SIMULATION REPORT - Novel traction systems for sustainable railway futures in LICs

Deliverable 3.1

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HVT038 – University of Birmingham

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Abstract

This report presents generic simulations to aid in the establishment of vehicle architectures for decarbonised trains in Sub Saharan Africa, utilising the latest version of the Single Train Simulator (STS) in order to test four typical train service types. It is found that while many services vary in their requirements, medium haul passenger and freight work may be best served by a mixed traffic locomotive.

Keywords	Railway simulation; duty cycles; novel traction systems; zero carbon trains, rail transport,
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ACRONYMS

BCRRE	Birmingham Centre for Railway Research and Education
GUI	Graphical User Interface
HVT	High Volume Transport
kWh	Kilowatt Hours
STS	Single Train Simulator
MATLAB	“Matrix Laboratory” (Software)
ULR	Ultra Light Rail

EXECUTIVE SUMMARY

This report sets out simulations conducted into a range of railway duty cycles. This was conducted to provide target performance metrics to determine suitability of and specifications for novel traction systems for use on railways in Sub Saharan Africa. These metrics will be used to assess the performance metrics of concept designs that will be produced as part of this project.

In order to do this, several train types were investigated, using real-world examples where available to inform the simulation data. These were set to work on generic routes which simulated similar operational conditions to real life. These duty cycle simulations were created from the project team's previous experience on both practical and theoretical project. The following basic service types were simulated:

- A medium distance freight service;
- A medium distance, medium-speed passenger service;
- A small carriage shunting scenario; and
- A local service operated by an Ultra Light Rail (ULR) vehicle.

These duty cycles were selected as the project team's experience, both from previous projects, the High Volume Transport (HVT) programme and projects that are running concurrently, suggest that novel traction solutions suit lighter and slower trains as the energy requirements for these services are significantly lower than faster and heavier trains. This analysis is supported by the findings of deliverable 2.2 of this project, the Capability Analysis Report. Higher performance case studies were considered in the inception phase of this report, but initial simulations demonstrated that application of novel technologies was less likely to be successful in these scenarios when compared to the case studies selected and thus resource and time was directed towards the four case studies that are most suitable for the initial adoption of novel traction systems.

Basic models of these trains were compiled and then simulated using the latest version of the University of Birmingham's Single Train Simulator (STS). Once these were completed, observations were noted and energy requirements calculated based on presumed daily requirements. These were based on the expected duty cycles between refuelling or recharging opportunities.

Train Type	Freight Locomotive and 15 wagons EMD GT22C-3M	Passenger Locomotive and 6 carriages GE U26C	Shunting Locomotive and 6 carriages Henschel DHG1000	Ultra Light Rail Train (Severn Lamb ULR)
Train Characteristics	**Power:** 1900 kW **Weight (Loaded):** 1910t **Weight (Tare):** 560t	**Power:** 1500 kW **Weight:** 329t	**Power:** 560 kW **Weight (Loaded):** 310t **Weight (Tare):** 70t	**Power:** 140 kW **Weight:** 32t
Demonstrative Route Characteristics	**Route Length:** 120km **Route Speed:** 50km/h **Number of Trips:** 1x Loaded, 1x Tare **Total Distance Covered:** 240km	**Route Length:** 120km **Route Speed:** 120km/h **Number of Trips:** 3x Return Trips **Total Distance Covered:** 720km	**Route Length:** 1km **Route Speed:** 40km/h **Number of Trips:** 5x Loaded, 5x Tare **Total Distance Covered:** 10km	**Route Length:** 32km **Route Speed:** 60km/h **Number of Trips:** 5x Return Trips **Total Distance Covered:** 320km
Final Energy Requirements	**6208 kWh required at wheel**	**8374 kWh required at wheel**	**72 kWh required at wheel**	**1440 kWh required at wheel**
	= 6898 kWh of Battery Capacity	**= 9305 kWh of Battery Capacity**	**= 80 kWh of Battery Capacity**	**= 1600 kWh of Battery Capacity**
	= 467 kg of Hydrogen	**= 629 kg of Hydrogen**	**= 6 kg of Hydrogen**	**= 109 kg of Hydrogen**
	= 3200 l of Diesel	**= 4317 l of Diesel**	**= 38 l of Diesel**	**= 743 l of Diesel**

1. Introduction

The University of Birmingham's Birmingham Centre for Rail Research & Education (BCRRE) has been tasked with various research activities in relation to the decarbonisation of railways in Sub-Saharan Africa, ultimately culminating in the concept design of vehicle architectures.

This report is intended to simulate basic duty cycles and train types, in order to estimate the energy requirements for these trains. It builds on known data for existing train types, and is intended to inform the vehicle architecture design team in terms of the energy and fuel requirements for each type of locomotive. For the purposes of this report, a "duty cycle" is the operation of a train on an outward and return journey to and from a fixed point i.e. a passenger round trip between two termini.

Vehicle architecture is the focus of Work Package 3 of the project. Concept designs will be produced for the 4 classes of train during this work package. These will be compared against the metrics produced in this report to determine suitability for use in Sub-Saharan Africa. This work will be reported upon in deliverable 3.2 of this project, the architectural designs report, which will be completed by 31 October 2021.

Whilst it might seem in the first instance that there is very little difference between this report and the capability analysis report (Deliverable 2.2), these two papers have been created for different purposes, alas by using similar methodologies.

The capability analysis report seeks to answer the question "Can novel traction technologies be applied to these existing railway use cases". Four case studies were selected from railways in Africa and the use of different novel traction types was simulated using the Single Train Simulator. From these simulations the capability of the novel traction systems to satisfy each duty cycle was thus assessed.

This report seeks to answer the question "What is the minimum specification for a range of locomotives/rail vehicles that is used on the continent of Africa". The methodology applied is to use the Single Train Simulator to model 4 different use cases for 4 different types of train. The power and weight of the consists was taken from an existing type of locomotive and existing rail service. The energy required to be carried in each train type is then determined using the simulator results. This is translated into an energy requirement between refuelling by multiplying the energy figure from a single journey into the amount of journeys that could be achieved between refuelling/recharging opportunities.

Each duty cycle modelled is an abstract route simulation, using author selected gradients, stopping patterns and speeds. This is based on the project team's experience, both in terms of legacy railway operations and the nature of working practically with novel traction technologies in projects such as the HydroFLEX mainline trials.

