

Planning an Electric Vehicle Battery-Switch Network for Australia

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1. Introduction

With growing interest in electric vehicles (EVs) as a future vehicle technology, Australian and New Zealand governments are considering the possible impacts of EVs on infrastructure development, travel patterns, carbon emissions, power generation and energy consumption¹.

Current EV battery technology typically enables fully-electric vehicles to travel between 100 and 200 kilometres between recharges. The distance depends on the battery characteristics, vehicle mass, driving conditions and terrain. With at-home charging facilities, most drivers will be able to charge a vehicle's battery overnight (subject to power availability), then start the day with a full charge.

If a vehicle needs to travel further than the battery range will allow, then the battery must be recharged en route. Charging times are likely to be lengthy – a quick charge may take around 30 minutes and a trickle charge several hours. If a vehicle is stopped in one place for an extended period (for example, at a workplace during the day), then a charging period of several hours may be acceptable. However, on long continuous journeys, lengthy charging times are unlikely to be practical. This is seen by some as the main limitation of plug-in vehicles (Blackburn 2011).

One solution that is being implemented by EV service provider, Better Place, is the concept of a battery-switch station (see Figure 1). On specially-designed vehicles, batteries can be quickly removed and replaced, allowing drivers to resume their journeys in minutes rather than hours. Better Place is currently rolling out battery-switch stations in Israel and will commence an Australian roll-out in Canberra during 2012.

The geographic distribution of battery-swap stations is expected to be a key determinant in the take-up of EVs. The roll-out of stations will be staged over a number of years, so one of the initial challenges will be to determine locations that provide optimal coverage for the target market, given the small number of sites initially available. Coverage will depend on a range of physical and behavioural factors:

- the driving range of EVs between recharges;
- deviations required from drivers' routes needed to access battery exchange stations;
- the availability of recharge points at vehicle parking locations;
- typical distances travelled by EV users in a day;

¹ EV trials are currently being carried out in Western Australia and Victoria (Government of Western Australia 2011, State Government of Victoria 2011). Smaller trials have been carried out in Wellington (Clean Energy Finance News 2010), New South Wales (Smart Grid Australia 2011) and the Gold Coast (Gold Coast City Council 2010), with New South Wales also carrying out feasibility studies (AECOM 2009).

- **Figure 1: The battery switch station in Roppongi Hills, Tokyo, used in a 2010 electric taxi trial run by Better Place**



- “comfort thresholds” of the level of battery charge depletion that drivers will tolerate before seeking a new battery; and
- availability of suitable sites.

This paper describes a model for identifying the optimal geographic locations for battery-swap stations and how best to stage the roll-out over an extended time period.

The paper is structured as follows:

- Section 2 describes several location models described in the international literature and recommends a model that could be used with EV battery-swap stations.
- Section 3 considers driver behaviours relating to battery swapping, and develops a set of behavioural rules that might be considered in a model.
- Section 4 applies these principles in a working concept model of the Melbourne metropolitan area
- Section 5 concludes the paper with a summary of the key findings.

2. Location Models

2.1 Efficiency and exposure

Location models are commonly used to determine optimal sites for retail outlets, warehouses and other services. They are usually based on minimising the distance travelled by users of the service (efficiency) or maximising the number of people who pass the location (exposure).

The following sections provide a brief overview of three location approaches commonly used for modelling facilities for alternative-fuel vehicles²:

