NEW TRACTION POWER TECHNOLOGIES TO IMPROVE THE MELBOURNE TRAM NETWORK

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SUMMARY

The Melbourne Tram Network is the largest in the world with 250 kilometres of track and 490 trams. The city's fast-growing population has triggered a new approach to improve sustainability. The New Rolling Stock Program managed by Department of Transport Victoria included an out-of-the-box option analysis for traction power supply. It was undertaken to address forecast patronage growth and retirement of the high floor tram fleet while increasing the energy efficiency drawn from the Traction Power Supply. The effort included simulation of many combinations of standard and new technologies both on-board and wayside to assess their outcomes at both location and network levels. To avoid drastically increasing energy consumption, introducing new vehicles with on-board energy storage and optimising sectioning of the electrical distribution was found essential for a substantial improvement in energy management. The proposed upgrades enable better recovery of braking energy, minimising losses through local on-board re-use preference over transferring it to other trams. It means capital minimisation upgrades to key power network assets. To complete the improvement, an innovative energy management of the on-board energy systems will be required from tram suppliers to optimise both the on-board energy saving and the overall Traction Power Supply efficiency. Optimising upgrades necessary to supply the additional and higher passenger capacity vehicles included some additional substations. However, in some specific areas, side feeders and wayside energy storage systems were a cost-efficient part of the solution to avoid substation land acquisition. Simulations showed that even with the increase in passengers carried, the network energy consumption would be no greater than the present-day level. These systemic and holistic upgrades will reduce investments needed to adapt the network to the population growth in the future.

1. INTRODUCTION

The Melbourne Tram Network (MTN) is the largest in the world with 250 kilometres of double track and 490 trams. Due to strong population growth in recent years the network is now reaching capacity. Projections estimate that by 2051, Melbourne's current population of 5 million people will increase to 7.9 million. To support this level of growth, the public transport system must be upgraded to provide increased capacity and additional routes provided, to align with population growth areas.

To improve network capacity, the New Rolling Stock Program managed the Department of Transport Victoria, will introduce approximately 250 Next Generation Trams (NGT) to the network. These new higher capacity, low floor trams will replace the existing high floor fleet which are approaching their end of life.

Trams on the MTN are 75 per cent operated in multiple-use road environments including cars and cyclists. 25 percent comprises segregated tram only operation sections. Powered by the Traction Power Supplies through overhead lines, trams require energy for:

- Traction / vehicle propulsion; and
- Auxiliary equipment like passenger information; heating and air-conditioning.

Technological improvements available have resulted in key on-board systems (such as traction and braking systems) being more energy efficient than those fitted to previous generations of rolling stock. Combined with the use of lighter materials for vehicle construction, this results in the traction / vehicle propulsion component consuming less than previous generations of vehicles, per unit length.

Modern on-board equipment and features provide an improved passenger experience, including air-conditioning, higher acceleration performance, passenger information systems and many other sub-systems that did not exist 20 or 30 years ago. These improvements partially offset the reduction in the traction / propulsion system energy consumption.

In addition to the introduction of new trams, to further increase network capacity service frequency will increase on high demand routes increasing energy consumption on these routes.

2. PROBLEM STATEMENT

The introduction into service of new modern trams with increased service frequency will require a significant additional amount of energy to be delivered to the network. The main goal of the project was to identify the right solutions to achieve this in a sustainable and cost-effective way.

2.1 Auxiliary power consumption

The high floor trams to be retired are fitted with minimal on-board equipment. Maximum auxiliary power draw varies between 4 kW and 32 kW dependent on vehicle length and HVAC provision.

