Efficient Placement of Charging Infrastructure within Existing Bus Networks

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Abstract

The purpose of this research project was to review the current status of electric bus technology and build a mixed-integer optimisation model that aimed to minimise the cost of electric bus charging infrastructure.

The technology analysed was very short range, ultra-capacitor electric buses that can flash charge at en route charging stations. To minimise total charger cost, the model efficiently distributes charging stations at existing bus stops, such that simulated bus energy requirements are met.

The project focused specifically on Auckland's city-bound bus routes that run along Mt. Eden and Dominion roads. The exact number and placement of chargers along these routes is a function of user defined bus and charger parameters, and an upper bound on allowable delay to normal service caused by charging.

The project also demonstrated the importance of accurate energy consumption modelling for this technology. While the results obtained are specific to one electric bus technology and existing bus public transport network, this project puts in place a model framework that could be adapted to other transport networks or bus technologies.

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1 Background

Electric bus technology is making significant improvements in areas such as energy efficiency, greenhouse gas emissions, passenger comfort and local air pollution, and this is driving increased investment in the technology (Mahmoud, Garnett, Ferguson, & Kanaroglou, 2016).

Numerous major cities around the world have demonstrated a commitment to electric bus technology. For example, London's bus fleet now includes around 2800 electric buses (Transport for London, 2017). Changes are also taking place in New Zealand. Auckland mayor Phil Goff, recently made a pledge, alongside 11 other large international cities, to only purchase fully electric buses from 2025 (Williams, 2017). In Wellington, NZ Bus is working to refit existing buses with turbine hybrid systems through a US$30m deal with American company Wrightspeed (Green, 2016).

New Zealand is well suited to electric bus usage for three main reasons:

1. *The main mode of public transport is the bus*. In 2015, nearly 80% of all trips made on New Zealand public transport took place on the bus.
2. *Bus ridership is growing*. Nationally, there has been an average increase of 3.4% per annum since 2001 (Ministry of Transport, 2016)
3. *Sustainable electricity generation*. Around 80% of New Zealand's electricity, is generated through renewable sources (MBIE, 2016).

The main barriers to electric bus uptake are increased cost, increased vehicle mass, and reduced range. However, well-designed electric bus systems, tailored to specific operating environments, can overcome these barriers (Mahmoud et al., 2016; Miles & Potter, 2014). This is where optimisation can help.

1.1 Project Aims

There are three main aims for this project:

1. Model electric bus energy consumption for a selection of Auckland bus routes.
2. Optimise the number and position of en route charging stations needed to meet these energy requirements, for very short-range buses. At the same time limit any delay to normal service that charging causes.
3. Design the optimisation model such that it can be easily adapted to alternative electric bus specifications, technologies, and different transport networks around the world.

1.2 Broader scope

For this project, only one bus technology has been investigated. However, if this project were replicated for a range of technologies, transport providers would have a location specific tool, enabling them to compare bus technologies for targeted routes within their networks. This could: reduce risk for transport agencies looking to invest in new technology; help transport agencies operate electric buses on the most appropriate routes; and, ultimately increase the uptake of more sustainable technologies.

2 Electric Bus Technology

Electric buses use an electric motor to deliver either all or partial vehicle propulsion. Different types of electric buses vary in how the electricity is generated (MRCagney Pty Ltd & Callaghan Innovation, 2017).

1. *Hybrid electric buses* use an onboard generator to capture kinetic energy during braking and (under some configurations) directly charge batteries and/or ultra-capacitors using the internal combustion engine.
2. *Battery* and *ultra-capacitor electric buses* require electricity to be transferred to the bus intermittently during operation and/or during overnight depot charging.
3. *Fuel cell electric buses* generate electricity onboard using fuel cells.
4. *Trolley electric buses* receive electricity during operation, via overhead wires.

2.1 Ultra-Capacitor Electric Buses

This project focused on fully electric buses that use ultra-capacitors as the sole source of onboard energy, and recharge at charging stations. However, it should be noted that ultra-capacitors, as an energy storage device, can be employed in all of the electric bus technologies listed above (Bubna, Advani, & Prasad, 2012; Hamilton, 2009).

When compared with batteries, ultra-capacitors have increased life cycles, a higher power density and faster charging or discharging times (Benz, 2015). They also have a long life expectancy, are relatively inexpensive, and can operate in a very wide range of temperatures (Chandramowli, 2014).

