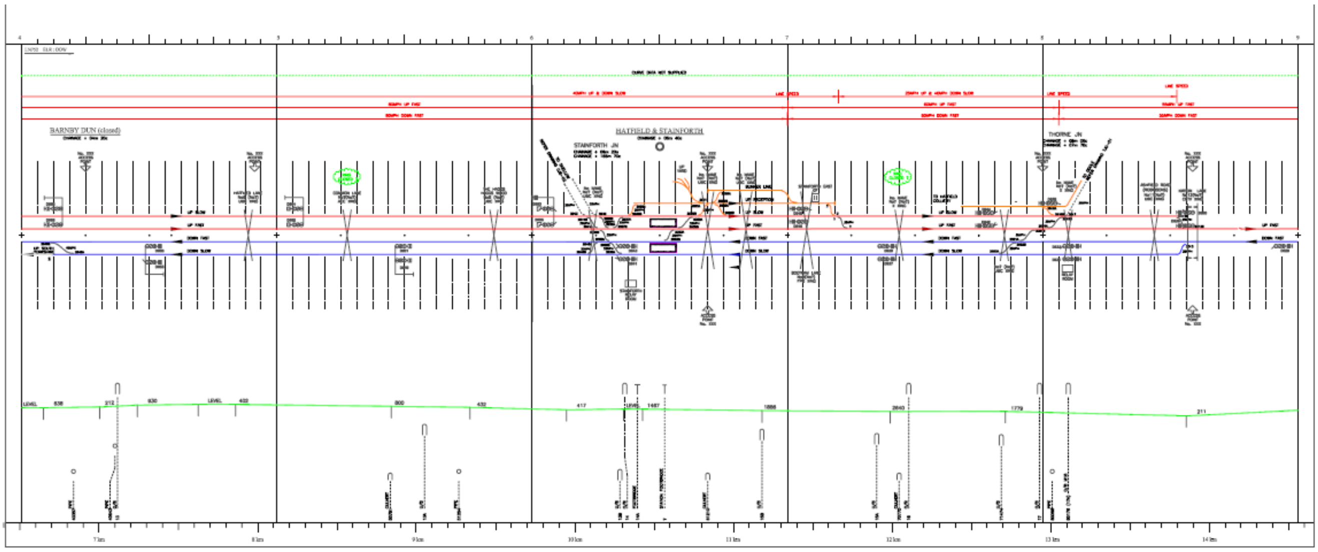
Note that the hybrid battery charge declines by 21% in Figure B.16.

APPENDIX C: SENSITIVITY OF SIMULATIONS TO ROUTE DATA SOURCES

For each route, gradient data were primarily sourced using Google Earth. This is done by mapping out the route, and picking out key points from the elevation profile to calculate a simplified version for the simulator's use. This also allows any errors in the data to be identified and excluded; Google Earth has a preference for road elevations rather than rail elevations, and will not show the rail elevation through a tunnel or under a bridge.

In order to test the effect of the accuracy of the data, a test of a route was performed. The route selected was that from Doncaster to Scunthorpe in the UK; this was chosen because detailed route data were available in the form of highly detailed 5-mile diagrams, commonly used in the UK (for an example, see Figure C.1).

Figure C.1: 5 mile diagram for the Handfield & Stainforth area between Doncaster – Scunthorpe [18]



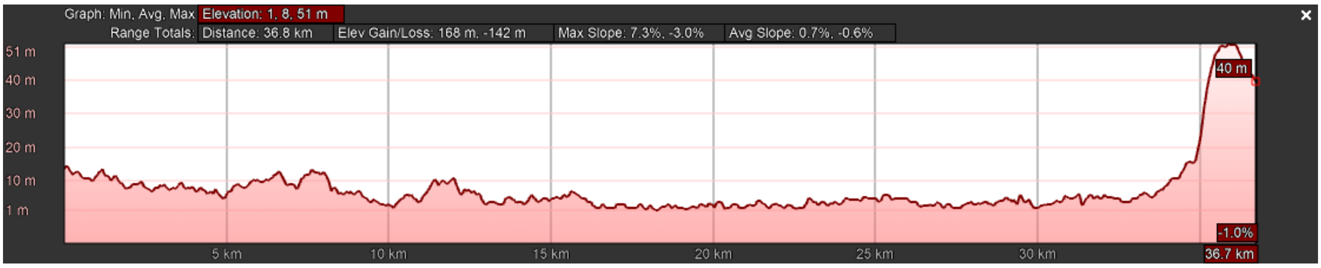
In addition, the route was mapped in Google Earth (see Figure C.2 and Figure C.3), and then modelled to three levels of accuracy:

- High detail; at least one data point in each kilometre of route
- Medium detail; key points picked out, around half the number of data points
- Very low detail; one point at the start of the route and one at the end

Figure C.2: Google Earth picture of the Doncaster – Scunthorpe route

Figure C.3: Google Earth gradient profile for Doncaster – Scunthorpe

Figure C.3: Google Earth gradient profile for Doncaster – Scunthorpe



Each route was simulated with a train of 200 tonnes, with a traction power of 1200 kW, auxiliary power of 50 kW and the following generic Davis constants:

$$R=3+0.1V+0.001V^2$$

It should be noted that these characteristics do not correspond to any real train; they are merely being used for comparison purposes. The speed limit is assumed to be 100 km/h throughout.