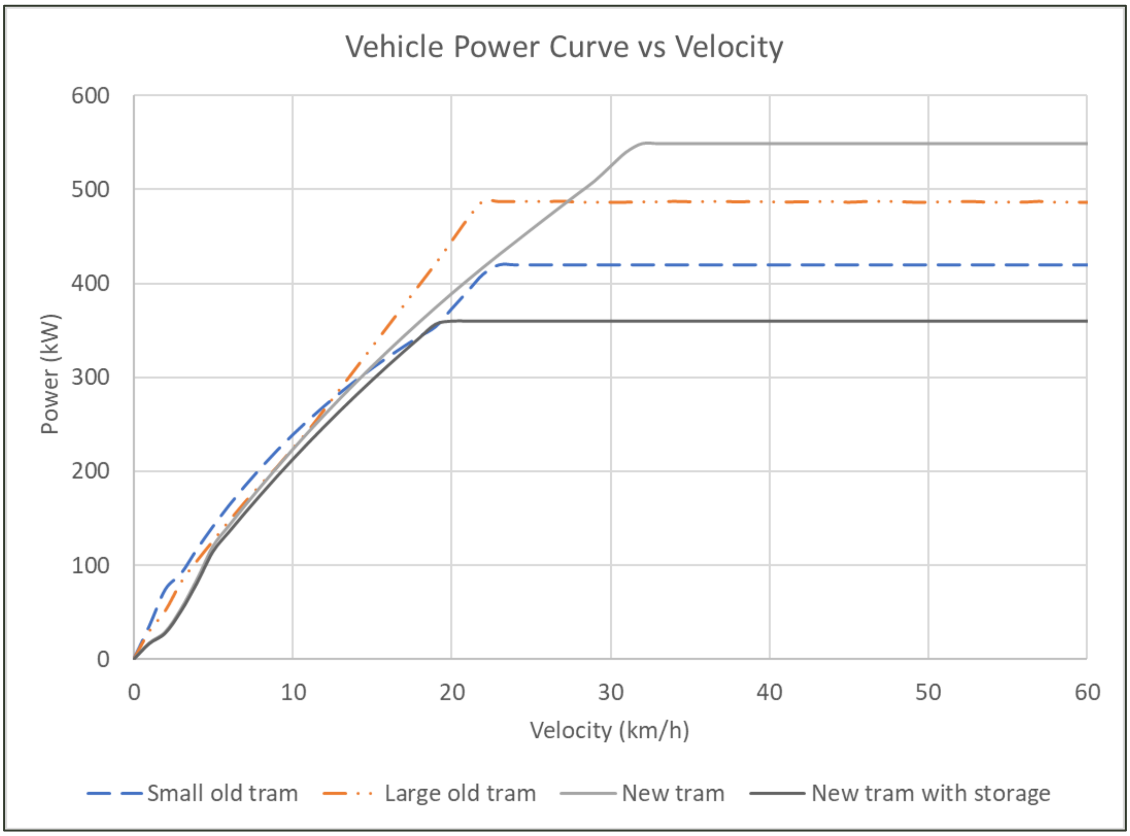
In comparison, new modern trams are fully air-conditioned and fitted with modern on-board equipment. They are expected to have a maximum auxiliary power draw of 50 kW which represents an increase of 52% from the longer high floor trams to be retired and 11 times more than the shorter variant.

2.2 Traction power consumption

High floor trams have a maximum traction power of 420 kW for the short variant and 486 kW for the longer variant.

In comparison, new modern trams with higher passenger capacity fitted with standard traction-braking technology would have a maximum power of 550 kW which represents an increase of 30% from the shorter high floor trams and 15% from longer high floor trams as shown in the vehicle power curves for each group of like trams as shown in Figure 1.

Figure 1 - Vehicle Power Curve



3. BASELINE ENERGY CONSUMPTION

To ensure rolling stock can operate at full performance, the traction power supply network must be able to provide the required maximum power and energy. While this characteristic is available from tram supplier datasheets, the energy consumed by the rolling stock over the time is not readily available. As such the team had to establish these figures for the overall consumption of the network. The Department of Transport Victoria owns a full TrainOps® model of the Melbourne Tram Network. This model has been jointly developed by the Department and LTK using LTK's operation and electrical network simulation software TrainOps®. Using the results of network simulation, the energy consumption of the existing network has been evaluated and compared with the energy bill.

To determine the current energy consumption of the overall Melbourne Tram Network, a model was developed to characterise the energy consumption of all tram types used on the Melbourne Tram Network. This model was adapted from the methodology developed by the Optimal Strategy to Innovate and Reduce Energy Consumption In Urban Rail Systems (OSIRIS) rail research project (Iordache 2013). Completed in December 2014, OSIRIS consisted of 17 project partners including major stakeholders such as railway manufacturers, public transport operators and universities. Its goal was to enable a reduction in the overall energy consumption within Europe's urban rail systems by 10% from 2012 levels by 2020.

Workshop 1 of the OSIRIS project identified a method for standardising duty of rolling stock and building energy consumption figures. Adapting this methodology, the energy consumption of all tram types used on the MTN was established. Single vehicle runs were simulated on the same chosen route, with traction and auxiliary consumption integrated and linearised per kilometre which enabled the maximum energy consumption for every tram class to be determined.

