

# Balancing level of service for a battery-electric university intercampus shuttle bus

Robbie Napper<sup>1</sup>, Ilya Fridman<sup>1</sup> and James Reynolds<sup>2</sup>

<sup>1</sup>Monash University, Mobility Design Lab, 900 Dandenong Rd, Caulfield East VIC 3145

<sup>2</sup>Monash University, Institute of Transport Studies, Wellington Rd, Clayton VIC 3800

Email for correspondence: [robbie.napper@monash.edu](mailto:robbie.napper@monash.edu)

## Abstract

This study theoretically examined the balance between battery size, charge time, vehicle headway and passenger capacity for a Battery-Electric Vehicle (BEV) university intercampus shuttle bus service in Melbourne, Australia. Unlike current diesel buses, BEVs must consider energy storage and recharge opportunity during operation in order to provide an effective transport service. The quantity of energy stored on-board a BEV bus is vital for reaching designated stops, though simultaneously may hinder its ability for passenger accommodation.

Focusing on a particular service, four scenarios for BEV buses were explored through mathematical modelling. Transport service calculation techniques were expanded to consider battery and charge capacity for BEV operations. Results highlighted the existence of operational compounding that occurred with the scaling of battery size and fast-charge rates during operation. Buses with larger batteries were able to match headways determined by the existing diesel service; however, this was achieved at a substantial cost to the service's hourly passenger capacity, posing a question of whether emphasis should be placed on moving more people or achieving shorter headways.

Findings are discussed for their significance to approaches for future planning and operation of BEV bus services. Further research is suggested to consider more complex commercial routes with greater designated stop numbers. Considering the interplay of passenger boarding and alighting time with vehicle charging in greater detail is also suggested to further build on this study's contributions.

## 1. Introduction

Commercial and research interest in Battery-Electric Vehicle (BEV) buses has seen significant growth in recently years. In Australia, however, the overwhelming majority of buses are still powered with diesel fuelled Internal Combustion Engines (ICEs) (Australian Bus and Coach, 2015). This mature technology has provided excellent flexibility for the bus network and also created a "fill up and go" mentality in bus operation where energy is only a concern for the overnight turnaround at bus depots and unconsidered during operational periods. Despite technological maturity and practical advantages, diesel technology is reaching a development ceiling where further emission reductions are disproportionately expensive compared to the provided benefits.

BEV technology offers significant benefits to the public transport's energy and emissions profile by switching energy demand from imported oil to locally made electricity, which may be in part or whole generated from renewable sources (Cook, 2012; Seligmann, 2010). Even with comparatively "dirty" electricity the local air quality for the bus operation is still advantaged (Honner et al., 2016). BEV buses also present challenges, foremost among them being the provision of sufficient energy to perform their duty in a cost-effective manner.

A European study, for example, found that while BEV buses presented the greatest reduction in energy consumption, they continued to have the highest life-cycle cost when compared to diesel and diesel-electric hybrids (Lajunen, 2014). Ally and Pryor (2016) found similar results when comparing diesel, hybrid and hydrogen fuel-cell buses in Australia. Their life cycle analysis suggested that while fuel costs might be low, diesel buses were still the cheapest alternative when considering total cost of vehicle ownership. These results were largely due to the prohibitive costs of commercial traction batteries. These, however, may become cost competitive in coming years with increasing technology adoption, diesel prices, and decreasing battery prices. This view is supported by predictions that battery cost may decrease significantly through increases in manufacturing quantities alone (Nykqvist & Nilsson, 2015). Though batteries may one day prove cost-competitive through price reductions, careful consideration still required in the medium term to develop an effective bus service. Further to this, batteries bring with them an increase in vehicle mass, evident in contemporary BEV buses, such as the Build Your Dreams (BYD) eBus (BYD, 2014). This mass competes with passenger capacity on-board the vehicle, significantly hindering its ability to move passengers—the services primary role.

This consideration of balancing sufficient battery size and passenger capacity, has received little attention in transport literature. The present study aimed to investigate this balance and the implications for delivering an effective transport service with BEV buses. It focused on the need to schedule charging time and highlighted the reality of operational compounding with BEVs. Transport service calculation techniques were applied and expanded to consider the impacts of battery capacity and charging capacity on route bus operations. It was outside this study's scope to provide recommendations on energy generation, battery pricing and vehicle life-cycle cost. Focus was instead placed on the specific challenge in addressing the interplay between energy storage specification and effective service provision, which is far less an issue in diesel ICE buses. The analysis focussed on an intercampus shuttle bus service in Melbourne, Australia. The selected route was short and layover played an important role in designing services and vehicles for operation. The selected service was of interest because the trip generator was the university conducting this research. The problem was local, but furthermore, trips were generated by the university and thus presented future opportunity for optimisation. The degree of risk associated with new technology may be more palatable in a university context than in the broader public realm, with the risk being offset by potential advancements in technology and know-how.

The paper is structured as follows. The next section presents previous research literature addressing BEV bus operations. Study parameters are then described, including the vehicle, route and service characteristics included in the study. Results are then described, followed by a discussion identifying areas for further research. Details for the calculation model are presented in the Appendix.

## 2. Literature review

Range anxiety is an important driver of decision making for private electric vehicles in Australia, given the vast distances between cities. In contrast, for a route bus the range requirements are much more known; indeed, the operational characteristics are planned to such a large extent that designing the timetable *and* the vehicle become a realistic proposition. If a vehicle's operational characteristics are known, then within a certain tolerance energy use can also be predicted. Range anxiety is replaced with range planning, a factor that positions BEV buses at the vanguard of a shift from petroleum to electric traction by virtue of investment in charging infrastructure often missing from electric vehicle strategies for private cars.

## 2.1 Operating BEV buses

It is well understood that operational considerations vary between diesel and BEV buses. In a review of route bus powertrains, Mahmoud et al. (2016, p.683) concluded that current operational demands are “well-aligned with diesel buses” suggesting that there is a need to reconsider design and operation of vehicles with battery-electric technologies. At the same time, BEVs have also been identified to have more “rigid” operational constraints than diesel buses (Chao & Xiaohong, 2013, p.2726). This perhaps explains why numerous studies have explored the complexities of BEV scheduling and operation.