The minimum number of duty cycles between refuelling/refilling opportunities is based upon the likely service patterns of each type of rolling stock. For example when a freight train is being loaded or unloaded it is common that the locomotive is taken out of service for a period of time as this operation takes a significant amount of time. This "downtime" allows for servicing to take place, along with crew changeovers and other necessary functions. Whilst currently this time might not necessarily be used to refuel a locomotive, due to the energy density of the diesel freight locomotive benchmark that has been used as a benchmark, the lower energy densities of novel energy sources such as hydrogen and batteries mean that less energy can be carried per unit volume than in legacy traction types, thus using this opportunity to refuel is a valid way of making novel traction viable.

Conversely, for example, in the project team's experience, the passenger services such as those modelled have more limited amount of time for servicing at a terminal as passengers load and unload themselves onto trains far faster than freight does. As such, there is less time for servicing a passenger train, thus refuelling at termini might not be practical, therefore more trips between refuelling opportunities must be accounted for.

The purpose of this modelling is thus to determine the minimum amounts of power generation and energy storage that must be present on trains of each of the types described. This will be used to inform the design of novel traction architectures that will be produced later in this work package.

2. Train Simulation

2.1 The Single Train Simulator (STS)

The Single Train Simulator (STS) is a software simulation tool developed by researchers at 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 formula

m(1+λ)α=F(T-(a+bv+cv^2+mgϑ))

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

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

where 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 modeled using the formula

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

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

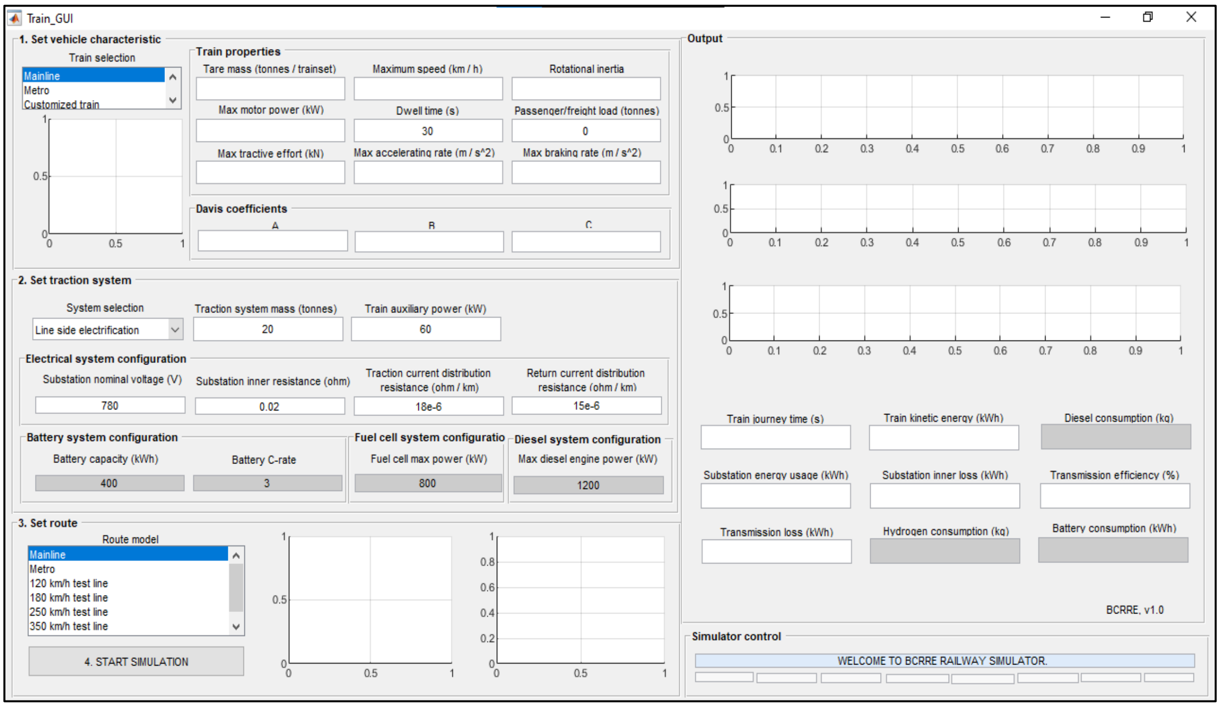
$$\boldsymbol{P = F_T\, v}$$

2.2 The Graphical User Interface Single Train Simulator

The Single Train Simulator 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]).

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

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; and
- 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 here, 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;
- 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; and
- 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 simulation method selected for the work of establishing performance benchmark as part of this piece of work was to use the battery electric simulation with battery efficiency set to 100%. This setting was chosen as it models the complete energy requirement at the wheels of each locomotive simulated. This allows for the fuel requirements for each type of prime mover to be calculated subsequently on by accounting for the efficiency of each type of energy storage on top of the of the figure produced by the simulations produced in this report.

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

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.

3. Simulation Results

A series of generic simulations was performed, in order to determine requirements for various types of trains. The Single Train Simulator was set up to calculate performance using the battery locomotive simulation mode. This provided the most optimal was to determine overall energy requirements at the wheel, rather than the details of any potential specific hybrid or novel traction system.

When the data for energy required at wheel was obtained for each duty cycle, this was multiplied by the number of duty cycles were required to be completed between refuelling opportunities. For definition, a duty cycle is considered to be the operation of the train between fixed points. In this instance this is a return trip from and back to the loading point of the train. One trip is modelled as being laden, the other is tare.

The routes used in this report are not based upon any specific route (as circumstances will vary considerably between use cases) but are instead generic for benchmarking purposes. There is, however, some similarity to real-life practice; a 120 km route is used twice below, which is in the same order of magnitude as many routes in Africa including that from Kaduna – Abuja. Similarly, the shunting route is based upon data collected from Kidderminster in the U.K., where there is a locomotive and carriage depot and a station; similar arrangements are present in Kampala, for example.

The justification for the number of trips between refuelling opportunities is based upon the logical minimum amount of work each train has to do between the opportunities to refuel, refill or recharge. For example, it has been noted from data gathering from legacy research [12] and the ongoing HydroShunter project that the shunting locomotive has long periods of downtime during the day that could provide opportunities for refuelling. Passenger trains have opportunities for refuelling during time spent at terminals and freight locomotives experience downtime during freight loading and unloading opportunities.

The HydroShunter project consists on a partnership between a UK heritage railway (Severn Valley Railways) and the University of Birmingham to convert a historical Class 08 locomotive to run on hydrogen power [13]. The project has seen a full retrofit of a diesel locomotive into hydrogen power, based on a bespoke design pack to fit the components of a hydrogen fuel cell system into the existing vehicle.