The whole network was then simulated using the existing rolling stock to establish the energy consumption of the then present 2018 services. The network was then simulated using new trams operating at a higher service frequency to establish the baseline energy consumption for complete low-floor fleet in the year 2031. The total MTN energy consumption would rise from 2018 operations with existing ageing fleet of 153 GWh to 200 GWh for 2031 all low-floor fleet without OESS at the increased service frequency planned. This is an increase of 30 per cent, assuming no wayside or on-board energy storage systems.

4. Engineering approach

In order to run new modern vehicles on the network at increased service frequency, the maximum power and the energy consumption will increase, requiring costly upgrades to the network. In order to determine the preferred upgrade approach, an options analysis was conducted to analyse the benefits of new proven technologies and standard techniques to ensure upgrades were undertaken in a sustainable manner and cost effectively.

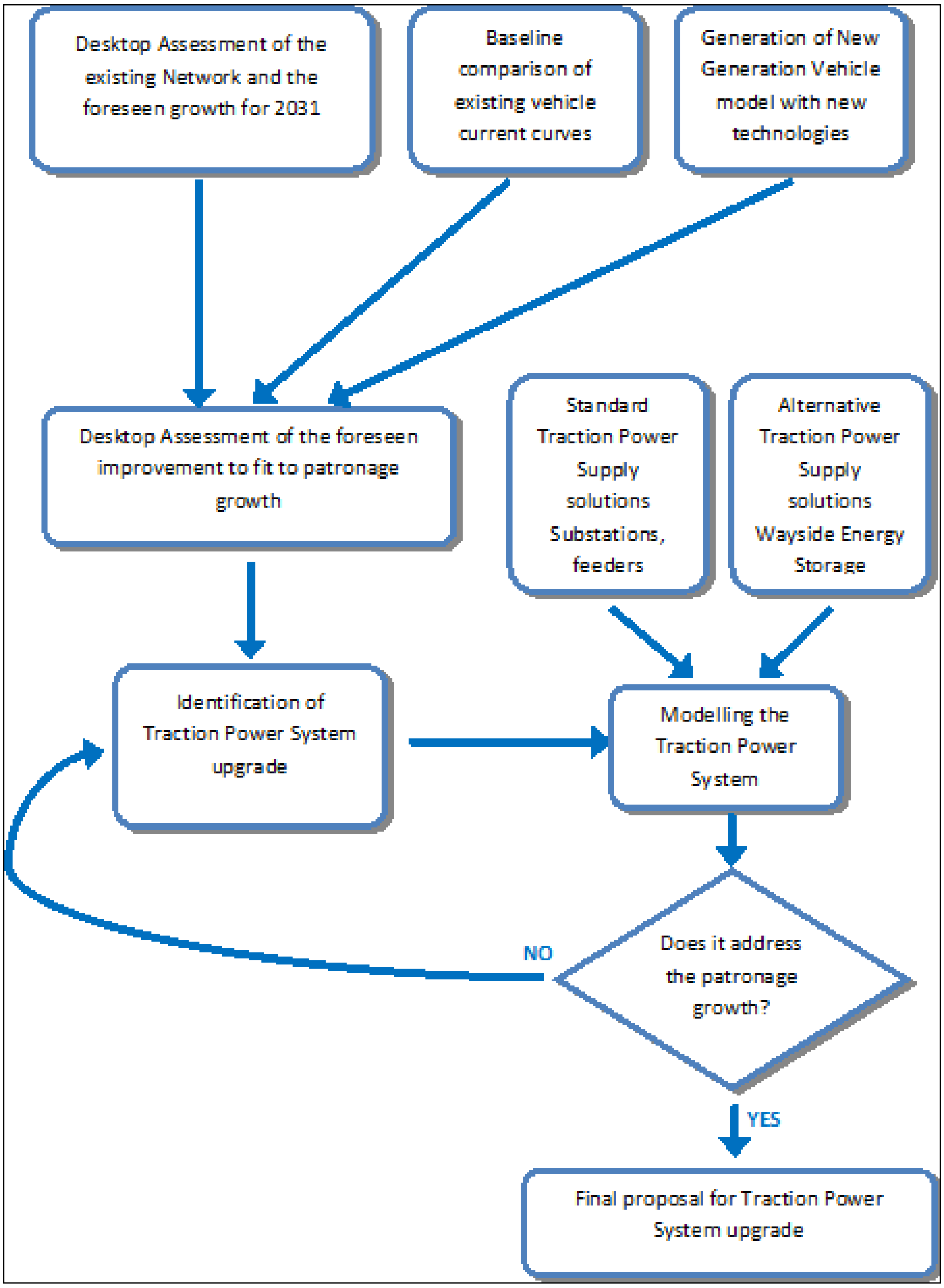
4.1 Engineering Process

Rather than addressing the increase in power and the energy consumption by adding only substations, an innovative solution mitigating standard techniques (substations, feeders, re-sectioning) has been produced. This includes more recent proven technologies like on-board and wayside energy storage.