Wang & Shen (2007, p.1238) defined the BEV scheduling problem as a “vehicle scheduling problem with route and fuelling time constraints”. This is because commercially available traction batteries are still unable complete a whole day’s service on a single charge, requiring multiple recharge instances to maintain operation—a characteristic that makes BEV buses significantly different to their diesel counterparts that operate all day on a single tank of fuel. Partial en route charging has been suggested to remedy range problems, otherwise referred to as range anxiety, providing successful BEV scheduling (Li, 2014; Wen et al., 2016). The required number of daily charge instances is dependent on energy storage capacity, leading to questions of appropriate battery size.

In an economic study, Miles & Potter (2014, p358) highlighted the financial challenges of BEV bus operation, suggesting that battery pack size is “crucial to both technical performance and commercial viability” of a bus service. BEV buses are difficult to schedule as they have shorter driving ranges and longer refuel—recharge—times than ICE buses. Driving range may be increased by increasing battery pack size, though Kulkarni, Kapoor & Arora (2015) emphasise that this is nonlinear due to mass-compounding, in which the increased weight of battery packs results in greater energy requirements leading to further increases in battery weight being required. Vehicle design thus becomes more complex as structural elements must be reinforced to accommodate greater battery mass. Both the battery and structural elements increase vehicle kerb weight, in-turn reducing passenger carrying capacity which is governed by varying national regulations on total vehicle mass. Larger batteries also increase vehicle purchase cost that may already be difficult to justify when compared to ICE buses. In order to encourage BEV bus uptake and realise successful services, it is important to strategically align a vehicle’s energy storage capacity with operational energy demand.

## 2.2 Balancing a BEV bus service

Reuer, Kliewer & Wolbeck (2015) extended traditional vehicle scheduling to include battery capacity and recharge ability. Their study showed successful results for early years of BEV adoption, though the authors suggested that further work was needed to balance the number of vehicles and charge stations in a service. Minimising infrastructure cost is indeed an important financial consideration for bus operators. De Filippo, Marano & Sioshansi (2014) addressed this through a university bus system simulation that aimed to reduce charging infrastructure while maintaining service levels. Their study found that a first-in-first-out policy resulted in longer queuing times when multiple buses shared a single charge station. Instead, prioritisation of buses with highest state-of-charge (SoC) was recommended as they recharged faster, thus reducing dwell times. This addressed charge infrastructure investment, though questions of optimal battery size remained.

Erkkilä et al. (2013) suggest the major choice of opportunity charging with less operational flexibility or overnight charging with a more flexible service. Questions of battery size may, once again, be raised as buses can only operate as long they have sufficient on-board energy storage. Ke, Chung & Chen (2016) explored different time-of-day charging scenarios, finding that BEV bus systems presented lower overall costs if vehicles were recharged during daytime operation rather than back at the depot overnight. Their simulation found that the cost of taking a vehicle out of service for charging was greater than the higher daytime

electricity rates. Miles & Potter (2014) presented similar findings, suggesting that small battery packs with frequent opportunity charging can reduce impact on dwell times and service cost—a vital factor for successful bus operation.

Batteries and charge infrastructure present different cost implications to a bus service: the former a per-vehicle investment, whereas the latter may be shared between multiple buses. Battery exchange models have, to some extent, challenged this concept by removing lengthy charge times from the equation; instead, batteries were replaced quickly with the use of automated stations (Chao & Xiaohong, 2013; Li, 2014). Results from these studies suggested that battery exchange may be successful for low-frequency suburban lines, urban streetcar lines and short-range shuttles, providing there is a nearby depot for battery exchange (Chao & Xiaohong, 2013). Li (2014) did, however, conclude that battery exchange cannot be recommended as the best choice for economic purposes due to additional capital investment requirements. This result reflects the nature of battery exchange scenarios, where large upfront investment is required to create a stockpile of spare batteries.

To date, a great deal of research has been conducted on the prospect of BEV bus operation and associated considerations that arise from this transition. It is particularly evident that well-considered energy storage is vital to a successful BEV bus service. This aspect alone influences purchase price, operating schedule, environmental footprint, vehicle mass and passenger carrying capacity. Yet, the balance between a vehicle's energy storage capacity and a service's passenger capacity remains unexplored.

In order to contribute to existing literature, this study aimed to understand the interconnected relationship between on-board energy storage, vehicle schedule and passenger capacity for a BEV bus service. The objectives were to discover how these three variables influenced each other and make some attempt to balance them in the context of a university shuttle service.

### **3. Study parameters**

Study parameters were grouped under two categories: vehicle and service. Data were then collected from academic and industry literature to inform study parameters, develop models and simulate service. Throughout this process, a number of variables were considered: two BEV test buses were developed based on different energy storage capacities; charge stations were modelled in either one or two locations along route; and a current diesel bus service was referenced. Variant results were then compared to inform the balance between passenger capacity, service frequency and on-board energy storage. Each study parameter is detailed in corresponding subsequent sections.

#### **3.1 Vehicle parameters**

The Volgren Optimus was referenced to provide example of a 12.5-metre, low-entry Australian route bus (Volgren, 2014). Route buses in this type of configuration commonly exhibit a kerb mass of 10 500 kg (personal communication, September 7, 2013). This served as a reference point for developing a BEV Test Bus.

**Table 1: Vehicle mass data for BEV Test Bus**

Item	Mass modification stage (kg)
<b>Volgren Optimus 12.5-metre low-entry bus</b>	10 500
<b>ICE components (engine, transmission, drive axle)</b>	-2152
<b>BEV components (motors, drive axle)</b>	1509
<b>BEV Test Bus (dry) mass</b>	9857
<b>State vehicle mass allowance</b>	16 000
<b>Remaining mass allowance</b>	6143

Table 1 shows how the mass data were modified to develop an estimation for BEV test bus specification. Key ICE components were removed (Volvo, 2011a, 2011b; ZF Friedrichshafen, 2016) and replaced with BEV alternatives (ZF Friedrichshafen, 2016) resulting in a vehicle mass of 9857 kg. Many components differ between BEV and ICE buses, though only the largest few were considered in this exchange. It was assumed that other BEV system components would exhibit similar contributions to overall vehicle mass as their ICE counterparts. This estimation was a 'dry mass' as fuel—battery pack—was not yet included. It was acknowledged that this calculation only provided a general estimate for BEV bus mass and not detailed mass for a specific vehicle. Following this exchange an estimated mass capacity of 6143 kg remained for passengers and on-board batteries in compliance to the local, state mass regulations (Public Transport Victoria, 2015).