For the purposes of comparison, train power is assumed to come exclusively from a diesel engine.

The route profile and STS results for the route generated by the 5 mile diagram are shown in Figure C.4 and Figure C.5 respectively. Note the slight difference of the route profile and the Google Earth gradient profile due to Google Earth's inaccuracies.

Figure C.4: Route profile in the STS generated from the 5 mile diagrams

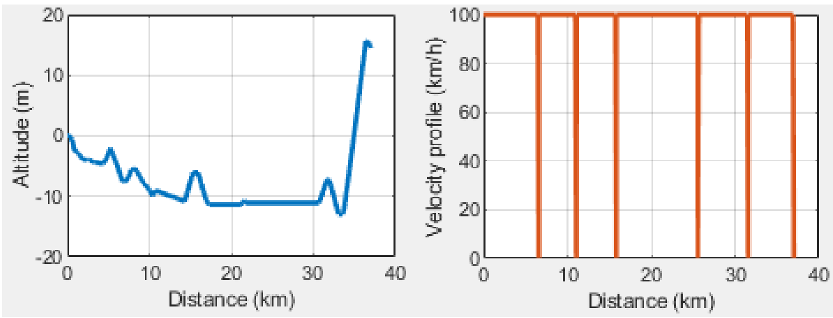
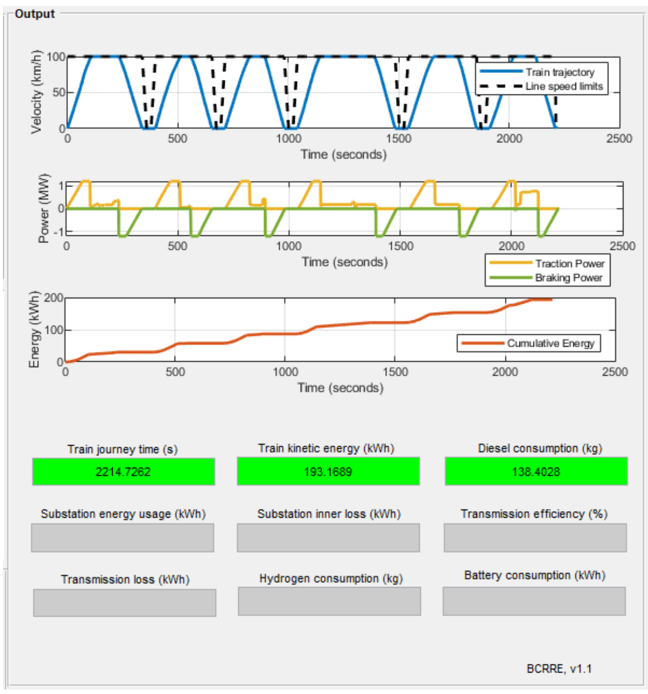


Figure C.5: STS results for Doncaster – Scunthorpe using the 5 mile diagrams



The route profile and STS results for the detailed Google Earth map are shown in Figure C.6 and Figure C.7 respectively. Note the data are far more erratic than for the 5 mile diagram, but the results are similar.

Figure C.6: Route profile in the STS generated from the detailed Google Earth map