An overview of the process is shown on the chart of Figure 2. At first the team conducted a desktop analysis of the Traction Power network, starting with the existing network and then incorporating the route upgrades and the new tram acquisitions. Based on the existing TrainOps® model of the MTN, scenarios combining standard and new technologies have been modelled and then compared under normal system operation and degraded operation (N-1 rectifier outage conditions). Numerous simulations were necessary to achieve the optimal outcome.

A mix of the best options for each area of the network have been combined to simulate the optimum network, all offering the same coverage as the standard approach along with additional improvements. These will enable less energy consumption, reduced impact on land acquisition, and sustainability for future operational growth.

Figure 2 : Engineering Process



4.2 TrainOps® Modelling

The TrainOps® model has been upgraded with the network improvements necessary to address the increase in power and the energy consumption. Standard traction power upgrades were then simulated with the model. As the TrainOps® software did not support energy storage models at the time of the project, wayside and on-board tools were built separately to design the new tram traction-braking characteristics emulating energy storage functionality. This new tram with OESS then replaced the new tram without storage in the TrainOps® model.

Figure 3 is a TrainOps® model output that shows the pantograph voltage of trams running on an existing route, modified to fit the patronage growth as seen for 2031 before traction power supply upgrades. As can be seen, the voltage doesn't meet the standard voltage criteria of the network. Figure 4 shows a simulation with Traction Power Supply Upgrades that allow the line voltage to meet the criteria and to safely operate the route.