**Table 2: Vehicle specification for BEV Test Bus 1 and 2**

Item	Test Bus 1	Test Bus 2
<b>Vehicle mass (kg)</b>	9857	9857
<b>Vehicle size: L x W x H (m)</b>	12.5 x 2.5 x 3.2	12.5 x 2.5 x 3.2
<b>Energy storage capacity (kWh)</b>	50	75
<b>Battery mass (kg)</b>	959	1424
<b>Average energy consumption (kWh/km)</b>	1.5	1.5
<b>Estimated range on single charge (km)</b>	25	37.5
<b>Passenger capacity (per vehicle)</b>	79	72
<b>Passenger mass (kg)</b>	5135	4680

Batteries are the primary method of energy storage on a BEV. From the commercially available chemistries, lithium-ion is currently considered the most promising for traction application (Gerssen-Gondelach & Faaij, 2012). The rate at which batteries can be charged and discharged is relative to their rated amp-hour capacity and described through Coulomb units, usually referred to as C or C-rate (see Larminie & Lowry, 2012 for further explanation of this measure). In theory, with charge capacity scaling with battery size, it would take 1-hour to recharge any battery pack from 0 to 100 state-of-charge (SoC) at a rate of 1C and 30-minutes at a rate of 2C. In practice, battery packs vary and not all may be recharged in under an hour. Amongst the various lithium-ion battery types, lithium titanate oxide (LTO)



are commonly applied in cases where fast, opportunity charging is desired. Burke, Miller & Zhao (2012), for example, found that LTO batteries could withstand a 6C—or 10min—recharge without apparent degradation. Two BEV test buses were specified with different battery pack sizes (calculation of which is described further in Section 4.1). Battery mass was referenced from manufacturer sheets for 50 and 75 kWh battery packs (Altair Nanotechnologies, 2012), incorporated onto Test Bus 1 and 2 respectively. Similar to other literature (e.g. De Filippo, Marano & Sioshansi, 2014) this research assumed that these battery packs could operate from 20% to 95% SoC to reduce potential stress on the pack and retain an emergency energy buffer.

Following this, passenger capacity was calculated based on remaining allowable vehicle mass and passenger mass of 65 kg per passenger in accordance with national regulations (Department of Infrastructure and Transport, 2012). Test Bus 1 was capable of accommodating 81 passengers, which was equivalent to a full passenger load on current ICE buses, while Test Bus 2 accommodated 8 fewer passengers due to the extra 25 kWh of energy storage. In summary, the smaller pack allowed greater passenger accommodation, while the larger pack allowed the vehicle to travel further at the loss of passenger capacity.

An average energy consumption of 1 – 2 kWh/km has been reported for standard BEV buses (International Association of Public Transport, 2012). A halfway figure of 1.5 kWh/km was applied in the model and assumed to include energy recovered through regenerative braking. Estimated driving range was then calculated based on energy storage capacity and average energy consumption.

### 3.2 Service parameters

The Monash Caulfield – Clayton Intercampus Shuttle service was selected for analysis in this study. This service provides direct shuttle transport with no scheduled stops along the route. It is, however, liable to stoppages caused by traffic lights, but also benefits from some bus priority measures at these traffic lights in the form of an advanced bus signal and lane, fast-tracking the bus ahead of road traffic.

**Figure 1: Map illustrating Intercampus Shuttle route**

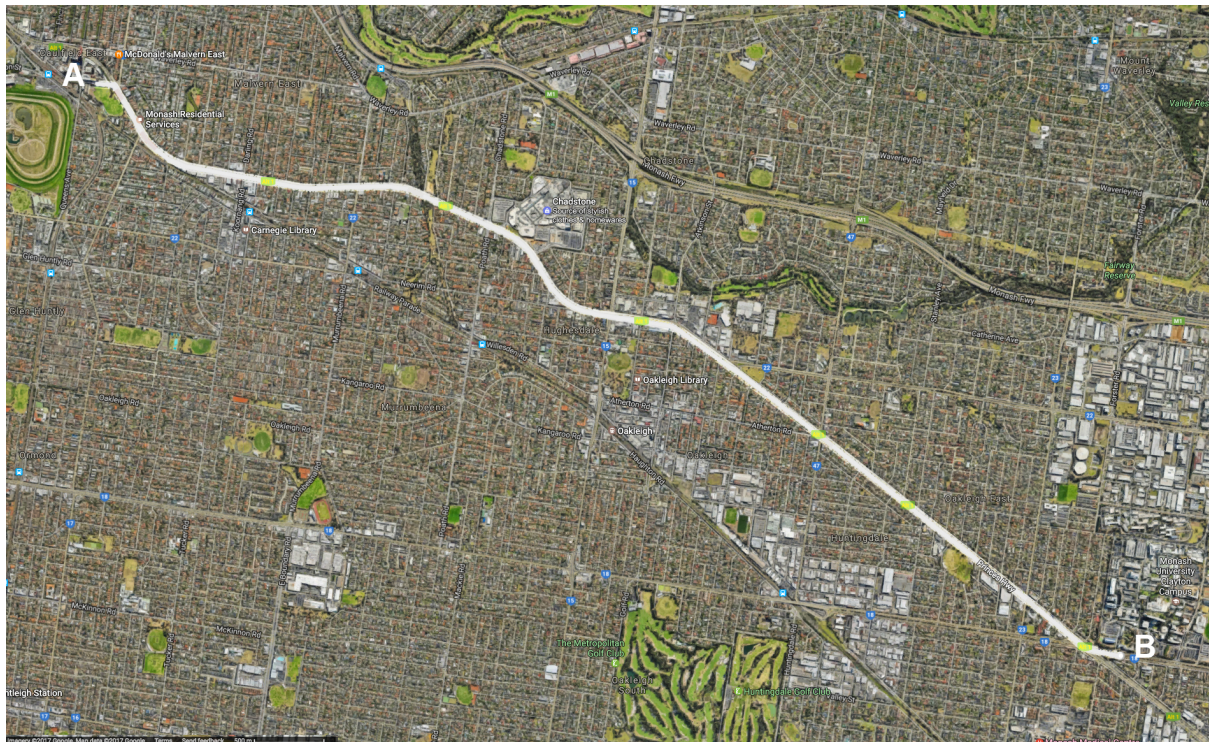


Figure 1 shows a map of the studied route with stops A and B, while Table 3 summarises the existing service characteristics. The buses used for this service have a capacity of 81 passengers, which has been adopted as the figure here.