This data will be used to inform design choices in the concept design work conducted in Work Package 3. It is of particular importance as novel zero emissions energy storage technologies such as hydrogen and batteries are less energy dense than legacy fossil fuel, and thus take up more volume compared with legacy traction systems. This is the constraining factor when incorporating these designs into legacy rolling stock. As such, an indication of the kWh energy storage required by a battery, the amount of fuel required by a diesel engine and the amount of hydrogen is given in each section.

3.1 Freight Locomotive Simulation

In order to determine the requirements for a decarbonised freight locomotive for Sub-Saharan Africa, first a search for existing locomotives of suitable size was undertaken. An example locomotive is the EMD GT22C-3M (see Figure 2)[4] which has the key specifications listed in Table 1. This locomotive has been chosen as it is an example of a freight locomotive that has a maximum power output that is conceivably achievable with the present state of the art of novel traction technologies.

Figure 2: External view of EMD GT22C-3M locomotive [4]

Table 1: Key characteristics of the EMD GT22C-3M [4]

Characteristic	Value
Engine Power	1847 kW
Tractive Effort	262 kN
Mass	110 tonnes
No. of Axles	6
Track Gauge	1067 mm

This locomotive was tested with a hypothetical empty and loaded train (details of the configurations are shown in Table 2), on a hypothetical 120 km route, with a 1 in 100 uphill gradient for 60 km, and a 1 in 100 downhill gradient for the remaining 60 km (see Figure 3). This route was inspired by the Abuja Kaduna route in Nigeria. The aim was to create a generic simulation of a freight train travelling between industries within the route, and although it is acknowledged (as above) that particular routes elsewhere may differ slightly from the case here, the 1 in 100 gradients were felt to be sufficiently challenging to represent a more difficult route; the Abuja Kaduna route features a majority of gradients less severe than this. The Davis equations were calculated using a Canadian National method [5]. More information on the calculation of the Davis constants is given in Appendix A. The rationale for selection of the idealised route is discussed in the introduction section to this report.

Figure 3: Gradient profile of the freight test route

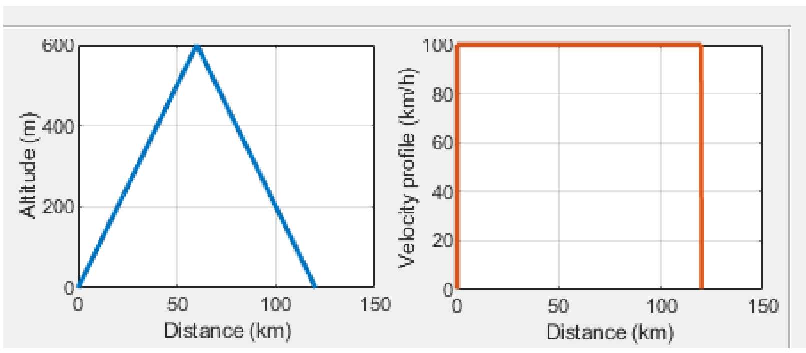


Table 2: Key characteristics of the empty and loaded train configurations

Characteristics	Empty Train	Loaded Train
Mass / tonnes	560 (including loco)	1910 (including loco)
Davis Equation	R = 9.3 + 0.2V + 0.011 V^2	R = 19 + 0.7V + 0.008V^2

Simulation results for the empty and loaded trains are shown in Figures 4 and 5 respectively.

Figure 4: Simulation results for the empty freight train on the hypothetical 120 km route

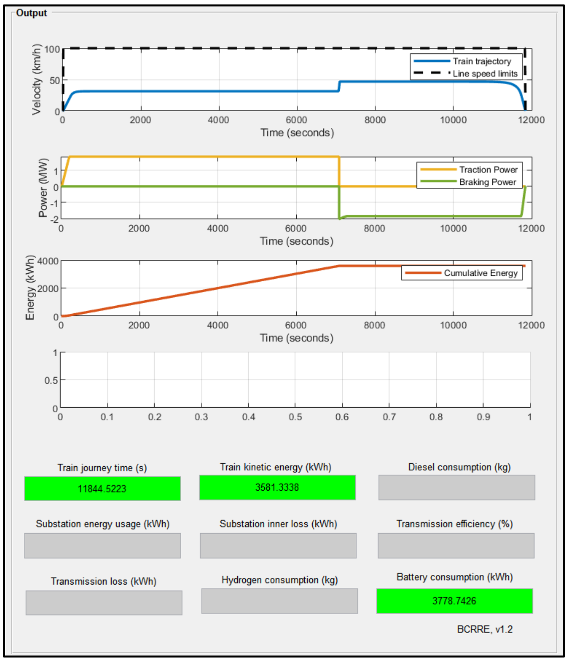
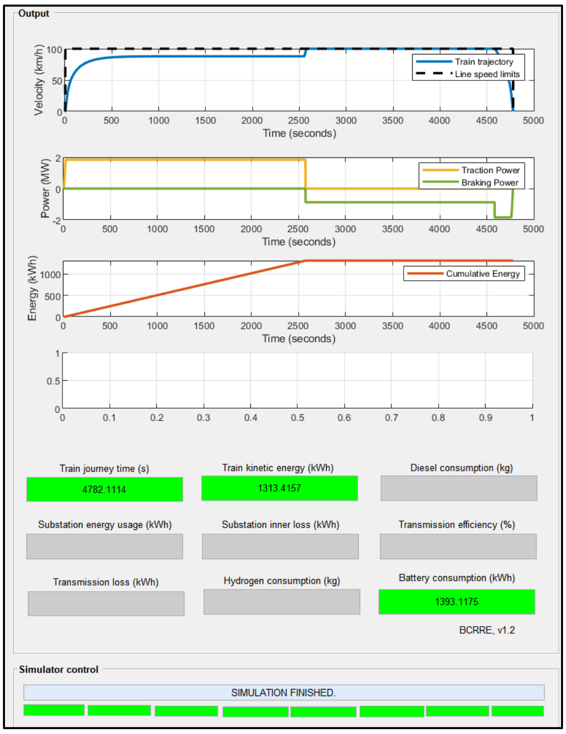


Figure 5: Simulation results for the loaded train on the hypothetical 120 km route



Note that:

- The full train uses full power (1847 kW) for a considerable period (nearly 7000 seconds or 117 minutes) while climbing the hill;
- The empty train uses full power (1847 kW) for a smaller, but still considerable period (over 2500 seconds or 42 minutes) while climbing the hill; and
- There appears to be scope for regenerative braking, as no traction power is used when travelling downhill, with near-full braking power applied for much of the run.