Figure 3 : Simulation of a route in 2031 without Traction Power Upgrade

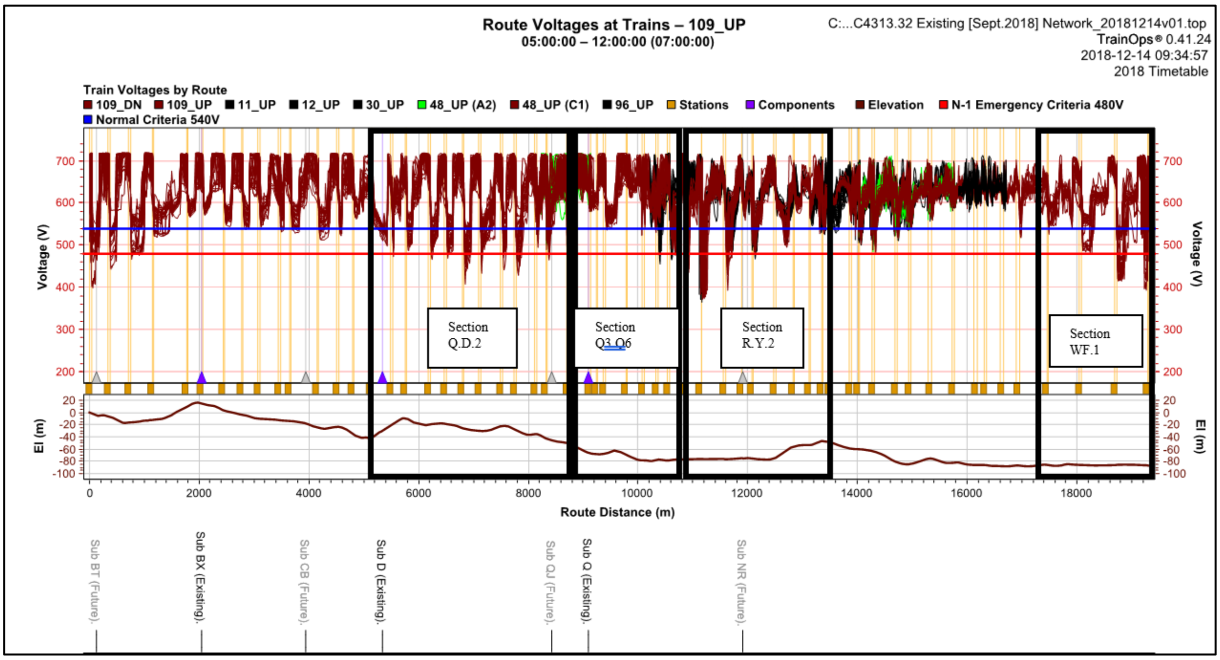
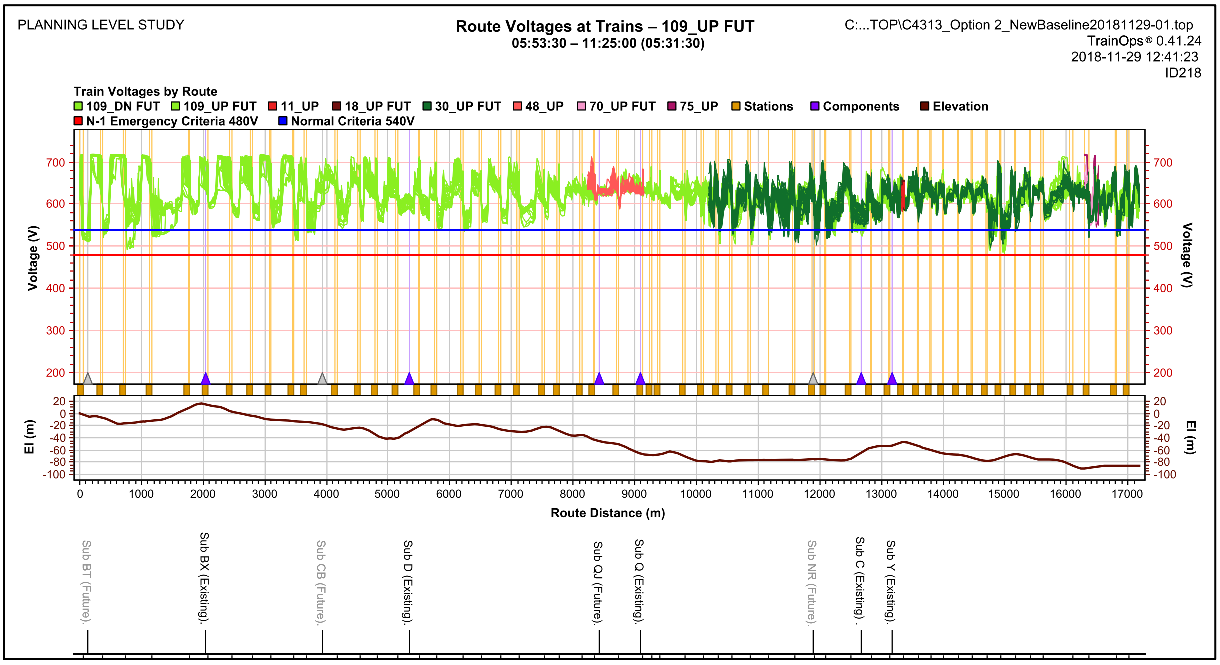


Figure 4 : Simulation of a route in 2031 with Traction Power Upgrade



5. TECHNICAL SOLUTION

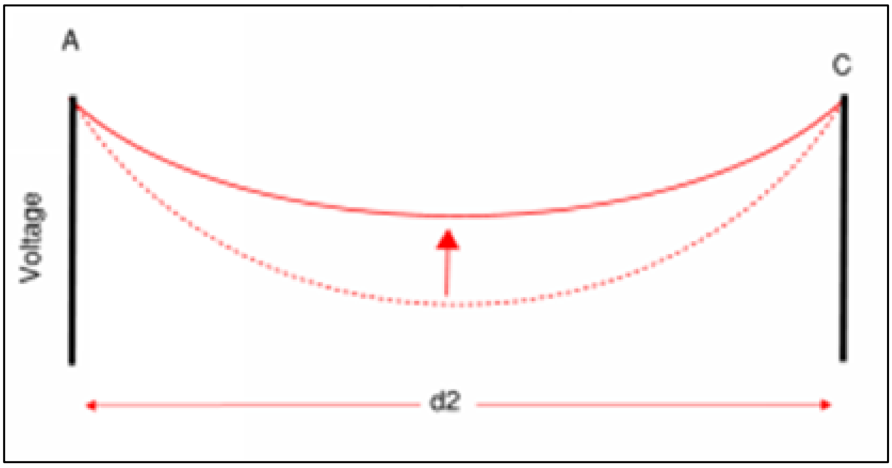
5.1 Option 1: Standard Traction Power Supply Solutions

The standard base approach to increase power supply to a rail network is to install additional traction power substations. Installing substations in a dense city is a very difficult and costly task as it requires land acquisition and has long lead time to deliver the solution.