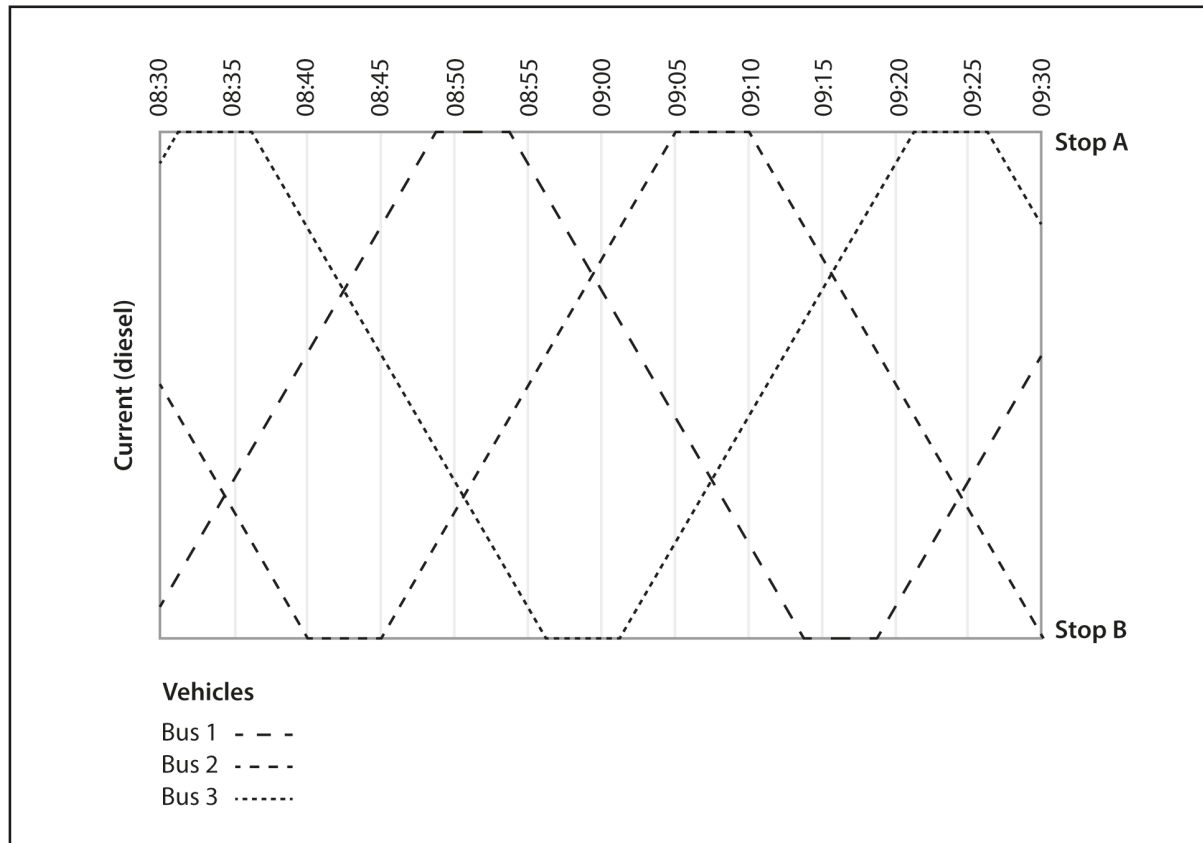
Travel time and distance data were generated using Google maps at hour intervals throughout the day. This was cross-checked with current vehicle schedules to estimate average travel time and distance. The route has a round-trip distance of 19.7 km, with buses scheduled at 16- to 17-minute headways. Buses take in the order of 20 minutes to travel in each direction, depending on traffic conditions, with a 5-minute layover at each campus to allow for passenger alighting and boarding. Three buses are used on the route during most of the day, when the service is at peak operation capacity. This is reduced to only two buses in the evenings, during off-peak operation.

Monash University's division of Facilities and Services provided patronage data for the Monash Caulfield – Clayton Intercampus Shuttle. This service has a maximum capacity of 291 and an average demand of 294 passengers per hour during the teaching periods, resulting in passengers having to wait for the next bus during peak times. These figures indicate that there is little room in this service for BEV inefficiencies related to charging.

**Table 3 – Service Characteristics**

<b>Characteristic</b>	<b>Current ICE service data</b>
<b>Travel time between stops</b>	20 minutes
<b>Stop dwell time</b>	5 minutes
<b>Round trip time</b>	50 minutes
<b>Vehicles in peak daytime hours</b>	3 vehicles
<b>Vehicles in off-peak night hours</b>	2 vehicles
<b>Headway</b>	16 – 17 minutes
<b>Frequency</b>	3.6 services / hour
<b>Vehicle capacity (max.)</b>	81 passengers
<b>Service capacity (max.)</b>	291 passengers / hour
<b>Service demand (avg.)</b>	294 passengers / hour

**Figure 2: Space-time diagram of current schedule for the Intercampus Shuttle**



### 3.3. Test Bus Simulation

The two test buses were simulated for the shuttle service. Further details of the calculation methods and formulas are outlined in the Appendix. These vehicles were tested with either one or two charge stations located at either of the university layovers—referred to as stop A and B in this study. Test bus performance was assessed against the current operation schedule with regards to dwell time, headway, frequency and service passenger capacity.

## 4. Results

**Table 4: Intercampus Shuttle service schedule with charge consideration**

	Schedule				
	Diesel	Test Bus 1 (50 kWh battery)		Test Bus 2 (75 kWh battery)	
Number of charger stations	0	1	2	1	2
Stop A – Stop B travel time (min)	20	20	20	20	20
Stop B dwell time (min)	5	5	6	5	5
Stop B – Stop A travel time (min)	20	20	20	20	20
Stop A dwell time (min)	5	12	6	8	5
Headway (min)	16.7	19.4	17.4	18.2	16.7