One significant disadvantage of ultra-capacitors is their lower energy density: an ultra-capacitor can hold only 10% of the energy that a lithium-ion battery of equivalent mass can hold (Benz, 2015). Due to this low energy density, ultra-capacitor electric buses must recharge very frequently during service. Usually overhead charging systems are utilised at bus layover points and en route bus stops (Chandramowli, 2014). While ultra-capacitors cannot hold a large amount of energy, charging can take place at very high power ratings (Hamilton, 2009). Charge times of 30 seconds can supply sufficient energy for five kilometres of travel (Chandramowli, 2014).

3 Literature Review

Only a small amount of literature exists on charger location optimisation models for bus networks. However, the somewhat related problem of distributing electric vehicle (EV) charging points (for commercial or private vehicles) is well documented (see the full project report (Stewart, 2017) for further discussion of EV literature). The important difference with bus charger distribution problems is that buses travel along fixed routes to known schedules.

Kunith et al. (2017) create a mixed-integer linear optimisation model to minimise both the number of charging stations and bus battery capacity. The model solves for all routes, trips and individual buses in a network and therefore gives insight into the total cost of switching to an entirely electric bus system.

Xylia et al. (2017) also formulate a charger location mixed-integer problem for an entire network. This project targets the Stockholm bus network. A point of difference to the aforementioned article is that Xylia et al. (2017) do not minimise bus battery capacity, but instead model a range of bus and charger technologies: biodiesel, biogas, and battery electric with either conductive or inductive charging systems. The model then investigates the trade-offs between solutions that minimise total cost against solutions that minimise total energy consumption across the bus network.

Sebastiani et al. (2016) solve a bi-objective optimisation problem that aims to minimise additional stopping time required to recharge and the number of required chargers. Modelling techniques employed include both discrete event simulation and metaheuristic optimisation. Simulation is used for energy consumption calculation and aims to capture the stochastic processes encountered in bus operation. The heuristic then determines good bi-objective solutions given each discrete energy consumption result.

Other optimisation literature covering electric bus operation but less relevant to this project include: Chao and Xiaohong (2013) who investigate locating a single battery switching point to serve buses in a network (replacing discharged batteries during operation); Qin et al. (2016) investigates trade-offs between charging routines and total energy costs, under energy pricing schemes dependent on network demand.

4 Problem and Model Description

A considerable cost encountered when transitioning from conventional buses to battery or ultra-capacitor electric buses is that of charging infrastructure. High power, overhead chargers can be very expensive (Eudy, Prohaska, Kelly, & Post, 2016) and therefore it is important that charger positioning is carefully considered.

In this project, a model was developed to minimise the total cost of charging infrastructure required to meet the energy demands of ultra-capacitor electric buses operating along a defined set of existing bus routes. The model selects specific bus stops, along the given routes, where electric bus chargers are best installed . Electric buses would charge at these stops, during service, using high power, overhead or induction chargers – a more detailed discussion of charging systems is available in the full project report (Stewart, 2017).

Because charging must occur en route (for this type of electric bus technology), any delay to service that charging causes will also increase the commute time of those using the bus. For this reason, as well as minimising total charger cost, it was important for the model to also investigate trade-offs between delay to normal service caused by charging, and the minimised total charger cost.

Here “delay to normal service caused by charging” means the delay incurred when a bus is ready to continue to the next stop but must remain stationary to allow for charging to take place. It does not include instances where a bus is stationary, charging and passengers are boarding or alighting the vehicle. For a particular trip, the total delay to normal service caused by charging is the difference in time taken to complete that trip by a bus that does not require en route charging and an ultra-capacitor electric bus.

In choosing an optimal charger distribution the model needed to consider:

1. *Inter-stop energy consumption and bus energy capacity* (see *Section 6*). By calculating bus energy consumption for every inter-stop section, the model can ensure that bus state of charge, during service, always lies within an allowable range.
2. *Expected bus dwell times*, for loading and unloading passengers, at each stop along the routes. From this, the model could then prioritise placing chargers in locations where the bus normally stops for longer periods of time. Charging at these locations will cause less delay to normal service.
3. *Relative charger installation cost and available power output* at every bus stop. Certain locations are likely to be more suited to high power charger placement (for example stops that are closer to transformers).
4. *The proportion of routes that use each stop*. For obvious reasons, it is preferable that chargers are placed at stops that service a large number of routes

Bus routes included in the model were all routes that run along Auckland’s Mt. Eden and Dominion Roads, excluding *Express*, *Link*, *Flyover* and *SkyBus* (airport) services. This included routes: 255, 258, 267, 274 and 277. These two public transport corridors created an interesting problem space as the routes converge and diverge along their separate paths, have varied elevation profiles (see *Figure 1*) and a range of start and end points. See the full project report (Stewart, 2017) for further discussion of the network.