Therefore, to minimise the number of new substations required to meet the increase in power demand, other standard traction power technologies have been evaluated. The two primary technologies that were assessed were sectioning optimisation and side feeders.

- Sectioning Optimisation: on a large legacy network such as Melbourne, the power is distributed from the substations to different routes by sections for fault management. One route is made of several sections and some sections are connected to other route's sections. To allow a better energy exchange from braking trams to accelerating ones, the sectioning needs to be reviewed. This is essential with more powerful trams. Optimising sectioning of the electrical distribution means that the highest current paths between trams must be assessed and their resistance minimised to reduce losses. This process included the study of connections between two separate routes when a current path can be improved. Connecting routes that were not connected before requires the re-design of the fault detection to suit the new connected routes and the trams operated on these routes.
- Side Feeders: Reducing the line resistance by adding side feeders (parallel cables) can be specifically efficient when running a higher power consumption service. The addition of side feeders reduces the line voltage drop between substations. This can be thought of as tightening a hanging wire with each additional feeder providing a diminishing return. Figure 5 shows how an additional side feeder, or a reduction in the effective resistance between the substations, flattens the voltage profile.

Figure 5 : Variation of voltage profile with section length and power upgrade strategies



5.2 Option 2: Alternative On-board Storage Solutions

Many tram manufacturers can now supply their trams with On-board Energy Storage Systems (OESS). Several new tram or Light Rail Train lines, mainly in Europe and China, use OESS to run without being powered by overhead wires. This is known as wire-free operation.

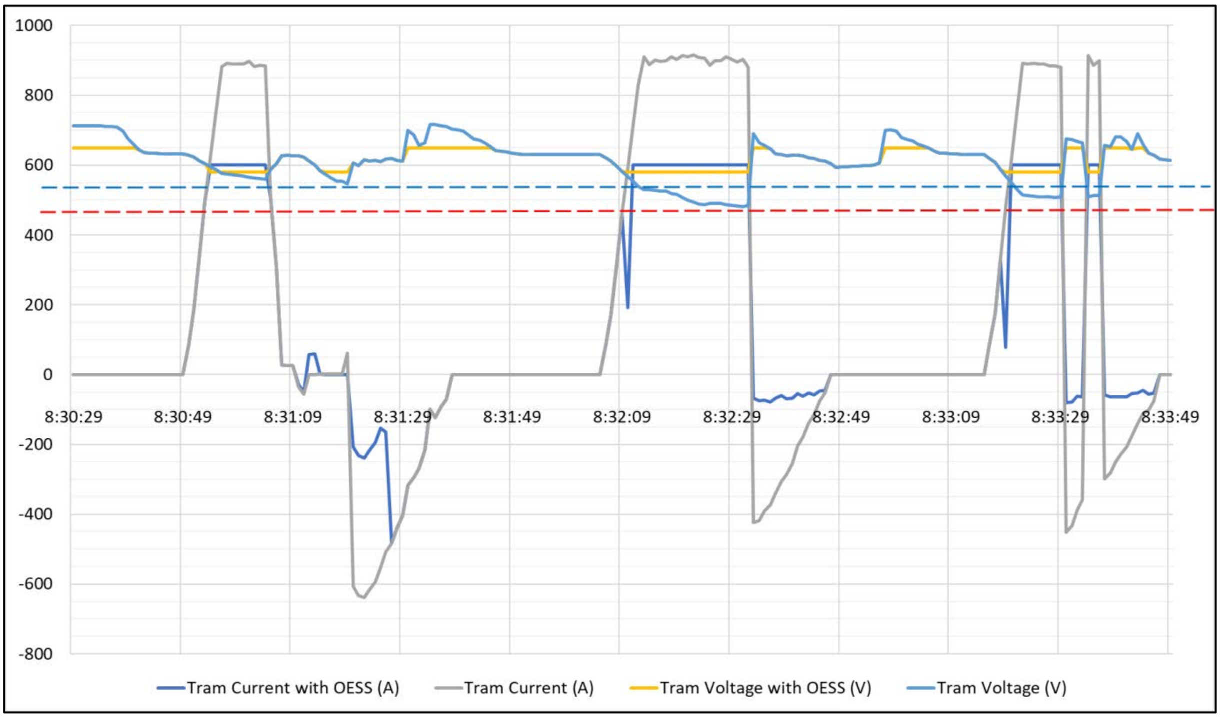
Unlike European networks which are new modern single lines with limited need to reduce peak power, the MTN is relatively complex with many routes, most of them shared with road traffic. While wire-free operation is the typical reason for implementing OESS, in the Melbourne context the primary purpose would be to reduce both energy consumption and peak power demand. Several trials were undertaken from 15 years ago to evaluate the outcomes of supercapacitor based OESS for energy saving and voltage stabilisation as described by Moskowitz & Cohuau (2010). Since then, OESS have been adopted by the market when the need was revealed and OESS characteristics have continued to be updated over the past 10 years as energy storage component technology has continued to evolve.