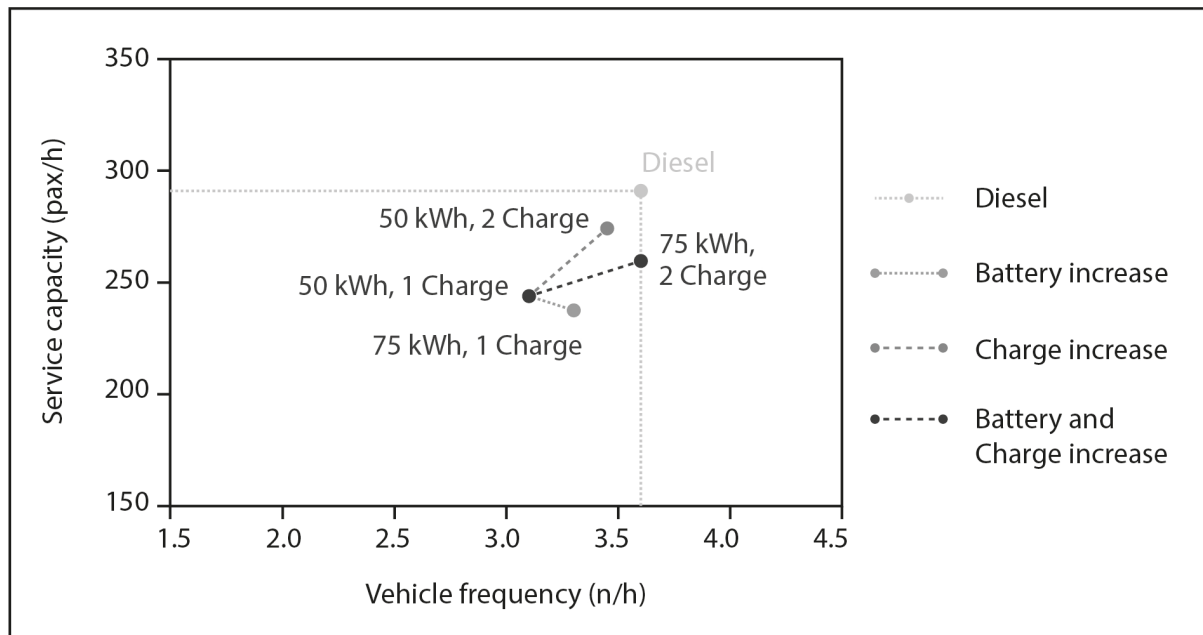
<b>Vehicle frequency (n/h)</b>	3.6	3.1	3.45	3.3	3.6
<b>Vehicle capacity (pax)</b>	81	79	79	72	72
<b>Service capacity (pax/h)</b>	291	244	272	237	259

The results of test bus design simulations are shown in Table 4. These compare 2 sets of variables—a 50 or 75kWh battery, and using 1 or 2 charge stations for the service. They are simulated to provide enough charge opportunity for continuous BEV bus operation, i.e. no overall charge depletion over the working day.

Results showed a clear correlation between increase of battery size and reduction of recharge requirement as well as the time spent charging. Reasons for this were twofold: first, the larger batteries used less of their total SoC to complete the same journey, thus, were less-dependent on recharging to complete a return trip; and second, they were charged at a higher power than the small battery packs resulting in a shorter charge time to replenish equivalent energy—done to maintain comparable fast-charge rate across both packs. It should be noted that recharge in this experiment was simulated at a rate of 4C. This is somewhat higher than the 2C rate suggested by Altair Nanotechnologies (2012), though lower than findings from Burke, Miller & Zhao (2012) who claim that LTO chemistry may be charged at rates as high as 6C without apparent degradation. Again, this was simulated to achieve shortest dwell time in the services.

Charging impact on dwell time was further reduced through the inclusion of two charging stations allowing buses to replenish energy storage at either layover, rather than waiting to complete a full loop. This did not reduce the total charge time requirement, though did divide it across both designated stops, minimising service delay at either end and reducing subsequent increases on dwell time by aligning the need for a timing point with the simultaneous task of charging. When combined with the larger battery pack of Test Bus 2, the incorporation of two charge stations created a vehicle schedule matching the current service operated by diesel ICE buses.

**Figure 4: Service capacity and vehicle frequency for Intercampus Shuttle**



As shown in figure 4, the incorporation of two charge stations also presented a clear advantage when considering service passenger capacity. All BEV services showed a

reduction to hourly passenger capacity when compared to the current ICE service; however, this was mitigated in all cases through the inclusion of a second charge station. The advantage of larger battery packs, on the other hand, was not as evident. As the increase in energy storage capacity was achieved at the loss of 7 passengers per vehicle, the hourly passenger capacity showed substantial reduction, despite no increase to dwell time. Test Bus 1 with the smaller battery and two charge stations showed a greater hourly passenger capacity when compared with Test Bus 2 that had a larger battery, two charge stations and a shorter dwell time.