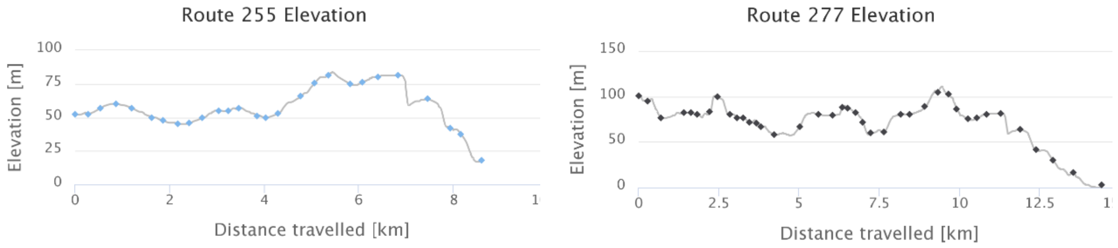

Figure 1. Route elevation profiles. Bus stops are marked with dots.

4.1 Mixed-Integer Problem

A mixed-integer optimisation problem (MIP) was formulated using the Python optimisation library PuLP, and solved with either CBC or Gurobi. *Table 1* gives the parameters, notation and assumed values, used in the mixed-integer problem. The problem formulation is outlined on the following page.

4.1.1 Parameters and Notation

Table 1. Mixed-integer problem parameters, notation and assumed values

Notation	**Description**	**Chosen value(s) [units]**
I	Set of all stop ids	From GTFS feed
L	The set of all route ids	From GTFS feed
$n(l)$	Number of stops on route l	
$S(l)$	Ordered list of stop ids on route l relative to the direction of travel	
$S(l)_j$	j^{th} stop on route l for $j = 0, 1, \dots, n(l) - 1$. This indexing is used when relative stop positions are required	
$E_{j\,k}$	Bus energy consumption from stop j to k. Note: if $j = S(l)_a$ then $k = S(l)_{a+1}$	Varies $[kWh]$
P_i	Power transfer rate at stop i charger[1]	$P_i = 300\ kW\ \ \forall i \in I$
C_{max}	Capacitor maximum energy capacity (i.e. fully charged)	10 kWh

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[1] While the IP formulation allows stop specific values, a constant was used; gathering actual stop specific data was beyond the scope of this project.

C_{min}	Capacitor minimum allowable energy capacity	$2\ kWh$
$R_{l\,s}$	Maximum allowable delay to service, caused by charging on route l at stop s. Reducing this duration for a particular stop will discourage charger placement at that stop.	$R_{l\,s} = 120$ seconds $\forall\, l \in L,\ \forall s \in S(l)$
$b_{l\,s}$	Assumed average number of passengers to board/alight on route l at stop s. Note: $b_{l\,s} = \max\{\#\,boarding, \#\,alighting\}$ on route l at stop s. This allows average dwell time to be easily defined by $kb_{l\,s}$	Varies
c_i	Relative cost of placing a charger at stop i[2]	$c_i = 1 \quad \forall\, i \in I$
k	Assumed average boarding/alighting time per person	4 [seconds/passenger]
V	Maximum allowable (total) delay to service caused by charging	Varies

4.1.2 Problem Formulation

Decision Variables:

$$x_i = \begin{cases} 1 & \textit{if charger placed at stop } i \\ 0 & \textit{otherwise} \end{cases} \quad \forall \mathrm{i} \in \mathrm{I}$$

$$C_{l\,s} = \textit{bus state of charge on route } l \in L \textit{ entering stop } s \in S(l)\ \ [kWh]$$

$$\textit{For a bus on route } l \in L \textit{ at stop } s \in S(l) \textit{ define:}$$

$$t_{l\,s} = \textit{time spent charging } [sec]$$

$$z_{l\,s} = \textit{average delay to service (tardiness) caused by scheduled charging } [sec]$$

$$q_{l\,s} = \textit{difference in charging time and passenger boarding time } [sec]$$

Objective Function:

$$\min \sum_{i \in I} \mathrm{c}_i x_i$$

Minimise the total (relative) charger cost.