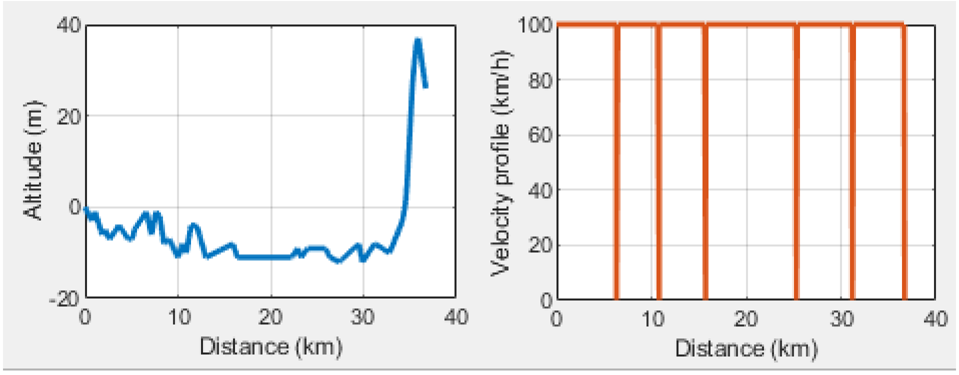
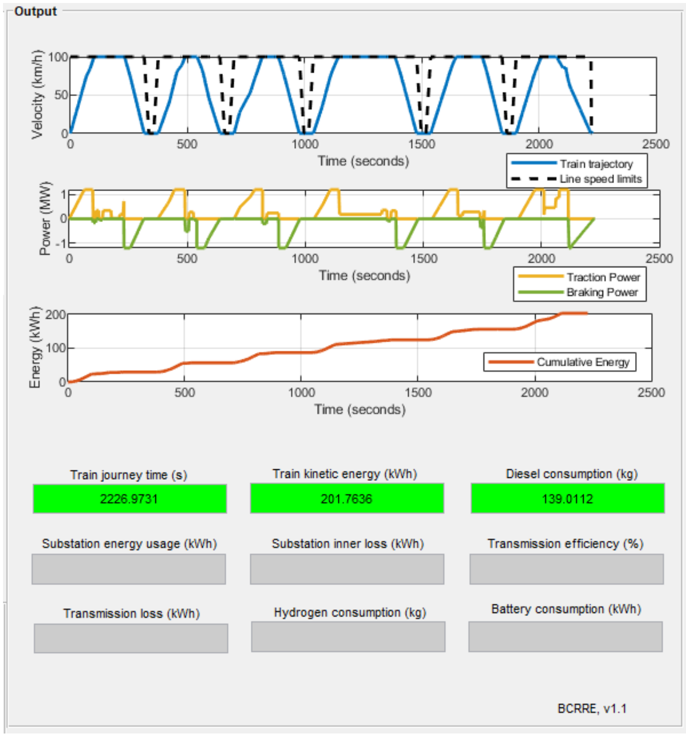


Figure C.7: STS results for Doncaster – Scunthorpe using the detailed Google Earth map



The route profile and STS results for the medium detail Google Earth map are shown in Figure C.8 and C.9 respectively. Note that this is smoother than the detailed Google Earth model but the results are similar.

Figure C.8: Route profile in the STS generated from the medium detail Google Earth map

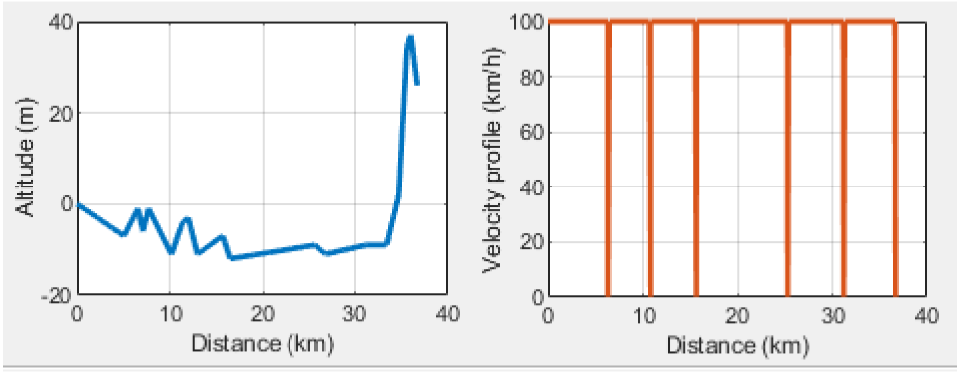
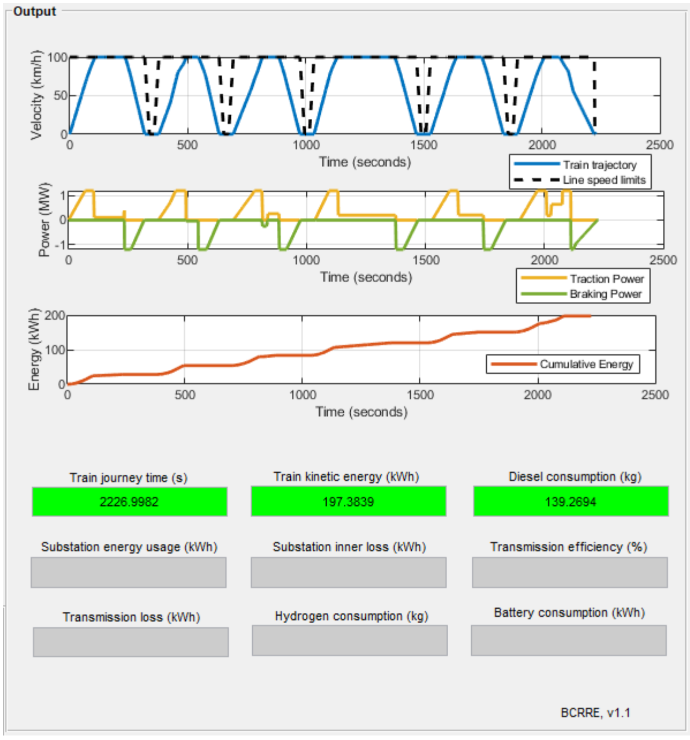