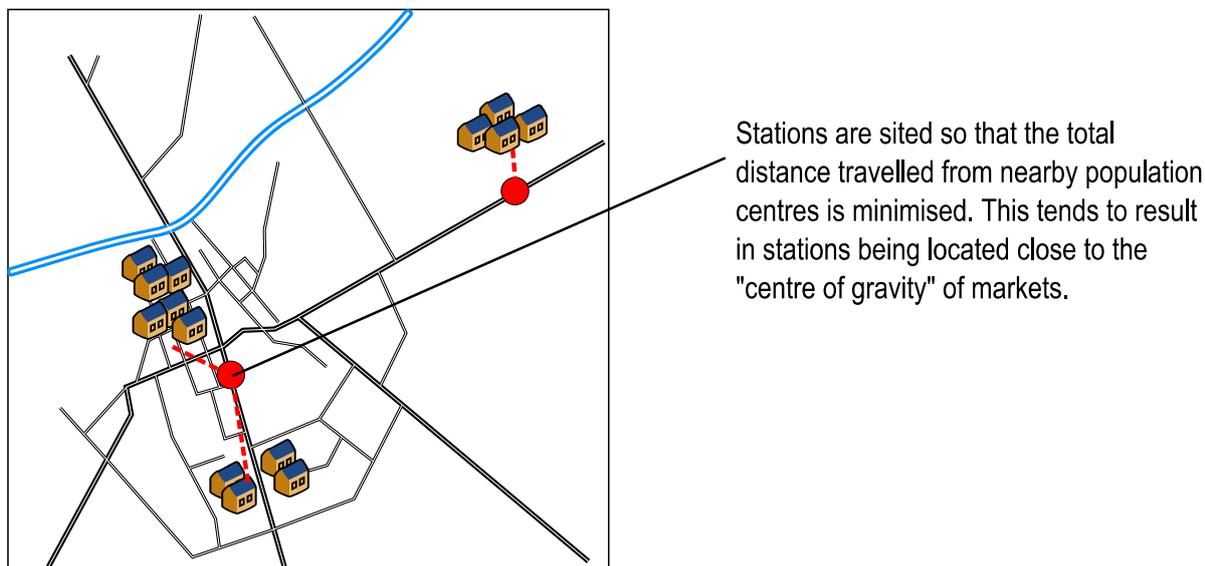
- the p-median model;
- the flow-capturing location model; and
- the flow-refuelling location model.

We show that the third of these – the flow-refuelling location model – has many of the desirable characteristics needed for modelling battery-switch stations.

2.2 The p-median model

The p-median model is one of the most commonly-used models in location analysis. In simple terms, it attempts to locate p facilities so that the sum of the distances travelled by each customer to the nearest facility is minimised. Figure 2 illustrates the basic concepts of the p-median model.

■ **Figure 2: The p-median model**



We assume that most EV drivers will charge their vehicles at home, and are unlikely to require a battery-swap when setting out from home. It is more likely that drivers will swap batteries on longer journeys at some intermediate point along their route.

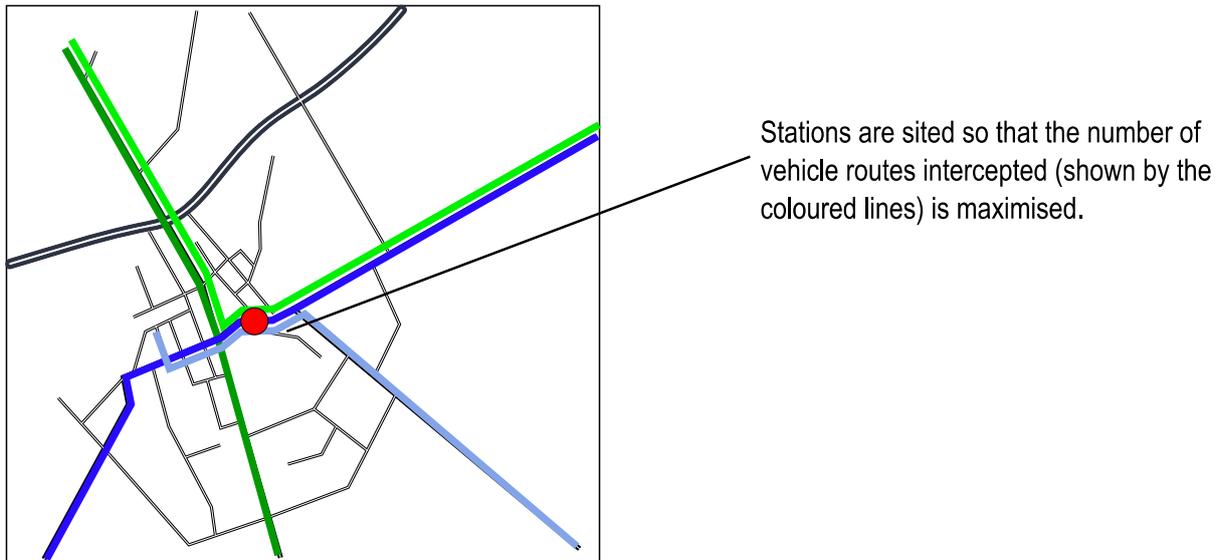
A p-median model based on home locations is therefore not likely to accurately reflect real battery-swapping behaviour. A better approach would be to identify the driving routes of EV trips and locate stations to intercept these routes. This is the intent of the flow-capturing location model described in the next section.

2.3 The flow-capturing location model

The flow-capturing location model (FCLM) considers the routes used by drivers, then seeks to locate stations so as to maximise the number of routes intercepted by the stations. Figure 3 shows a simple application of the capturing model.

² Much of this discussion is based on the work of Upchurch & Kuby (2010).