Constraints:

$$\boldsymbol{s.t.}: \qquad C_{l\,s} \geq C_{min} \quad \forall\, l \in L,\ \ \forall\, s \in S(l)$$

During every trip, the onboard ultra-capacitor never drops below the minimum state of charge.

$$C_{l\,S(l)_0} = C_{max} \qquad \forall\, l \in L$$

The ultra-capacitor enters the initial stop fully charged. Note: $S(l)_0$ is the first stop on route l.

$$C_{l\,s} + t_{l\,s}\, P_s \leq C_{max} \quad \forall\, l \in L,\ \ \forall\, s \in S(l)$$

During every run, the onboard ultra-capacitor is never charged beyond maximum capacity. Notice: $t_{l\,S(l)_0} = 0\ \forall l \in L$ due to constraint above.

$$C_{l\,S(l)_j} = C_{l\,S(l)_0} + \sum_{i=1}^{j} \left(t_{l\,S(l)_{i-1}}\, P_{S(l)_{i-1}} - E_{S(l)_{i-1}\,S(l)_i} \right) \quad \forall\, j = 1, \dots, n(l) - 1$$

The ultra-capacitor state of charge when entering the j^{th} stop on route l (excl. stop 0). Calculated by summing all previous charging occurrences and inter-stop discharges.

$$t_{l\,s} \leq x_s (kb_{l\,s} + R_{l\,s}) \quad \forall\, l \in L,\ \ s \in S(l)$$

Time spent charging on route l at stop s is 0 if no charger placed at stop s; otherwise less than the total passenger boarding/alighting time plus an upper bound for delay to service caused by charging ($R_{l\,s}$).

$$q_{l\,s} = t_{l\,s} - k\, b_{l\,s} \quad \forall\, l \in L,\ \ s \in S(l)$$

Difference in charging time ($t_{l\,s}$) and passenger board/alight time ($kb_{l\,s}$) on route l, at stop $s \in S(l)$. Note $q_{l\,s}$ will be < 0 when the charging time is less than the passenger board/alight time.

$$z_{l\,s} \geq 0,\ \ z_{l\,s} \geq q_{l\,s} \quad \forall\, l \in L,\ \ s \in S(l)$$

The delay to normal service caused by a charging time ($t_{l\,s}$) on line l, at stop $s \in S(l)$, given the passenger board/alight time ($kb_{l\,s}$). The two inequalities are equivalent to: $z_{l\,s} = \max_{l \in L,\ s \in S(l)} \{0, q_{l\,s}\}$

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[2] Again, gathering actual stop specific data was beyond the scope of this project. In setting $c_i = 1$ for all stops, the objective function value will simply be the total number of charges in the network.

$\sum_{s\in S(l)} (z_{l\,s}) \le V \quad \forall\, l \in L$	The total average delay to service, caused by charging, in each route modelled, is no more than the given maximum allowable average delay to service (V). This creates and epsilon constraint type approach where modifying the right-hand side (V) allows investigation of trade-offs between delay and cost, without creating a multi-objective problem.
$x_{s(l)_0} = 1 \quad \forall\, l \in L$ $x_{s(l)_{\mathrm{n(l)}}} = 1 \quad \forall\, l \in L$	A charger will be placed at all initial and final stops. Driver breaks and scheduled layovers at route start and end points make these locations ideal charging points. Note: $S(l)_{\mathrm{n(l)}}$ is the last stop on route l.
$x_i \in \{0,1\} \quad \forall i \in I$	$x_i = 1$ if charger placed at stop i and 0 otherwise.
$t_{l\,s}, C_{l\,s}, z_{l\,s} \ge 0 \in \mathbb{R} \quad \forall\, l \in L,\ s \in S(l)$	Charging times, energy capacities, and average delay times, for all routes and stops, must be non-negative, real values
$q_{l\,s} \in \mathbb{R} \quad \forall\, l \in L,\ s \in S(l)$	Differences in charging times and passenger boarding times, for all routes and stops, can be any real number.

4.2 Assumptions

Operational assumptions are specified within both the MIP parameter description and the constraints defined in the MIP formulation above. Other operational assumptions:

1. *Chargers can only be placed at bus stops*. Future projects could consider other possible charger locations such as at traffic lights.
2. *Bus stop chargers are always available for use* and not occupied by another bus or out of service due to maintenance or breakdown.
3. *Charger power output is constant*, and not affected by factors such as number of buses charging or local grid loads.
4. *Stored energy is linearly dependent on charging time*.
5. *Ultra-capacitors are 100% efficient*. All charge added to the ultra-capacitor during charging, or regenerative braking, can be utilised by the bus.
6. *Boarding and alighting times are equivalent*. That is, the length of time it takes for a passenger to board the bus is the same as the time it takes them to disembark. This simplifies defining bus stop dwell times.
7. *Bus dwell times are sufficiently defined by* $k\ b_{l\,s}$ (the product of average boarding/alighting time and the number of passengers boarding/alighting on route l at stop s).
8. *The relative bus dwell times at stops along a particular trip are independent of the time of day or time of year*.