3.2 Passenger Locomotive Simulation

In order to determine passenger requirements, a hypothetical train was simulated based upon some real-life data. An example locomotive is the GE U26C (see Figure 6)[6], which has the key characteristics shown in Table 3 (data from [7]). This locomotive has been chosen as a benchmark as it is used in passenger service on the African continent and has a power output that is achievable using the present state of the art of novel traction technologies.

Figure 6: GE U26C hauling a freight train in Kenya [6]

Table 3: Key characteristics of the GE U26C [7]

Characteristic	Value
Engine Power	1500 kW
Tractive Effort	260 kN
Mass	88.9 tonnes
No. of Axles	4
Track Gauge	1000 mm

This locomotive was incorporated into a hypothetical train consist with 6 passenger coaches, with the characteristics listed in Table 4. The gradient and length of the route was identical to that used for freight, however, stops were added in at 20 km intervals, and the speed limit was raised to 120 km/h in order to simulate a passenger duty cycle (see Figure 7). The aim was to create a generic simulation of a passenger train travelling between stations within a route similar to the Abuja – Kaduna route in Nigeria.

Figure 7: Gradient profile for the 120 km route with stops (note the changed velocity profile on the right)

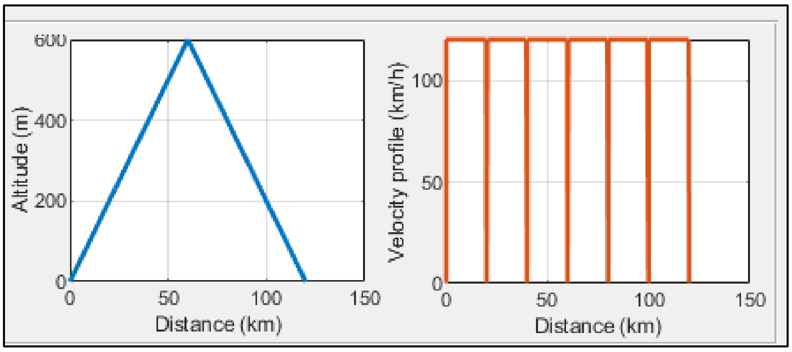
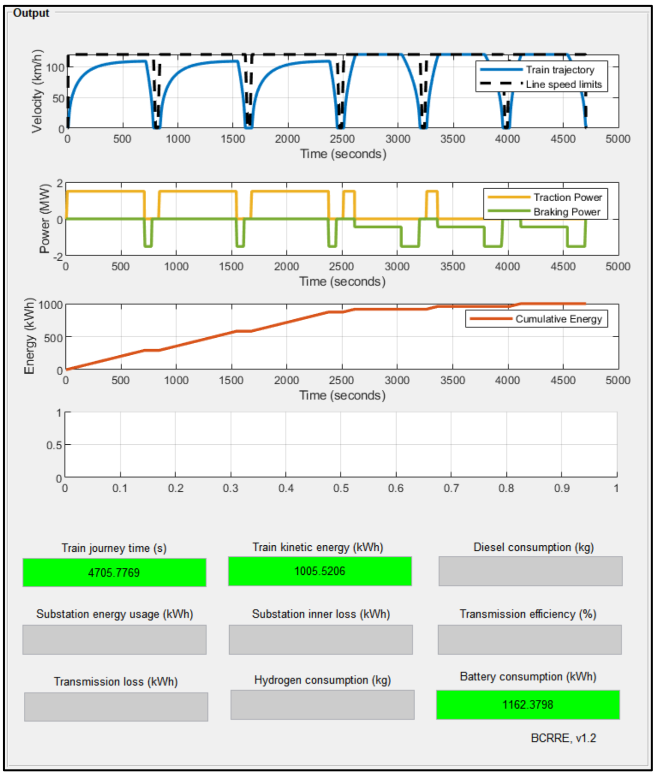


Table 4: Key characteristics of the passenger train

Characteristic	Value
Mass / tonnes	328.9 (including loco)
Davis equation	R = 3.3 + 0.11V + 0.0095 V^2
Aux. power / kW	120 (20 per coach)

Simulation results for the passenger train are shown in Figure 8.

Figure 8: Simulation results for the passenger train on the hypothetical 120 km route with stops



Points to Note:

- Much less braking is required in the passenger case, particularly uphill, as compared with the freight train. However, this does not mean that regenerative braking would not be of some use;
- The train does not reach the line speed on the 1 in 100 gradient; this might be achieved using additional power; and
- Full power is applied for a maximum of around 800 seconds (14 minutes), which is considerable time, if not as excessive as the freight duty cycle.

3.3 Shunting Locomotive Simulation

In order to test a shunting locomotive, basic characteristics were taken from a Ugandan Railways Class 62 (Henschel DHG1000) (see Figure 9). This loco has been selected as it is in use on the continent in a carriage shunting and trip working role. Although it is acknowledged that this locomotive has a hydraulic transmission [8], and may therefore be difficult to convert to battery or hydrogen-powered operation, this was seen as a suitable basis to establish local requirements. The key characteristics of this locomotive are shown in Table 5.

Figure 9: A Uganda railways Class 62 hauling a goods train [8]

Table 5: Key characteristics of the Ugandan Railways Class 62 [8]

Characteristic	Value
Engine Power	570 kW
Tractive Effort	Not known
Mass	Not known
No. of Axles	4
Track Gauge	1000 mm

In this scenario, the shunter was considered moving 6x 40 tonne carriages, and then returning to its original position, on level track for a km. This duty cycle was inspired by data gathered by project team members on the HydroShunter project and should be considered typical of shunting that occurs at passenger terminals of loco hauled rolling stock across the world. Details of these configurations are shown in Table 6. More information on the calculation of Davis equations is presented in appendix A.

Table 6: Key characteristics of the empty and loaded shunter configurations

	Empty (Shunter Only)	Loaded Train
Mass / tonnes	70	310 (including loco)
Davis Equation	R = 0.9 + 0.01V + 0.009V^2	R = 4.5 + 0.12V + 0.0092V^2

Simulation results for the shunter are shown in Figure 10 and Figure 11.