■ **Figure 3: The flow-capturing location model**



The capturing model is well-suited to applications such as the siting of roadside advertising billboards. In these cases, the objective is to maximise exposure, and locations are typically chosen along the most heavily-trafficked routes.

However, the capturing model does not consider the distance travelled by each driver along his or her route. If the model was to be applied directly to the EV battery-switch problem, it would result in many drivers seeing a station en route, but not necessarily at the locations where a swap was needed.

A more refined approach would consider the battery charge state of each vehicle and locate stations where battery swaps were most often required. This is the objective of the flow-refuelling location model described in the next section.

2.4 The flow-refuelling location model

The flow-refuelling location model (FRLM) is an adaptation of the capturing model proposed by Kuby and Lim (2005). Although originally designed for siting hydrogen refuelling stations, the refuelling model uses principles that are also applicable to battery-switch stations (with appropriate modifications).

The key difference between the capturing and refuelling models is in how they treat a route as “captured” by a refuelling station. The capturing model considers a route captured if a driver encounters a station anywhere along the route. The refuelling model, on the other hand, only considers a route serviced if a vehicle will have enough fuel (or electric charge) to travel between successive stations.

The refuelling model has been applied to several real-world examples, both at the statewide and metropolitan-area level. Kuby et al (2009) describe an optimisation study for hydrogen refuelling stations in Florida.

The model described in this paper is based on the principles of the refuelling model and has been extended to suit electric vehicle battery-switching requirements. The next section describes the behavioural assumptions underlying the model.

3. Battery Switching Logic

The optimisation model is based on a set of behavioural assumptions about how EV drivers will use battery-switch stations. The assumptions proposed in this paper were developed in consultation with Better Place Australia.

3.1 Definitions

The following terms are used in describing EV trips:

- **Full-charge threshold** refers to the typical distance that can be travelled by an EV with a fully-charged battery. It should include a margin of safety to allow for energy-depleting driving conditions such as hilly terrain and use of vehicle appliances such as air-conditioners. Most drivers are expected to swap batteries well in advance of the battery being fully depleted to avoid anxiety about the low charge.
- **Half-charge threshold** refers to the distance that can be travelled by an EV with a battery that is half charged. For simplicity, we assume that the relationship between battery charge and distance is linear, and that the half-charge threshold is exactly half of the full-charge threshold.

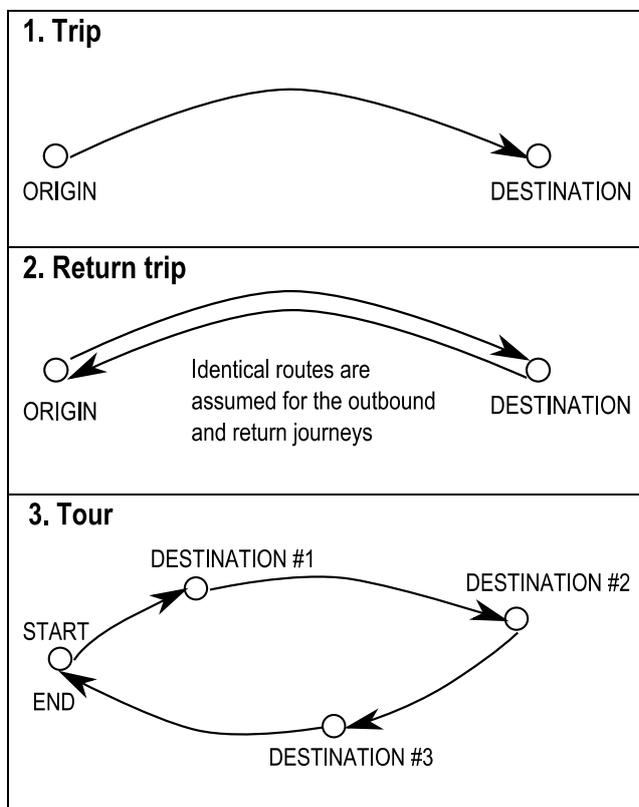
3.2 Tours and trips

Most transport models use individual trips as the basic unit of travel. Each trip has a single origin and single destination, and is generally associated with a single purpose and time of day.

However, when considering EV travel, a model ideally needs to consider the complete set of trips that a vehicle makes during the day. This will give a more accurate picture of battery depletion between charges. In this report, we refer to these 24-hour vehicle trip sequences as tours.

We originally approximated vehicle tours using the concept of a return trip. A return trip was defined as a single trip reflected so that the driver returns along the same path to the starting point (see Figure 4). Return trips were initially thought to be a reasonable approximation to tours, assuming that most tours have only short side trips to intermediate destinations.