**Figure 6 - Space-time diagram isolating a single vehicle on Intercampus Shuttle service**

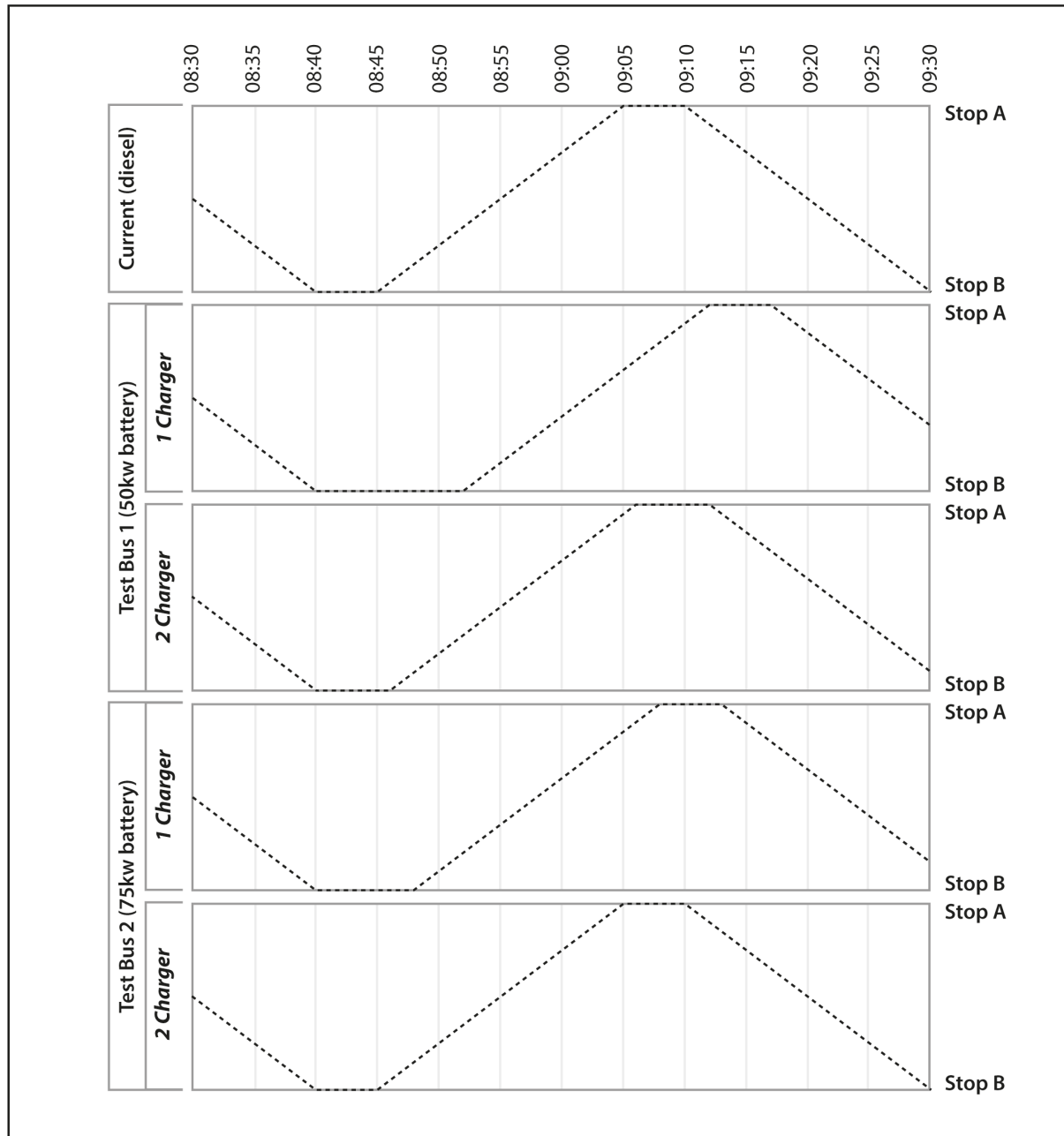


Figure 6 summarises these findings through space-time diagrams that show how single location charging can increase dwell time and delay vehicle service. For clarity, each vehicle is isolated in the three-vehicle service. To obtain a full picture of the service these may be expanded to replicate the schedules in Figure 2.

## 5. Discussion

A number of operational considerations have been brought to light through this study. Vehicle headway, dwell time, passenger capacity, number of charge stations and on-board energy storage all play related roles and must be considered together for the successful provision of a BEV bus service. Study results have highlighted their interdependence and their significance is discussed here in greater detail.

Assessment of vehicle headway and dwell time provided a distinct insight into the difference between BEV and ICE bus operation: shorter headway does not necessarily equal greater passenger capacity in a BEV service, which is currently the case for an equivalent diesel service. This is representative of one way that BEV operations will challenge engrained operational characteristics in bus scheduling. Headways for BEV buses were shorter when greater on-board energy storage capacity and a greater number of recharge instances were provided. When operated with two charge stations, buses were able to match headway and dwell times of the current diesel ICE service. As greater energy storage capacity was achieved through larger on-board battery packs, vehicle passenger capacity was in turn reduced. When considering results, it is evident that the per-vehicle passenger capacity reduction was more detrimental to service performance than an increase in headway. This indicates that a BEV bus service may match either the speed or passenger capacity of diesel ICE bus service, though not simultaneously at present. Understanding this, operators may need to decide whether they want to provide a faster service or move more people.

As mentioned in section 2.1, mass-compounding is already discussed in literature with regard to on-board energy storage and BEV structural design. When considering operation, battery sizing again raised concerns of a potential compounding effect. Large battery packs were less likely to reach a critical SoC when compared with the smaller ones for two reasons. First, greater energy storage meant that comparatively less of the battery's total SoC was depleted during a journey, thus reducing a vehicle's dependence on recharge requirements. Second, larger battery packs recharge with a higher power rate. Equation 8 above shows that the larger battery pack will accept more energy over a given period while charging at the same C rate as the smaller battery pack. This meant that Test Bus 2 with the larger 75kwh battery was not only less dependent on recharge instances, but when it was recharged the utilised energy storage was replenished in less time. It is predicted that this compounding effect could be optimised for bus operation with more research.

Service passenger capacity was observed to be highly sensitive to battery size as the mass of one displaced the other on-board a vehicle. The balance is therefore difficult as small battery packs require a greater frequency of longer charge instances, while larger batteries physically limit a vehicle's passenger capacity. Small battery packs may be specified to satisfy off-peak scheduling demands when dwell time is typically longer, though they could lead to significant passenger capacity losses during peak operation times when service frequency is critical. As a result, operational costs may increase if extra vehicles are required to meet peak-time passenger capacity needs. Large batteries also contribute numerous other challenges—beyond the evident passenger capacity reduction. Battery packs require space and contribute significant mass, both of which increase with energy storage capacity. Furthermore, this research has not dealt with the capital cost implications of the larger battery and the planning around batteries and charging infrastructure.

The service examined in this research can be described as high demand. Observations show that passengers are regularly left kerbside to wait for the next service. In these cases, a 20-minute wait must be endured if alternative transport or deferral are not an option. Operational capacity is, therefore, of some concern and should be accounted for in scheduling. In contrast, many outer suburban and off-peak bus services run passenger loads well below capacity. In a possible future of BEV operation, the differences in route priorities—mass transit or social safety net to name only two, must be considered. In the

immediate term, this will probably mean that the introduction of BEV buses will be confined to operationally appropriate routes. The staged introduction of BEV vehicles is another topic identified for future research.

It is also noted that the studied shuttle service involved all passengers boarding at one stop and then alighting at the next. The already allocated time at each stop was generous and no detailed analysis of passenger loading and alighting times has been included. On other routes with short-scheduled dwell times and large passenger loads in peak periods recharging is likely to have greater impact boarding and alighting times, as well as service capacity. Further research might investigate the interplay of passenger boarding and alighting time with vehicle charging in more detail, although clearly locating chargers where there are likely to be longer passenger loading periods is to be preferred so that charging and loading can be undertaken simultaneously.

The interconnected nature of battery size and charge requirements means that available operation time must be divided between driving and recharging vehicles. The significance of infrastructure in successful provision of a BEV bus service is, therefore, evident when considering study outcomes. Benefits of increasing recharge opportunities are twofold: allowing for a reduction of battery size that in turn maintaining passenger capacity; and distributing the impact of recharge dwell time across multiple shorter instances rather than a single lengthy charge. Further benefits may also arise when considering vehicle purchase cost. This is because utilisation rate of charge stations is different to costs of batteries in a transport service. Unlike batteries, which are a per-vehicle investment, charge stations may be shared between numerous buses operating in and around a certain service—providing that scheduling is planned accordingly. Incorporating smaller battery packs and a greater number of charge stations shifts financial investment from vehicle to fleet level, which may reduce the overall cost of technological investment.