Figure 10: Simulation results for the loaded shunter train on the hypothetical 1 km route

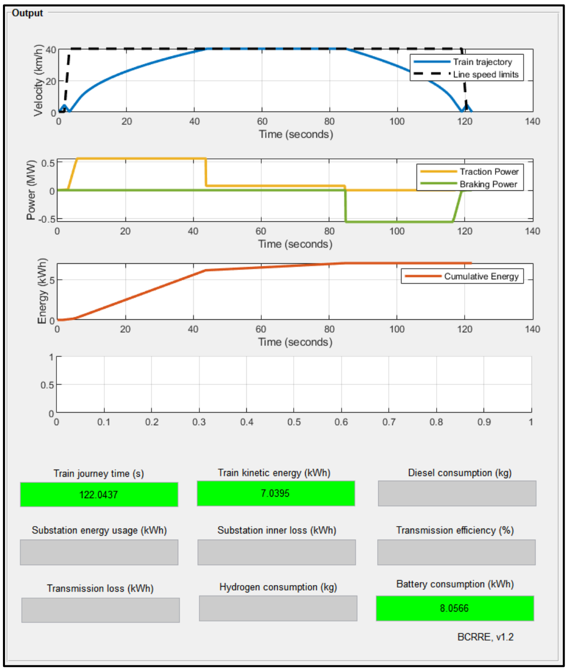
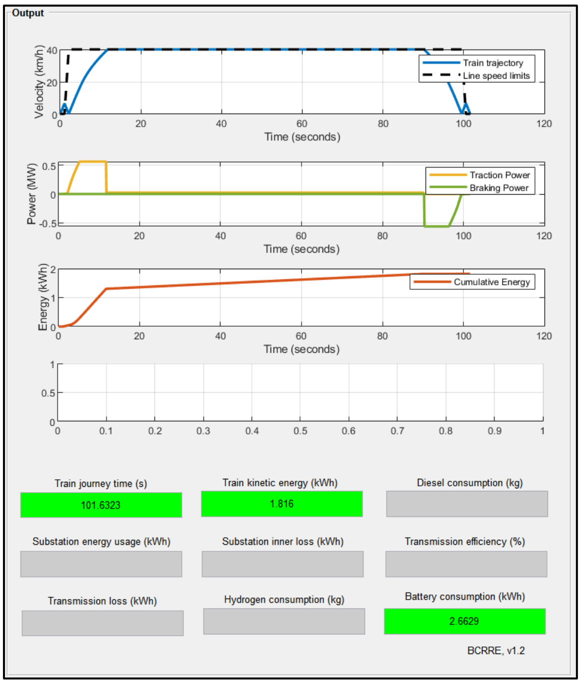


Figure 11: Simulation results for the empty shunter train on the hypothetical 1 km route



Notice:

- The loaded shunter takes far longer to reach the line speed of 40 km/h, but this is unlikely to be an issue with such low-speed work
- In both cases, full traction power is required for less than a minute before the train begins to coast
- This does not take into account time spent idling awaiting shunting duties; more energy may be required in reality.

3.4 Ultra Light Rail Train (ULR) Simulation

The Capability Analysis Report identified Severn Lamb's Ultra Light Rail (ULR) platform (Figure 12) as a potential option for some Sub-Saharan African routes Therefore, a single car ULR was also simulated, with the characteristics shown in Table 7, sourced from [8]. The ULR has been selected for analysis as it is ideally suited for novel traction systems due to the lightweight nature of the design, thus reducing the amount of energy and power needed to complete duty cycles.

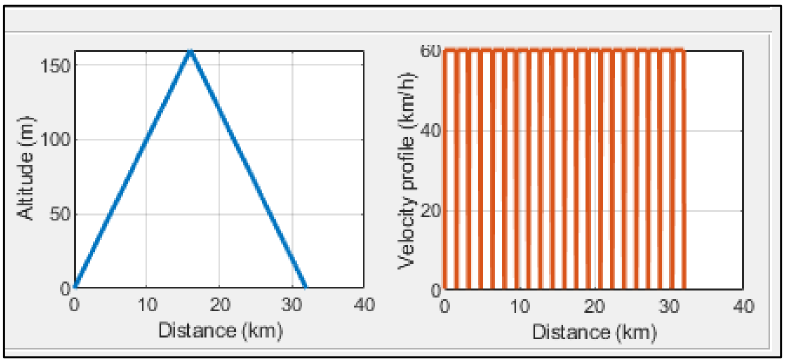
Figure 12: Exterior of ULR express vehicle [9]

Table 7: Key characteristics of the Ultra Light Rail vehicle [9]

Characteristic	Value
Engine Power	140 kW
Tractive Effort	Not known
Mass	22 tonnes
No. of Axles	4
Track Gauge	1435 mm

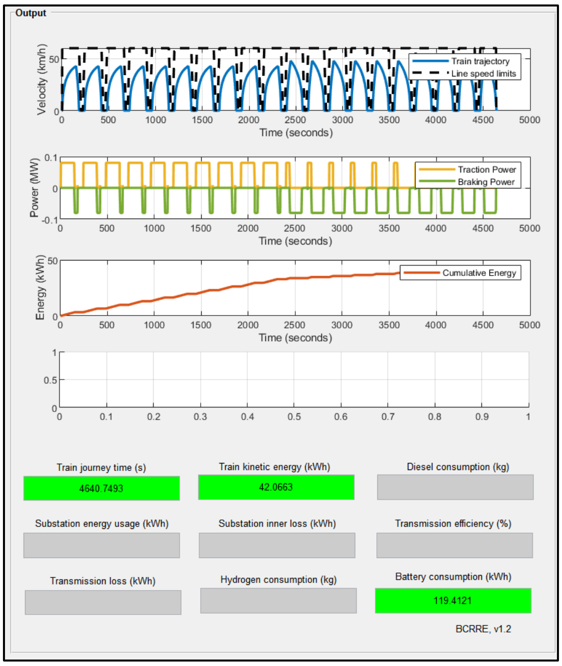
The single car ULR was tested on a 32 km route, with an uphill 1 in 100 gradient for the first 16 km, followed by a downhill 1 in 100 gradient for the final 16 km, and a stop every 1.6 km (see Figure 13). This route was inspired by the Kampala – Namanve route in Uganda.

Figure 13: Gradient profile for the 32 km route with stops for ULR testing



The simulation results are shown in Figure 13. It should be noted that the mass of the train was increased to 32 tonnes. The simulated mass includes a 10 tonne allowance for passengers and extra traction system equipment over the tare weight of the base diesel powered unit that was used as a benchmark. The Davis equation has been calculated to be **R = 0.9 + 0.018V + 0.0041V^2.** Simulation results are shown in Figure 14.