For other assumptions about bus performance, dimensions, capacities and energy consumption, please refer to the full project report (Stewart, 2017).

5 Data

The following section briefly describes the data sources used, and processing performed, in this project – again, for more detail refer to the full project report (Stewart, 2017). All data processing was performed using Python and relied mainly on the Python libraries Pandas, NumPy and GTFS Tool Kit.

Route data was sourced from the Auckland Transport GTFS feed[3], with the exception of route elevation data, which was obtained from the Google Maps Elevation API using HTTP requests. Auckland Transport supplied historical HOP data which was

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[3] GTFS, or General Transport Feed Specification, is a file format for storing all the timetable and geographic data for a public transport network. This universal standard allows transport agencies to easily share transport network information, and supports developers looking to build generic public transport tools (‘GTFS Static Overview’, 2016). Similarly, it means that this project could be easily adapted to other transport networks around the world, by simply importing different GTFS feeds.

processed to obtain average passenger boarding and alighting numbers at each stop along the modelled routes. Bus specification data came from a range of published and online sources. Bus specifications are discussed further in *Section 6* of the full project report (Stewart, 2017).

5.1 Data Processing Procedure

To begin with, the raw Auckland Transport GTFS feed is imported and loaded. This is done using two Python libraries: GTFS Toolkit and Clean Auckland GTFS[4].

Next the program compiles route and stop dependent data by performing the following set of functions for all specified bus routes:

1. *Select a representative trip*[5] *for each route*. Trip selection is determined by locating a journey that operates: on a specified route; on a given day (or days) of the week; and, in a particular direction (e.g. city-bound). The trip must also match, as closely as possible, a specified departure time. For the routes modelled in this project, the target parameters were weekday, city-bound services, departing during a specified peak morning commute time.
2. *Get appropriate stop and stop-time data*, from the GTFS feed, for the selected trip. Extracted stop specific data includes: stop codes, latitude and longitude coordinates, stop arrival and departure times.
3. *Attach stop elevations*. Elevation data, requested from Google Maps, is added.
4. *Import non-GTFS data*. This includes stop and route dependent passenger boarding/alighting volumes and maximum allowable delay caused by charging.

Auckland Transport HOP data was processed to obtain average passenger boarding and alighting numbers. Passenger volumes were derived from peak city-bound services, departing between 7am and 9am. *Figure 2* presents this operational data for route 277, with ordered stop IDs displayed along the x-axis.

The model then takes a Python object containing all ultra-capacitor electric bus parameters and energy consumption methods. Combined with the stop data described above (specifically inter-stop distances, durations and average road gradients) electric bus energy consumption is then calculated for every inter-stop section along the modelled routes (see *Section 6*).

Finally, charger data is imported for each stop in the modelled routes. This data stored in a user created CSV table or can be set as a specified constant. Charger data includes achievable power output and relative charge cost at each stop.

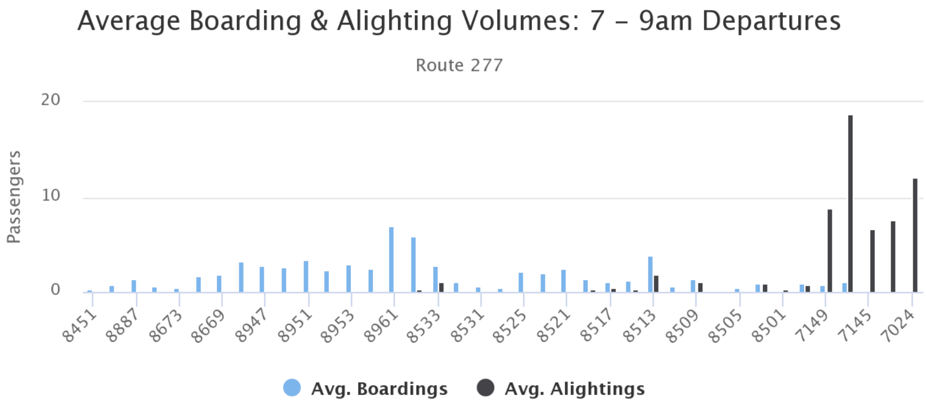

Figure 2. Average number of passengers to board and alight along route 277.

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[4] Both written by Alex Raichev (see https://github.com/araichev)

[5] In GTFS feed terminology, a *trip* is a unique journey along a route, arriving and departing a sequence of stops at specified times of the day, and operating over a defined time period. For example, the 274 to Waikowhai, departing Downtown on weekdays, at 6.10am is one unique trip.