## 6. Conclusions

This study explored the interconnected challenges of vehicle scheduling, charging, energy storage and passenger capacity for a BEV bus service. In an attempt to balance these factors and provide a comparable level of service to diesel ICE buses, four scenarios for BEV buses were explored. Study results showed that larger batteries provided greater operational flexibility as they were less reliant on infrastructure and presented minimal time penalty to service schedule. On the other hand, smaller batteries were more reliant on recharge instances during operation and required more time to recharge. This operational compounding is unique to BEVs, as their diesel counterparts do not need to place such emphasis on energy storage and refuelling. A further finding was that larger batteries reduced vehicle headway, though did not always increase service passenger capacity, which was, once again, a contrast to ICE buses. In the studied service, BEV buses with smaller batteries, greater charging frequency and longer headways were able to transport more passengers per hour than BEV buses with greater on-board energy storage and less dependence on infrastructure. These findings indicate that the context for BEV application must be carefully considered to specify an appropriate energy storage capacity and develop a suitable schedule. BEV and ICE buses differ in functional characteristics with some significant impacts on the scheduling process. Reconsideration of vehicle scheduling to incorporate energy storage capacity and recharge opportunity can mitigate passenger capacity reduction and dwell time increases.

## References

- Ally, J., & Pryor, T. (2016). Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study. *Energy Policy*, 94, 285-94.
- Altair Nanotechnologies. (2012). Nano lithium–titanate battery module. Retrieved from <http://www.altairnano.com/wp-content/uploads/2011/10/60Ah-DataSheet.pdf%3E>.
- Australian Bus and Coach. (2015). Bus sales data. Retrieved from <http://www.busnews.com.au/bus-sales-data/data/%3E>.
- Burke, A., Miller, M. & Zhao, H. (2012). Fast charging tests (up to 6C) of lithium titanate cells and modules: electrical and thermal response. paper presented to Electric Vehicle Symposium (EVS26), 6-9 May, Los Angeles.
- Build Your Dreams (BYD). (2014). BYD 12m Electric Bus Specifications. Retrieved from <http://www.byd.com/ap/ebus.html#spec>
- Chao, Z. & Xiaohong, C. (2013). Optimizing Battery Electric Bus Transit Vehicle Scheduling with Battery Exchanging: Model and Case Study. *Procedia - Social and Behavioural Sciences*, 96, 2725-36. doi: 10.1016/j.sbspro.2013.08.306
- Cook, P.J. (2012). *Clean energy, climate and carbon*. Clayton, VIC: CSIRO Publishing.
- De Filippo, G., Marano, V. & Sioshansi, R. (2014). Simulation of an electric transportation system at The Ohio State University. *Applied Energy*, 113, 1686-91. doi: 10.1016/j.apenergy.2013.09.011
- Department of Infrastructure and Transport 2012, Vehicle Standard (Australian Design Rule 58/00 – Requirements for Omnibuses Designed for Hire and Reward), Commonwealth of Australia.
- Erkkilä, K, Nylund, N-O, Pellikka, A-P, Kallio, M, Kallonen, S, Kallio, M, Ojamo, S, Ruotsalainen, S, Pietikainen, O & Lajunen, A 2013, 'eBUS - Electric bus test platform in Finland', paper presented to Electric Vehicle Symposium (EVS27), 17-20 November, Barcelona.
- Gerssen-Gondelach, S. J. & Faaij, A. P. C. (2012). Performance of batteries for electric vehicles on short and longer term. *Journal of Power Sources*, 212, 111-29. doi: 10.1016/j.jpowsour.2012.03.085
- Honnery, D, Napper, R, Fridman, I, & Moriarty, P 2016, 'Spatially differentiated energy and environment comparison of diesel and electric buses', presented to Australasian Transport Research Forum (ATRF), 16-18 November, Melbourne.
- International Association of Public Transport (UITP). (2012). *Report on electrified public transport bus systems*. Landshut: VDV/UITP.
- Ke, B. R., Chung, C. Y. & Chen, Y. C. (2016). Minimizing the costs of constructing an all plug-in electric bus transportation system: A case study in Penghu. *Applied Energy*, 177, 649-60. doi: 10.1016/j.apenergy.2016.05.152
- Kulkarni, A., Kapoor, A. & Arora, S. (2015). Battery packaging and system design for an electric vehicle. *SAE International*, 2015-01-0063. doi: 10.4271/2015-01-0063
- Lajunen, A. (2014). Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies*, 38, 1-15. doi: 10.1016/j.trc.2013.10.008
- Larminie, J & Lowry, J 2012, 'Batteries, flywheels and supercapacitors', in *Electric vehicle technology explained*, 2nd edn, John Wiley & Sons, Ltd, pp. 29-78. DOI: 10.1002/9781118361146.ch3