Figure 14: Simulation results for the ULR train on the hypothetical 32 km route



Notice:

- There are very frequent acceleration and braking events, both with relatively short durations; this may make regenerative braking and a hybrid system more viable; and
- The power proves insufficient to reach the line speed of 60 km/h in the required time, however, given the frequent stops, this is not surprising.

4. Simulated Train Requirements and Recommendations

The overall requirements for each type of train are summarised in Table 8. The figures for the required fuel specifications were created from taking the basic energy requirement from each simulation and multiplying it by the anticipated number of round trips between refilling or refuelling opportunities. An electric traction system architecture has been modelled, as this is the default of the STS.

As a measure to reduce optimism bias, and to account for extra activities such as shunting movements performed by the train engine, 20% extra energy has been allowed. This is added for redundancy as it is a standard allowance that is used by the project team when determining fuel requirements for HydroFLEX mainline trials.

This is then turned into a fuel requirement using the following factors:

- **Battery:** A 90% overall efficiency has been assumed;
- **Hydrogen:** A 40% overall efficiency has been assumed, with hydrogen energy density 33.3 kWh/kg;
- **Diesel:** A 20% overall efficiency has been assumed, with diesel energy density 9.7 kWh/L.

These figures have been selected based upon rounded down worst-case efficiency scenarios of each energy source with an additional factor added for the transmission losses within the powertrain [10][11]. The reason for the worst case assumption is to ensure that the amount of energy storage specification defined for each traction type will definitively be sufficient to achieve the necessary duty cycles.

As the differences in energy consumption between different types of final drive are small, such as modern electric, mechanical or hydraulic transmissions, the basic diesel electric simulation that the Single Train Simulator provides has been taken for the production of these benchmark figures.

Table 8: Overall energy requirements for the 4 locomotive types studied

Train Type	Freight Locomotive EMD GT22C-3M	Passenger Locomotive GE U26C	Shunting Locomotive Henschel DHG1000	Ultra Light Rail Train Severn Lamb ULR
Basic Energy Requirement	Loaded: 3779 kWh	1163 kWh	Loaded: 9 kWh	120 kWh
	Empty: 1394 kWh		Empty: 3 kWh	
Round trips between refilling	1 (1 empty trip, 1 full trip)	3 (3 trips out, 3 trips return)	5 (5 empty trips, 5 full trips)	5 (5 trips out, 5 trips return)
Distance between refilling (km)	240	720	10	320
Final Energy Requirement (+20% for eventualities)	6208 kWh required at wheel	8374 kWh required at wheel	72 kWh required at wheel	1440 kWh required at wheel
	= 6898 kWh of Battery Capacity	= 9305 kWh of Battery Capacity	= 80 kWh of Battery Capacity	= 1600 kWh of Battery Capacity
	= 467 kg of Hydrogen	= 629 kg of Hydrogen	= 6 kg of Hydrogen	= 109 kg of Hydrogen
	= 3200 l of Diesel	= 4317 l of Diesel	= 38 l of Diesel	= 743 l of Diesel

The recommended minimum specification is for each of the four types of locomotive simulated is as follows:

- **Freight Locomotive:**
  - Total installed power: at least 1900 kW continuous power;
  - Total usable on-board energy: 6300 kWh.
- **Passenger Locomotive:**
  - Total installed power: 1500 kW available for at least 15 minutes;
  - Total usable on-board energy: 8400 kWh.
- **Shunting Locomotive:**
  - Total installed power: 560 kW available for at least 1 minute;
  - Total usable on-board energy: 100 kWh.
- **Ultra Light Rail Train:**
  - Total installed power: 140 kW (per car);
  - Total usable on-board energy: 1500 kWh.

As has been stated previously, the metrics that have been produced in this simulation report will be used to define the minimum requirements for power generation and energy storage on each of the concept designs in each category that will be produced in this report. These designs will be presented on 31 Oct 2021 in the Architectural Designs Report (Deliverable 3.2).

5. References

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APPENDIX A: DAVIS EQUATION CALCULATIONS

A.1 – Freight Locomotive & Train

The freight locomotive modelled was the EMD GT22C-3M, and data for it was sourced from [4]. The first stage was to enter these data into the Davis calculation spreadsheet (see Figure A.1 and Figure A.2).

Figure A.1: Davis calculation spreadsheet input for the loaded freight train

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	110,000	1,800,000	1,910,000	kg
		121.0	1980.0	2,101	tons
N	Number of axles	6	60	66	
V	Velocity	30	30		mph
C	Streamlining value*	24	4.2		
a	Cross sectional area*	160.0	105.0		square feet
R	Resistance	744.0	5871.7	6,616	lb
		3310.8	26129.0	29440	N
		3.3	26.1	**29.4**	**kN**

Figure A.2: Davis calculation spreadsheet input for the empty freight train

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	110,000	450,000	560,000	kg
		121.0	495.0	616	tons
N	Number of axles	6	60	66	
V	Velocity	30	30		mph
C	Streamlining value*	24	12		
a	Cross sectional area*	160.0	105.0		square feet
R	Resistance	744.0	2381.4	3,125	lb
		3310.8	10597.2	13908	N
		3.3	10.6	**13.9**	**kN**

In this case, note the differences in the streamlining values for empty and loaded trains; this is based upon the empty and loaded values for coal gondolas in [5]. Note that the spreadsheet, for comparison purposes, calculates the resistance at 30 mph.