Figure C.9: STS results for Doncaster – Scunthorpe using the medium detail Google Earth map



The route profile and STS results for the detailed Google Earth map are shown in Figure C.10 and Figure C.11 respectively. Note that, despite the extremely simplistic gradient profile, the results are still relatively similar.

Figure C.10: Route profile in the STS generated from the very low detail Google Earth map

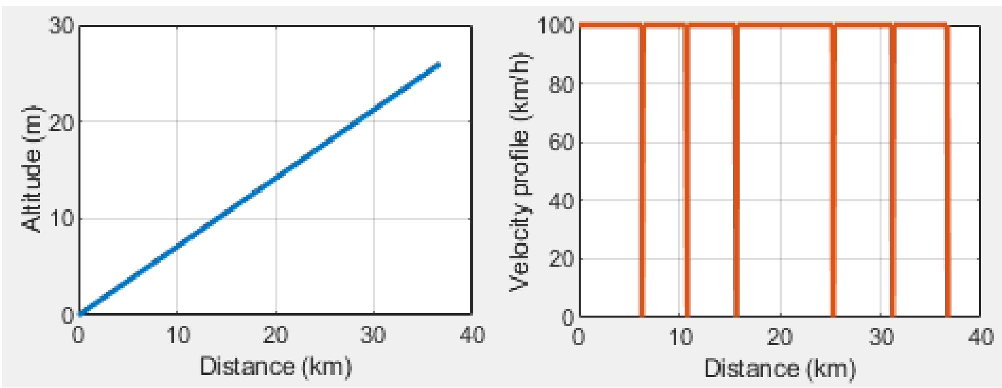


Figure C.11: STS results for Doncaster – Scunthorpe using the very low detail Google Earth map

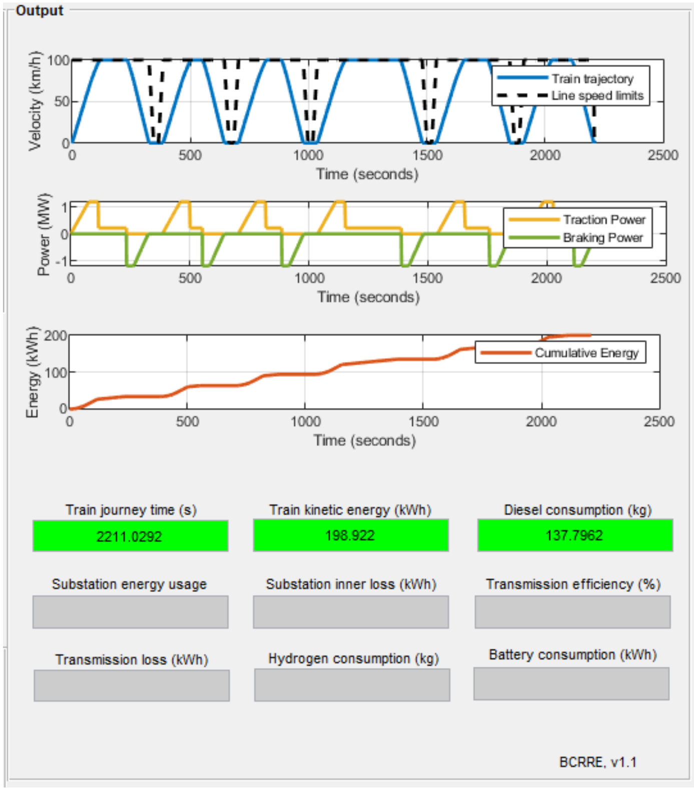


Table C.1 shows a comparison of the results from the various different models.

Table C.1: Comparison of the route data source options

Route option	Diesel consumption / l	% difference to 5 mile diagram	Train journey time / s	% difference to 5 mile diagram
5 Mile Diagram	162.83	-	2215	-
Detailed Google Earth	163.54	0.44%	2227	0.54%
Medium detail Google Earth	163.85	0.63%	2227	0.54%
Very low detail Google Earth	162.11	- 0.44%	2211	-0.18%

As can be seen, the level of detail makes little difference in this context. There are other reasons too for limiting the number of data points; for longer routes, it may prove too time consuming to justify a data point every km, and, given the limited improvement in accuracy, it may only be worth including important points such as peaks and troughs.

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