6 Energy Consumption modelling

An accurate energy consumption model was needed for this project for two main reasons: firstly, the very short range of the ultra-capacitor electric bus, relative to other bus types, makes it more sensitive to fluctuations in energy consumption; secondly, due to the large variation in elevation along the Mount Eden and Dominion Road routes, there would likely be significant variations in required power during operation, potentially affecting the optimal spacing of chargers.

This section briefly describes the energy consumption modelling approach. For a more complete description, as well as results analysis and validation, refer to the full project report (Stewart, 2017).

6.1 Energy Modelling Approach

Assessing the forces acting on the bus during operation is the first step required for a more accurate energy consumption model. A bus's electric motor and braking system produces a tractive force at the wheels. To create or change forward motion, this tractive force interacts with three other forces: rolling resistance, air resistance (or aerodynamic drag, and hill climbing resistance, that is, gravitational force, encountered along the line of travel when either moving up or down a slope.

If the bus's velocity is changing, the tractive force must also produce either acceleration or deceleration of both the bus and the motor components (Lowry & Larminie, 2012).

Following this, all required parameters were loaded, including: force equation coefficients; bus specifications such as peak torque, peak power, mass, gear ratios, powertrain and regenerative braking efficiencies; ambient temperatures for heating and cooling calculations; inter-stop distances, durations and road incline.

Finally, the force equations were combined and solved to give instantaneous bus velocity and power output. Specific driving manoeuvres were simulated between every stop and the inter-stop energy consumption calculated.

6.2 Energy Modelling Results

As expected, the results showed obvious variation in inter-stop power output along the modelled routes. An example of these results is shown in *Figure 3* for the final few kilometres of route 267 travelling into the city. Here, the column heights give inter-stop average ultra-capacitor power output in kWh/km and the column areas give total inter-stop energy consumption in kWh. The line series shows route and stop elevation. Notice that uphill sections, seen in the first half of the route, result in much greater average power output than the downhill sections of the second half of the route. Also, notice that shorter inter-stop sections lead to greater average power output (see the second to last column for a clear example of this). This latter relationship is due to the assumption that buses perform exactly two acceleration/deceleration cycles between every stop and because varied speed travel is more inefficient than constant speed travel. For the longer inter-stop distances, a higher proportion of the total distance covered will be completed at a constant speed (lower power output). Therefore, longer inter-stop distances will lead to reduced average power output.

There are some obvious flaws in the two acceleration/deceleration cycles assumption. However, the fact that a bus must accelerate and decelerate at least once in any inter-stop journey (assuming all stops are visited), regardless of inter-stop distance, means that a negative relationship between inter-stop distance and average power output is likely to exist.

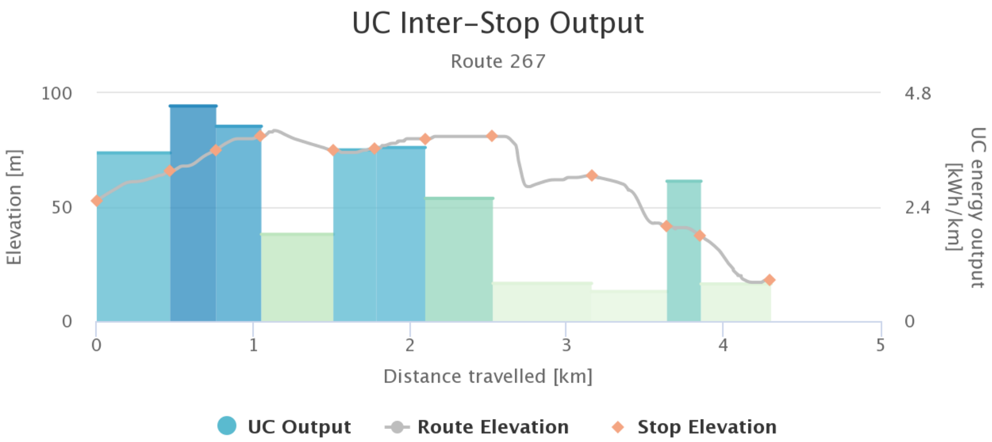

Figure 3. Inter-stop energy consumption (normalised by inter-stop distance) along a section of route 267 (city bound)

7 Results[6]

Figure 4 highlights the trade-off between delay to service caused by en route charging and the number of chargers required. The data presented is for all modelled Mt. Eden and Dominion Road routes and an assumed dwell time of 10 seconds at every stop. Only 12 chargers are required to meet bus energy requirements alone, but this would incur a long service delay to service. Installing 54 chargers reduces the amount of charging time required at each stop such that all charging could be completed while passengers board and alight and no additional delay would be experienced.