The following Figure x.3 and Figure x.4 show comparisons of the approximated resistance curves with equations A.1 and A.2 (for the loaded and empty trains respectively) with the curve generated by calculating the resistance using the Canadian National equation from [5].

$$\boldsymbol{R = 19 + 0.7V + 0.008V^2}$$ (equation A.1) (loaded freight train)

$$\boldsymbol{R = 9.3 + 0.2V + 0.011V^2}$$ (equation A.2) (empty freight train)

Figure A.3: Comparison of the Canadian National resistance calculation (orange) with the approximated Davis equation curve from equation A.1 (blue) (loaded freight train)

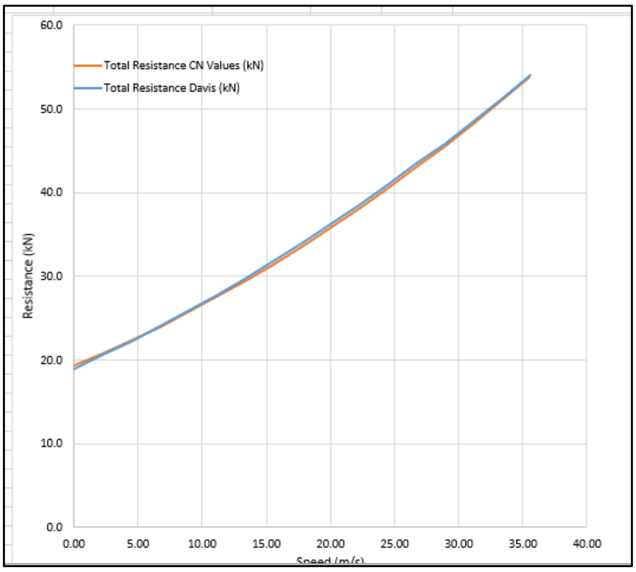
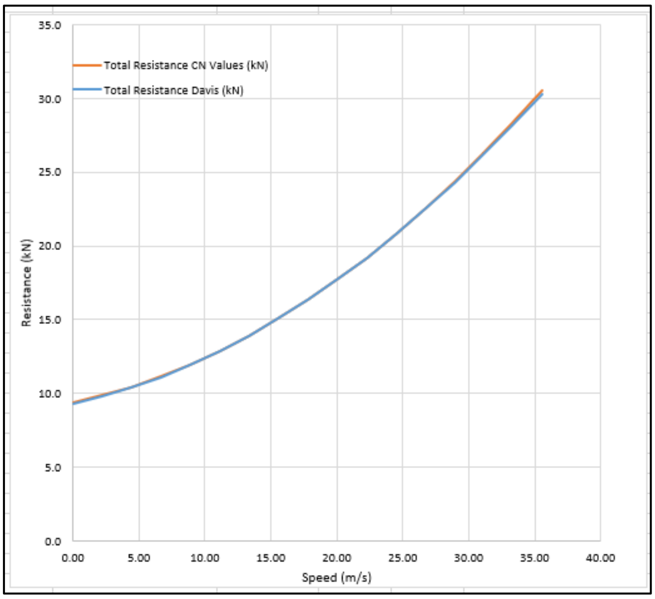


Figure A.4: Comparison of the Canadian National resistance calculation (orange) with the approximated Davis equation curve from equation A.2 (blue) (empty freight train)



Notice the close fit in both cases between the Canadian National formula and the approximation used for simulation.

A.2 – Passenger Locomotive & Train

The locomotive modelled for passenger duties was the GE U26C, with data sourced from [5]. The first stage was to enter these data into the Davis calculation spreadsheet (see Figure A.5).

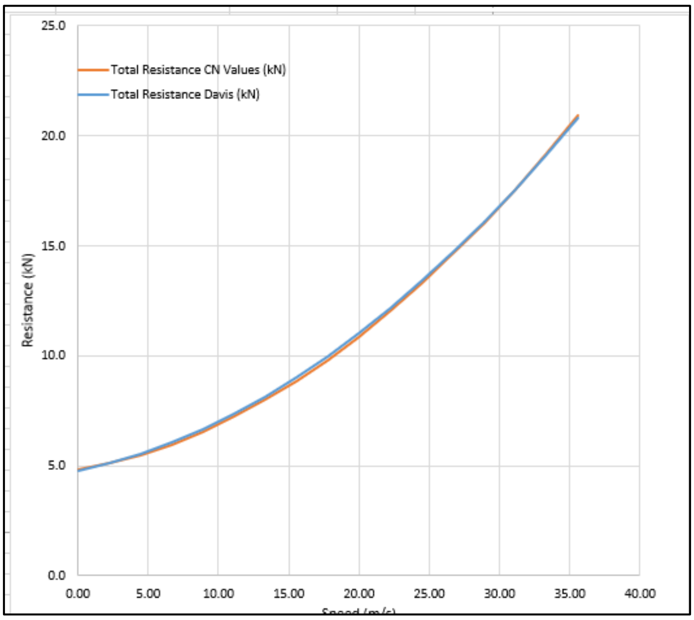
Figure A.5: Davis calculation spreadsheet input for the passenger train

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	88,900	240,000	328,900	kg
		97.8	264.0	362	tons
N	Number of axles	6	24	30	
V	Velocity	30	30		mph
C	Streamlining value*	24	3.5		
a	Cross sectional area*	160.0	130.0		square feet
R	Resistance	688.3	1106.6	1,795	lb
		3062.9	4924.1	7987	N
		3.1	4.9	**8.0**	**kN**

The following Figure A.6 shows a comparison of the approximated resistance curves with equationx.3 with the curve generated by calculating the resistance using the Canadian National equation from [5].

$$\boldsymbol{R = 4.8 + 0.13V + 0.009V^2}$$ (equation A.3) (passenger train)

Figure A.6: Comparison of the Canadian National resistance calculation (orange) with the approximated Davis equation curve from equation A.3 (blue) (passenger train)



Notice the close fit in both cases between the Canadian National formula and the approximation used for simulation.

A.3 – Shunting Locomotive & Train

Basic information on a typical African shunting locomotive was based upon a Uganda Railways Class 62 [7] although many values were assumed given the lack of data; for example, the "loaded" train is assumed to be made up of the shunter and 6 coaches, each of 40 tonnes, and the "empty" train just of the shunter itself. The first stage was to enter these data into the Davis calculation spreadsheet (see Figure A.7 and Figure A.8 for the empty and full trains respectively).