The energy saving figures and peak power reduction comparisons presented by (Frohlich & Klohr 2008) served as a basis for building the characteristics of a NGT with an OESS.

The OESS of the NGT has been characterised to limit the tram maximum power to 360 kW under the network voltage of 600 V as shown on Figure 6, 25 per cent lower than the longest length old high floor tram.

The NGT with an OESS was simulated on the same route used to characterise all the other trams and compared with a new tram without OESS. Figure 6 shows how the OESS limits the maximum power therefore reducing the current drawn from the overhead wire from 900 A to 600 A. Additionally, the OESS reduces voltage sags, keeping the line voltage higher than the network voltage limit of 540 V, shown as a blue dash line on Figure 6.

Figure 6 : OESS voltages and currents



In addition to the network stability improvement provided by an OESS installed on new trams, OESS will also provide the opportunity to remove short wire sections, with the new trams powered solely by the OESS rather than the overhead line. This is beneficial in sensitive areas like crossings and under low bridges. While not competing with wire-free trams operating longer wire-free distances, approaches with suppliers must show what length of wire-free section their latest energy storage technology will allow operation through.

To further enhance the benefits of OESS, it is proposed that manufacturers implement an innovative energy management system to manage in real time the best outcome between the on-board energy saving, traction power supply efficiency and short wire-free operation.

The installation of OESS can also bring a side effect to passenger comfort and safety. When a tram loses power from the overhead wire during acceleration, passengers experience a discomforting change of acceleration also called jerk. It is the derivative of the acceleration. The situation can cause passengers to lose their balance as described by Powell & Palacin (2015). Standard traction-braking equipment can't deal with this situation as the energy that would be needed to allow a more moderate variation in acceleration cannot be provided by a simple capacitor filter. However; this energy can easily be provided by the OESS as it represents only two to three per cent of its capacity.

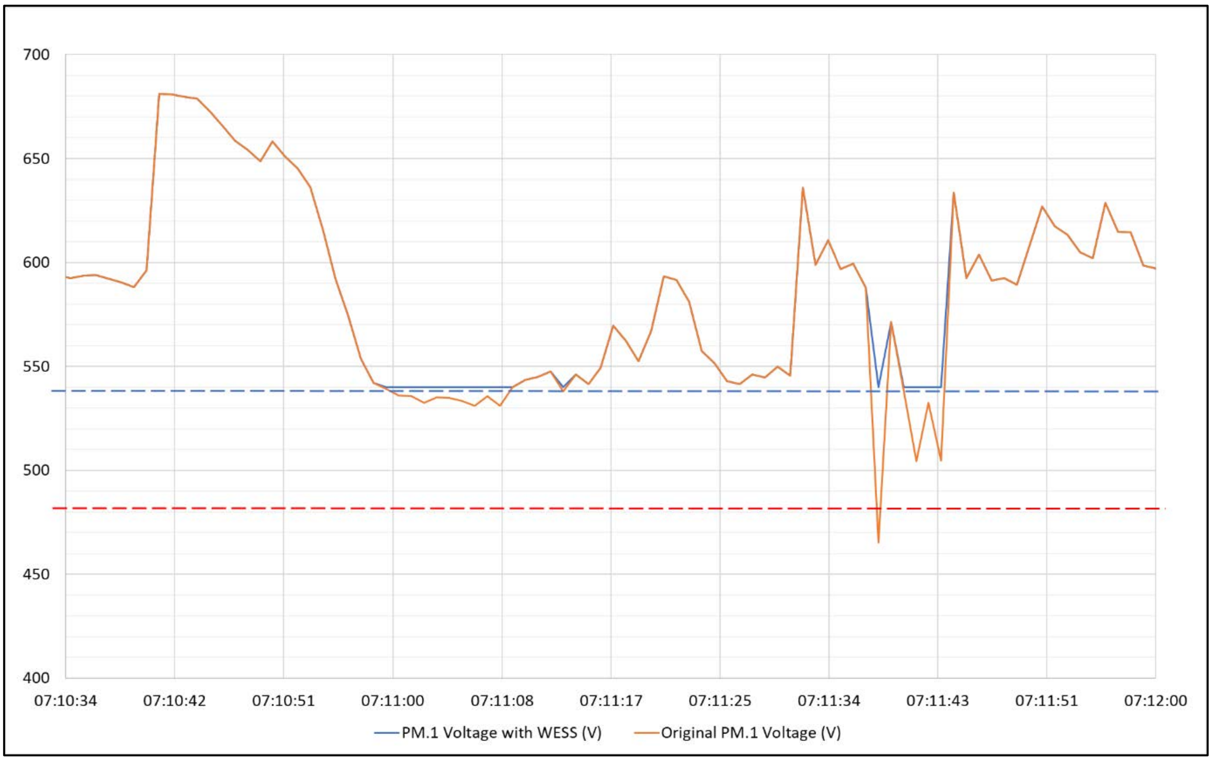
Lastly, it should be noted that increases in the energy density and specific power for the latest Lithium-Ion chemistry and hybrid Electric Double Layer Capacitors (EDLC), also known as supercapacitors, is advancing rapidly. It is expected that within 4 years these advancements will enable wire-free operation over longer sections without even requiring power supply distribution along the route except for both ends of the lines (Croset 2018).