For a transport company, an acceptable balance would likely be required. Public acceptance of new technology is important, and it is not difficult to imagine that those riding an electric bus service would not be happy with long additional delays. On the other hand, completely removing delay requires a fourfold increase in the number of chargers (and a similar increase in cost).

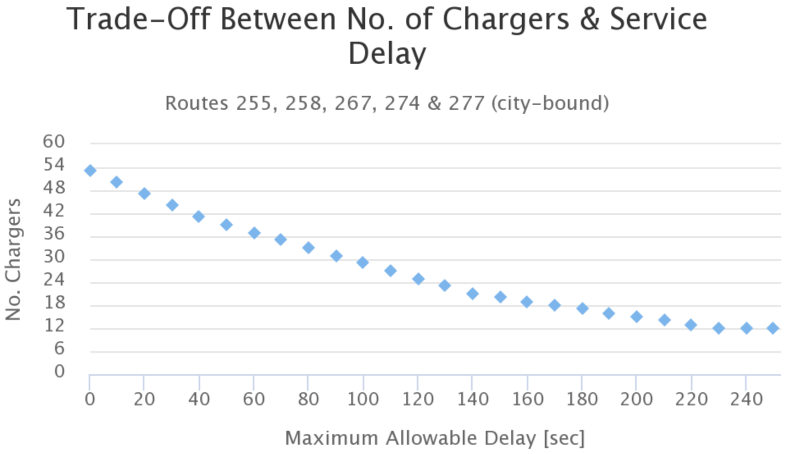

Figure 4. Trade-off between maximum delay to service caused by charging and the number of chargers required for all routes

Next two particular solutions are compared. One solution has no restriction on delay caused by charging. The other has a maximum allowable delay of 80 seconds across all routes. For both solutions real passenger data was used to define bus stop dwell times.

Figure 5 shows the average bus stopping and charging times, at each stop, along route 255. It can be seen that when no restriction is placed on delay caused by charging, only three chargers are required. When an 80 second upper bound is placed on the

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[6] All visualizations in this project were build using the Python libraries Folium (street map visualisations) and Python-Highcharts (plotting).

delay, it can be seen (in the right-hand side plot) that more chargers are installed, and that most of the charging time falls within the bus stopping times.

Bus state of charge along the same route (255), for both solutions, is displayed in *Figure 6*. These plots reiterate the increase in required chargers and shortened charging times per stop, which arises with increased restriction on delay caused by charging. In *Figure 6*, bus state of charge remains within the defined upper and lower bounds (see *Section 4.1*). It is also interesting to observe that the general trend for bus state of charge is to drop over the route. This response desired: by ending the trip with a low state of charge, recharging during scheduled layovers is best utilised without incurring additional service delay.

Finally, *Figure 7* (placed after the Conclusions) shows the route paths and the charger distribution under no restriction on service delay caused by charging. For analysis of the project results, see the full project report (Stewart, 2017).