■ **Figure 4: Definition of trips, return trips and tours**



However, a comparison of tours and trips from household travel surveys in Victoria, New South Wales and Queensland showed that tours were in fact substantially longer than return trips (Table 1).

Table 1: Victoria, NSW and Queensland tour and trip comparisons

	VIC	NSW	QLD
Name	Victorian Integrated Survey of Transport and Activity (VISTA 07)	Household Travel Survey (HTS)	South East Queensland Travel Survey (SEQTS)
Weekday car driver trips (unweighted sample size)	56,521	80,530	99,807
Weekday vehicle tours (unweighted sample size)	15,561	17,667	21,073
Average trip distance	11km	11km	12km
Average tour distance	40km	42km	52km
Percentage of tours longer than 120km	5.4%	5.0%	9.5%

Tours greater than 120km were considered as candidates for battery switching. Shorter tours were assumed to use batteries charged at home or a fleet depot. Despite the smaller sample size of tours (in comparison to trips), the final model used tours as the basis for determining station locations. The more realistic vehicle travel distances and routes provided by tours were considered to outweigh the reduced sample size.

3.3 Battery switching rules

Figure 5 shows the rules that were adopted in the model. The purpose of the rules was to determine whether or not a particular vehicle path could be serviced by a particular combination of battery-switch stations.

Three of the rules (#1, #3 and #4) relate to the spacing of stations along a vehicle's path. If the stations are too widely spaced, there will be insufficient battery charge for the journey to be completed.

The other two rules (#2 and #5) relate to the level of battery charge at the start of a vehicle's trip. Normally, we would assume that trips starting at a driver's home would start with a fully-charged battery³. However, trips that originate at locations without a charge point (e.g. a workplace or house with no off-street parking), would not necessarily start with a full charge. In these cases, it would be important that the vehicle has sufficient charge to make a round trip to the nearest battery swap station.

³ In other words, we assume that there will be a charging point at the driver's home and the driver will charge the battery while the car is parked at home.

■ **Figure 5: Battery switching rules⁴**

	<p>1. If the distance from the start point to the first station is more than the full-charge threshold then the path cannot be covered.</p>
	<p>2. If there is no charge point at the origin then the distance to the nearest station must be less than the half-charge threshold. This ensures that the vehicle can make a return journey to the nearest swap station.</p>
	<p>3. If distance between successive stations is more than the full-charge threshold then the path cannot be covered.</p>
	<p>4. If the distance from the last station to the furthest point on the path is more than the half-charge threshold, then the path cannot be covered (unless there is a charge point at the vehicle's destination).</p>
	<p>5. If there are no stations on the path, the vehicle must charge at the origin and the total distance must be less than the half-charge threshold (to allow for the return trip).</p>

LEGEND:

-  Battery-swap station
-  Half-charge distance
-  Full-charge distance
-  Vehicle path

⁴ In practice, these five rules can be simplified: a path is covered if each point on the path is within the half-charge threshold of a swap station, an origin with a charger, or a destination with a charger.

4. Model Specification

4.1 Inputs

The battery-switch station location model has three main sets of inputs:

- A representative sample of vehicle paths derived from a household travel survey. The paths must also include weights to allow the sample to be expanded to the full population.
- A set of candidate station locations specified as longitude and latitude co-ordinates.
- A set of model parameters, comprising:
 - the vehicle driving range (km)
 - the maximum detour distance that a driver will tolerate in order to find a battery-switch station
 - the assumed battery charge level at the start of each journey (half or full charge).

The vehicle paths were calculated using the RoadLink traffic assignment model (McPherson 1999). The RoadLink model took car trip (or tour) data from household travel surveys and determined the likely sequence of roads used by each traveller. Unlike traditional shortest-path approaches, the model uses information supplied by survey respondents about the roads actually used en route (if this information is supplied). This allowed paths to be determined that better reflected the actual routes taken by drivers.

The list of candidate station locations was chosen to provide exhaustive coverage of the entire network. Locations were initially determined by overlaying a grid of points at one-kilometre intervals on the network. This resulted in a very large number of potential station locations, some of which were not situated near roads.

A better result was obtained by extracting road intersections from a digital road network and using these points as the candidate list. This resulted in complete coverage of the road network, more precise locating of stations on roads and quicker model calculations.

4.2 Optimisation methodology

A stand-alone optimisation model was developed using the C# programming language for Microsoft Windows platforms. The software application makes use of third-party GIS components to read and write ArcGIS maps, enabling easy integration with geographic information systems and Google Earth (see Figure 6).