Figure A.7: Davis calculation spreadsheet input for the loaded shunter train

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	70,000	240,000	310,000	kg
		77.0	264.0	341	tons
N	Number of axles	4	24	28	
V	Velocity	30	30		mph
C	Streamlining value*	24	3.5		
a	Cross sectional area*	160.0	130.0		square feet
R	Resistance	602.4	1106.6	1,709	lb
		2680.7	4924.1	7605	N
		2.7	4.9	**7.6**	**kN**

Figure A.8: Davis calculation spreadsheet input for the empty shunter train (locomotive only)

CN Formula	R = (1.5 * W) + (18 * N) + (0.03 * V * W) + (C * a * V * V / 10000)				
		Loco	**Coaches**	**Total**	**Units**
W	Weight	70,000	0	70,000	kg
		77.0	0.0	77	tons
N	Number of axles	4	0	4	
V	Velocity	30	30		mph
C	Streamlining value*	24	0		
a	Cross sectional area*	160.0	130.0		square feet
R	Resistance	602.4	0.0	602	lb
		2680.7	0.0	2681	N
		2.7	0.0	**2.7**	**kN**

The following Figure A.9 and Figure A.10 show comparisons of the approximated resistance curves with equations A.4 and A.5 (for the loaded and empty trains respectively) with the curve generated by calculating the resistance using the Canadian National equation from [5].

$$\boldsymbol{R = 4.5 + 0.12V + 0.0092V^2}$$ (equation A.4) (loaded shunter train)

$$\boldsymbol{R = 0.9 + 0.01V + 0.009V^2}$$ (equation A.5) (empty shunter train)

Figure A.9: Comparison of the Canadian National resistance calculation (orange) with the approximated Davis equation curve from equation A.4 (blue) (loaded shunter train)

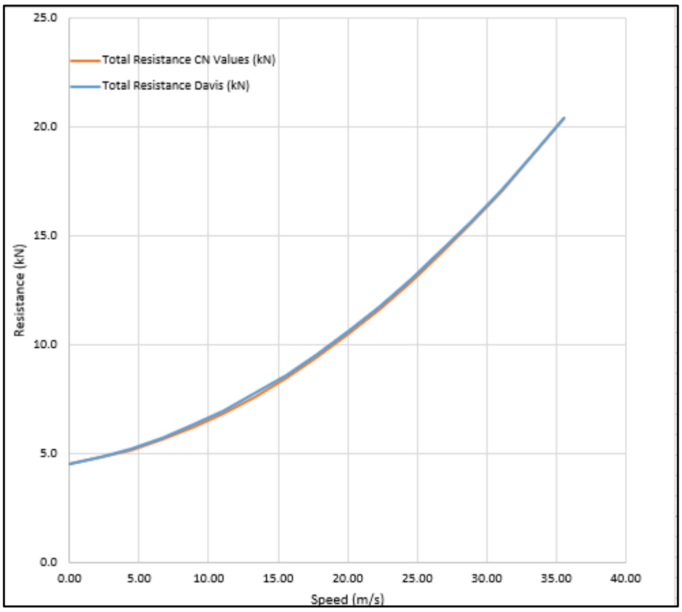
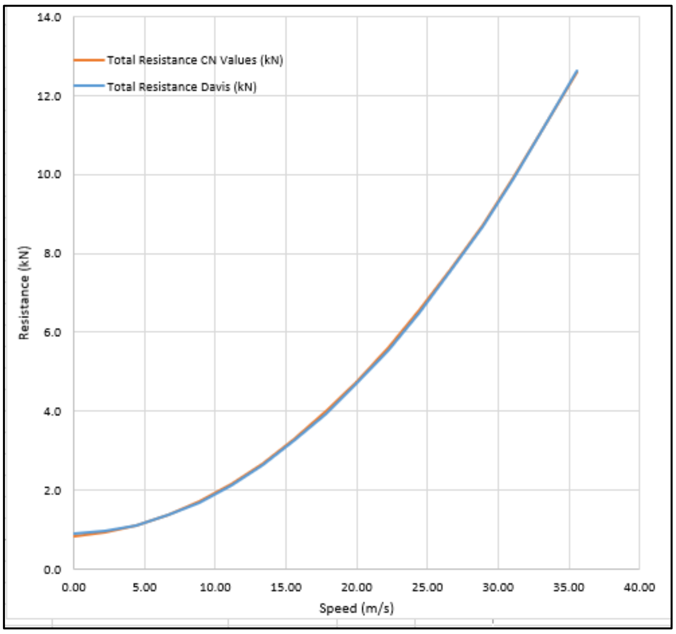


Figure A.10: Comparison of the Canadian National resistance calculation (orange) with the approximated Davis equation curve from equation A.5 (blue) (loaded shunter train)



Notice the close fit in both cases between the Canadian National formula and the approximation used for simulation.

A.4 – Ultra Light Rail Vehicle (ULR)

Information on the ULR was obtained from the data sheet in [8]. These data were inputted to the Davis calculation spreadsheet (see Figure A.11).

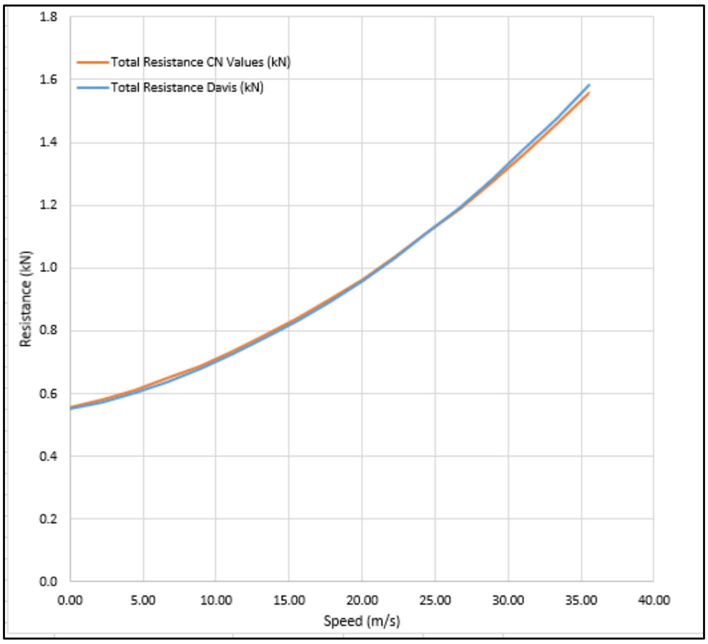
Figure A.11: Davis calculation spreadsheet input for the ULR vehicle

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	0	32,000	kg
		35.2	0.0	35	tons
N	Number of axles	4	0	4	
V	Velocity	30	30		mph
C	Streamlining value*	2	0		
a	Cross sectional area*	110.0	105.0		square feet
R	Resistance	176.3	0.0	176	lb
		784.4	0.0	784	N
		0.8	0.0	**0.8**	**kN**

The following Figure A.12 shows a comparison of the approximated resistance curves with equation A.6 with the curve generated by calculating the resistance using the Canadian National equation from [5].

$$\boldsymbol{R = 0.55 + 0.0095V + 0.00055V^2} \text{ (equation A.6)}$$

Figure A.12: Comparison of the Canadian National resistance calculation (orange) with the approximated Davis equation curve from equation A.6 (blue) (ULR train)



Notice the close fit in both cases between the Canadian National formula and the approximation used for simulation.

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