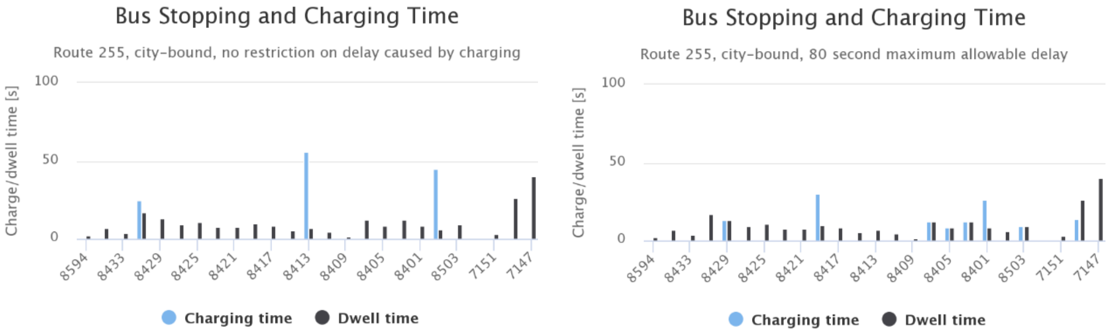

Figure 5. Bus stopping and charging time on route 255 for two separate solutions

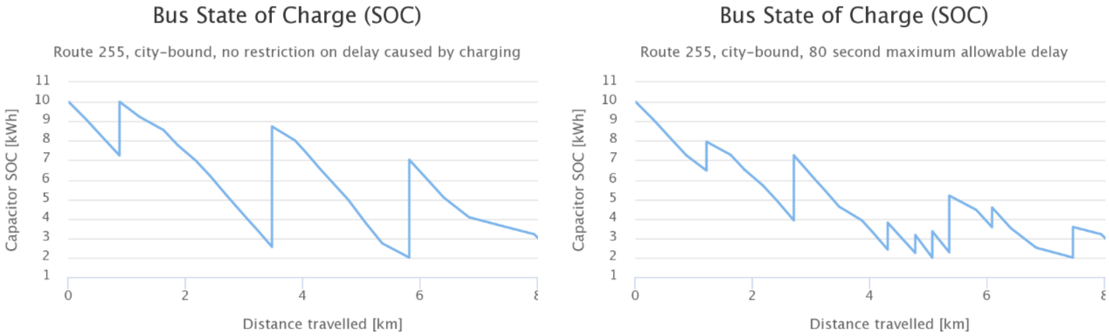

Figure 6. Bus state of charge on route 255 for two separate solutions

8 Conclusions

Using mathematical modelling, optimisation and visualisation techniques, this project has explored optimised charger infrastructure placement, for a public transport bus network, running ultra-capacitor electric buses.

This model showed that, under a set of specified parameters and assumptions, between 12 and 53 chargers are required to electrify Auckland’s city bound bus routes that run along Mt. Eden and Dominion roads – the exact number being a function of acceptable delay to service caused by charging. The model also demonstrated the importance of accurate energy consumption modelling for this technology and put in place a model framework that could be adapted to other transport networks or bus technologies.

Exploring ultra-capacitor electric bus technology has created an interesting bus network optimisation problem. Very short bus range, meant analysing a bus network at the individual route and stop level and creating a problem that was scalable – the model could produce meaningful solutions whether solved for one bus route or every bus route in a network.

Ultra-capacitor electric bus technology appears to be overlooked by public transport providers investing in electric bus technology, despite the many advantages of using ultra-capacitors for energy storage in place of batteries. It is likely that the reason for this is perceived limitations created by low energy capacities. However, this project explored how system design decisions can potentially mitigate these limitations.

8.1 Moving Forward

The following changes are areas of model improvement for future work:

1. Implement similar models for other electric bus and charger technologies.
2. Collect real location and technology dependent charger installation costs and power output.
3. Input actual energy usage rates and peak demand costs to evaluate running costs.
4. Model other costs such as bus purchase price and maintenance costs to compare total cost of ownership for different technologies.
5. Optimise vehicle energy storage capacity and charger cost in a bi-objective problem to investigate whether reducing the onboard energy copacity and increasing the number of chargers, leads to a reduction in total cost.
6. Add vehicle mass/passenger capacity as a decision variable. This would facilitate the investigation of trade-offs between passenger capacity and other variables modelled.
7. Whole network analysis. Running the model for an entire network and comparing costs across different corridors may reveal locations more suitable to particular technologies.

Validate energy consumption model. Real electric bus energy consumption data should be used to verify the values output by the energy consumption model.

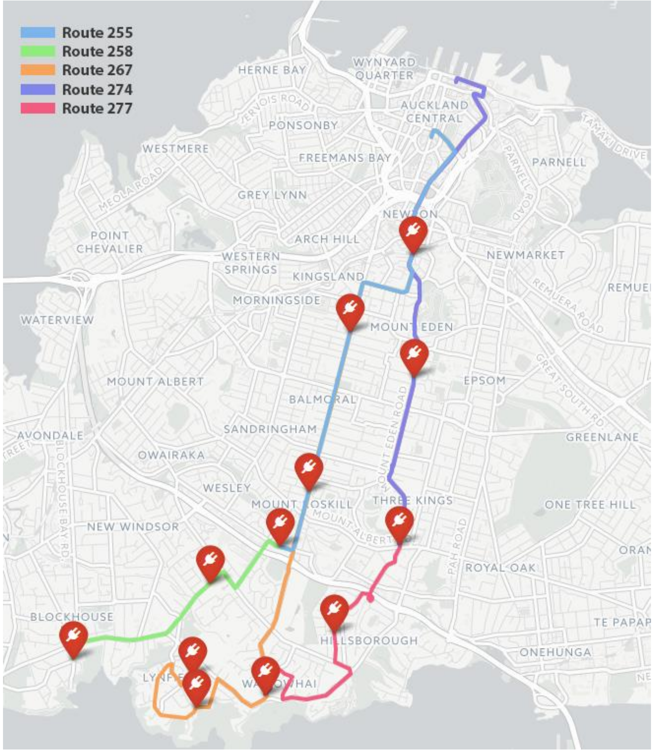

Figure 7. Final solution for city-bound routes with no limit on delay to service

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