- Li, J. Q. (2014). Transit Bus Scheduling with Limited Energy. *Transportation Science*, 48 (4), 521-539. doi: 10.1287/trsc.2013.0468
- Mahmoud, M., Garnett, R., Ferguson, M. & Kanaroglou, P. (2016). Electric buses: A review of alternative powertrains. *Renewable and Sustainable Energy Reviews*, 62, 673-84. doi: 10.1016/j.rser.2016.05.019
- Miles, J. & Potter, S. (2014). Developing a viable electric bus service: The Milton Keynes demonstration project. *Research in Transportation Economics*, 48, 357-63. doi: /10.1016/j.retrec.2014.09.063
- Nykqvist, B. & Nilsson, M. (2015). Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change*, vol. 5 (4), 329-32. doi: 10.1038/nclimate2564
- Public Transport Victoria (PTV) 2015, The Victorian bus and truck drivers' handbook, State Government of Victoria, viewed 10 May 2016, <https://www.vicroads.vic.gov.au/business-and-industry/heavy-vehicle-industry/bus-and-truck-driver-handbook>
- Reuer, J, Kliwer, N & Wolbeck, L, 2015 'The electric vehicle scheduling problem: A study on time-space network based and heuristic solution approaches', paper presented to Conference on Advanced Systems in Public Transport (CASPT), 19-23 July, Rotterdam.
- Seligmann, P 2010, Australian sustainable energy : by the numbers, Melbourne Energy Institute Victoria, Victoria.
- Volgren 2014, Optimus low-floor route bus. viewed 10 October 2015, [http://www.volgren.com.au/wp-content/uploads/2015/06/Optimus-Product-Sheets\\_2014.pdf%3E](http://www.volgren.com.au/wp-content/uploads/2015/06/Optimus-Product-Sheets_2014.pdf%3E).
- Volvo 2011a, Volvo B7RLE MK3 data sheet, viewed 4 November 2013, <http://www.volvobuses.com/bus/australia/en-au/Factsheets/B7RLE/Pages/Introduction.aspx%3E>.
- Volvo 2011b, Gearbox D864.5 factsheet, viewed 13 February 2014, <http://www.volvobuses.com/SiteCollectionDocuments/VBC/Downloads/Volvo-Factsheet-Voith-D864.5-EN.pdf%3E>
- Wang, H & Shen, J 2007, 'Heuristic approaches for solving transit vehicle scheduling problem with route and fueling time constraints', *Applied Mathematics and Computation*, vol. 190, no. 2, pp. 1237-49. DOI: 10.1016/j.amc.2007.02.141
- Wen, M, Linde, E, Ropke, S, Mirchandani, P, Larsen, A 2016, 'An adaptive large neighbourhood search heuristic for the electric vehicle scheduling problem', *Computers and Operation Research*, vol. 76, pp. 73-83. DOI: <http://dx.doi.org/10.1016/j.cor.2016.06.013>
- ZF Friedrichshafen. (2016). Product overview: Axle and transmission systems for buses and coaches. Retrieved from [http://www.zf.com/global/media/product\\_media/busses/product\\_overview\\_1/product\\_overview\\_axle\\_transmission\\_systems.pdf](http://www.zf.com/global/media/product_media/busses/product_overview_1/product_overview_axle_transmission_systems.pdf)



## Appendix: BEV service calculation model

This section describes parameters for the BEV service calculation model. Based on the collected data, calculation was divided into three focus areas: vehicle capacity, charging requirements and service schedule. These were applied to the two test bus designs presented in Section 3.1 using mathematical models in Microsoft Excel.

### Vehicle capacity

The process of calculating vehicle passenger capacity for each test bus can be described by the following formula.

Factors:

$E_B$  – Energy storage capacity of battery pack (kWh)

$M_B$  – Battery mass (kg)

$E_{SM}$  – Energy storage per unit mass (kWh/kg)

$M_V$  – Vehicle dry mass (kg)

$M_{VK}$  – Vehicle kerb mass (kg)

$M_{VT}$  – Permissible total vehicle mass (kg)

$M_p$  – Individual passenger mass (kg)

$C_V$  – Vehicle passenger capacity

$$M_B = \frac{E_B}{E_{SM}} \quad (1)$$

$$M_{VK} = M_V + M_B \quad (2)$$

$$C_V = \frac{M_{VT} - M_{VK}}{M_p} \quad (3)$$

Vehicle passenger capacity for Test Bus 1 and 2 was calculated based on permissible total vehicle mass, which is regulated by state authorities—as discussed in Section 3.1. Once battery pack mass was understood (1) it could be added to generate each vehicle's kerb mass (2), from which the remaining mass allowance dictated passenger capacity (3).

### Charging Requirements

Charging requirements were calculated on a combination of route and vehicle data in accordance with determined energy storage capacity.

Factors:

$D$  – Distance (km)

$E_A$  – Energy consumption average (kWh/km)

$E_R$  – Energy required (kWh)

$E_B$  – Energy storage capacity of battery pack (kWh)

$D_C$  – Drive cycles per charge

$D_D$  – Drive cycles per day

$C_D$  – Charges per day

$P_C$  – Power rate for charge (kW)

$T_D$  – Time charging daily (h)

$T_C$  – Time per charge instance (h)

$T_T$  – Time per trip (h)

$T_O$  – Time operating per day (h)

## Equations

$$E_R = DE_A \quad (4)$$

$$D_C = \frac{E_B}{E_R} = \frac{E_B}{DE_A} \quad (5)$$

$$D_D = \frac{T_O}{T_T} \quad (6)$$

$$C_D = \frac{D_D}{D_C} = \frac{T_O DE_A}{T_T E_B} \quad (7)$$

$$T_D = \frac{E_B C_D}{P_C} = \frac{T_O DE_A}{P_C T_T} \quad (8)$$

$$T_C = \frac{T_D}{D_D} = \frac{DE_A}{P_C} \quad (9)$$

Recharge opportunity and the time required per charge instance ( $T_C$ ) were calculated using equations 4 – 9. These involved calculation of the energy storage requirement ( $E_R$ ), number of drive cycles per charge ( $D_C$ ), drive cycles per day ( $D_D$ ), charges per day ( $C_D$ ) and time charging daily ( $T_D$ ). Once charging requirements were understood, vehicle scheduling could be attempted with sufficient allowance for recharging the on-board battery pack.

## Service Capacity

Service capacity was calculated based on travel time, dwell time, frequency and vehicle capacity as shown in the following.

Factors:

$T_{ij}$  – Travel time between stops i and j

$W_i$  – Dwell time at stop i, including any layover (such as for battery charging)

$S$  – total number of stops

$T_R$  – Round trip time (including dwell time and layover)

$V$  – Vehicles

H – headway

F – Frequency

$C_v$  – Vehicle passenger capacity

$C_s$  – Service passenger capacity

$$T_R = \sum_{i=1}^{S-1} (W_i + T_{(i)(i+1)}) + W_s + T_{(s)(1)} \quad (10)$$

$$H = \frac{T_R}{V} \quad (11)$$

$$F = \frac{1}{H} = \frac{V}{T_R} \quad (12)$$

$$C_s = C_v F = \frac{C_v}{H} = \frac{C_v V}{\sum_{i=1}^{S-1} (W_i + T_{(i)(i+1)}) + W_s + T_{(s)(1)}} \quad (13)$$

Equation 10 shows how round trip time is the summation of dwell time (including layover) at each stop and the travel time between stops, with the final  $T_{(s)(1)}$  representing the time required for the vehicle to return from the final stop to the starting point. As the route considered in this paper consists of only two stops, this equation simplifies to only four components, being the dwell time at the two stops and the travel time between from one to the other and back again.

The average headway during the peak period of service is the round-trip time divided by the number of vehicles (11), which allows service frequency to be calculated (12). Equation 13 shows the service capacity, which is related to the passenger capacity of each vehicle, the number of vehicles, the travel time between stops and the dwell time at each stop.