5.3 Option 3: Alternative Traction Power Supply Solutions

For routes that will not be operated with NGT but will see an increase of service frequency and tram size (due to the cascading of existing trams), voltage sags and peak power are issues that need to be solved by other means. The guidelines for braking energy recovery systems in urban rail networks issued by Devaux, F.O., Tackoen (2014), as well as the results of trials summarised by Croset (2016) in Optimizing Urban DC Supply Networks, were used to define the routes where an optimum outcome would be delivered by a Wayside Energy Storage System (WESS). A WESS is a device installed at an optimal position alongside the track capable of recovering braking energy from multiple nearby trams, delivering back the energy when needed. The needs are defined by the local set up defined to power tram accelerations nearby and / or stabilising the line voltage. The maximum distance that can be covered by this WESS depends on the sectioning, the power of the substations, the power of the trams and the resistance of the line. Built from line simulations a tool was set up to define the size and the main characteristics of the system. Several routes have been identified where a standard substation could be replaced by a WESS. To assess the suitability of a WESS, identified routes were simulated with a standard substation then with a WESS. The results demonstrated that two routes would benefit from the installation of a WESS instead of a substation. Figure 7 represents an electrical single wire diagram for studying the use of a WESS at Port Melbourne (PM) to enable the introduction of larger trams on this route. Figure 8 shows the effect of a WESS keeping the line voltage within the standard values, higher than 540 V shown as a blue dash line.

Figure 7 : WESS studied area

Figure 8 : WESS effect on voltage



6. Conclusion

The operation of new modern trams at an increased service frequency requires significant additional amount of energy to be delivered to the network. Rather than solely achieving this through the addition of new substations, three primary options were assessed to determine how this could be achieved cost effectively across the network.

The core means of addressing the increased energy demand on the MTN has been the introduction of an NGT with an OESS and dedicated with a dedicated on-board energy management system. While some additional substations would still be required even with the implementation of new trams with OESS, the number of substations required could be minimised further through the addition of side feeders and WESS at selected locations.

By considering the entire network, a blended use of technological solutions has been adopted to meet an increase in energy demand cost effectively and reducing land acquisitions required for new substations.

Following the validation through TrainOps® simulation of the optimum blend of solutions the new network consumption has been calculated and compared with today's consumption and 2031's consumption without OESS. The consumption as calculated for the optimum blend of solutions shows only a mere 1% increase as shown on Figure 9, compared with today's baseline consumption. In comparison, a 30 per cent increase above today's baseline energy consumption could be expected for new trams without OESS.

Figure 9 : Total Network Optimum Consumption

Estimate of Total Network Energy Consumption	GWh
2018 (current) operations with existing ageing fleet	153
2031 New trams **without** OESS at increased service frequency	200
2031 New trams **with** OESS at increased service frequency	156

By assessing both conventional and innovative technologies, the optimum blend of solutions has been established that will transform the journey in an NGT into a vibrant journey attracting more passengers to the world-famous MTN. The proposed solutions will improve the energy consumption and limit the investments needed to adapt the network to the population growth anticipated in the future.

Department of Transport Victoria has started an interactive design process with several manufacturers to leverage the maximum benefit to Victoria's manufacturing industry and create more jobs for a flexible and diverse workforce.

The design process will provide the Government with several well-informed proposals to choose the best new trams for Victoria's needs.

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