The optimisation model used the following steps, following the approach used by Kuby and Lim (2005):

1. Individual vehicle trips reported in the household survey were concatenated to form tours.
2. All vehicle paths that did not require a battery switch were removed from the sample. (i.e. tours shorter than the assumed vehicle range of 120km).
3. Each candidate station location was successively tested to determine the incremental number of vehicle paths that could be completed if the station was assumed to be operational. The battery-switch rules described in Figure 5 were used to determine whether paths could be served. The station that enabled the greatest increment in vehicle paths served was added to the final list of ranked stations.

4. Step 3 was repeated, with previously-ranked stations considered to be operational. At each iteration, the next most effective station location was determined and added to the ranked list.

5. When no more trips could be serviced by adding a further station, the process terminated.

This “greedy” algorithm will not always produce an exactly optimal solution, but produces near-optimal solutions that are usually sufficiently accurate for planning purposes. Lim and Kuby (2010) discuss several heuristic extensions to the refuelling algorithm to improve optimality.

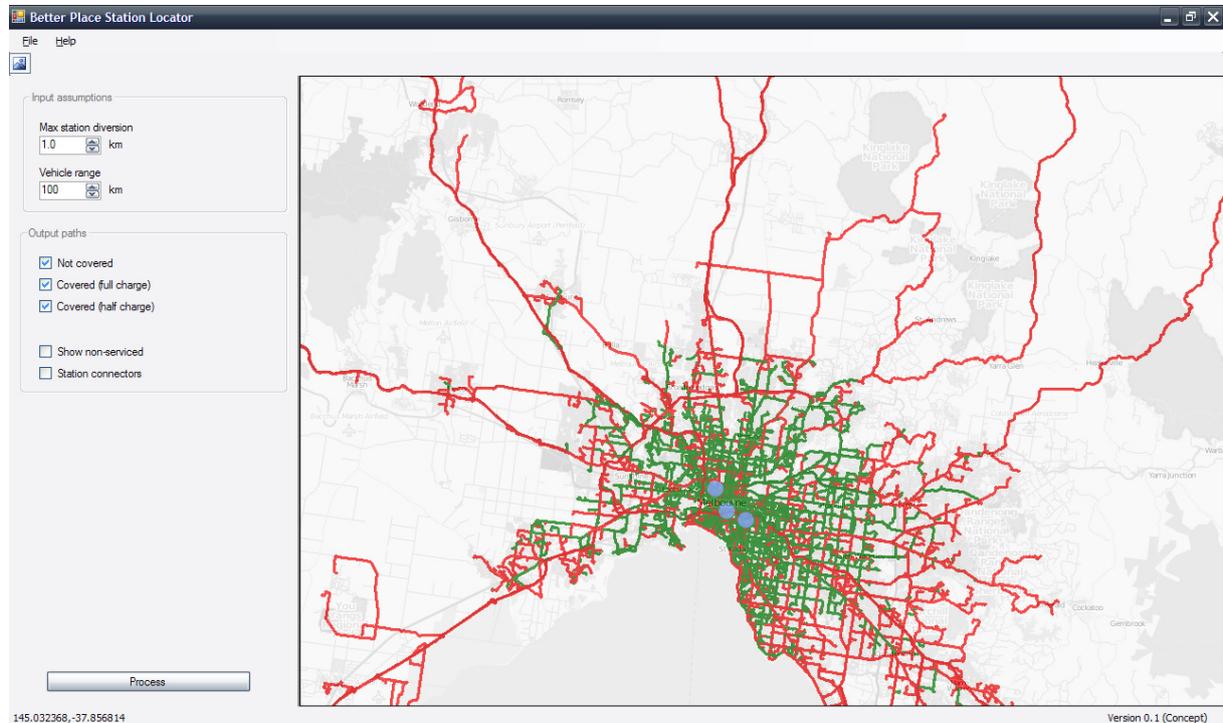
4.3 Outputs

The outputs from the model are:

- a GIS database of station locations;
- the incremental number of vehicles served by each station;
- the incremental number of vehicle kilometres served by each station.

The stations are ranked according to the total number of additional vehicle tours that are enabled by the station. Stations with the highest ranks (1, 2, 3...) will have the biggest impact and could be considered for construction early in a roll-out of battery-switch stations.

■ **Figure 6: Screenshot of optimisation model software**



5. Outcomes

5.1 Sensitivity tests

A series of sensitivity tests were performed to determine the impact of the model assumptions on the distribution of stations. The tests considered the following variables:

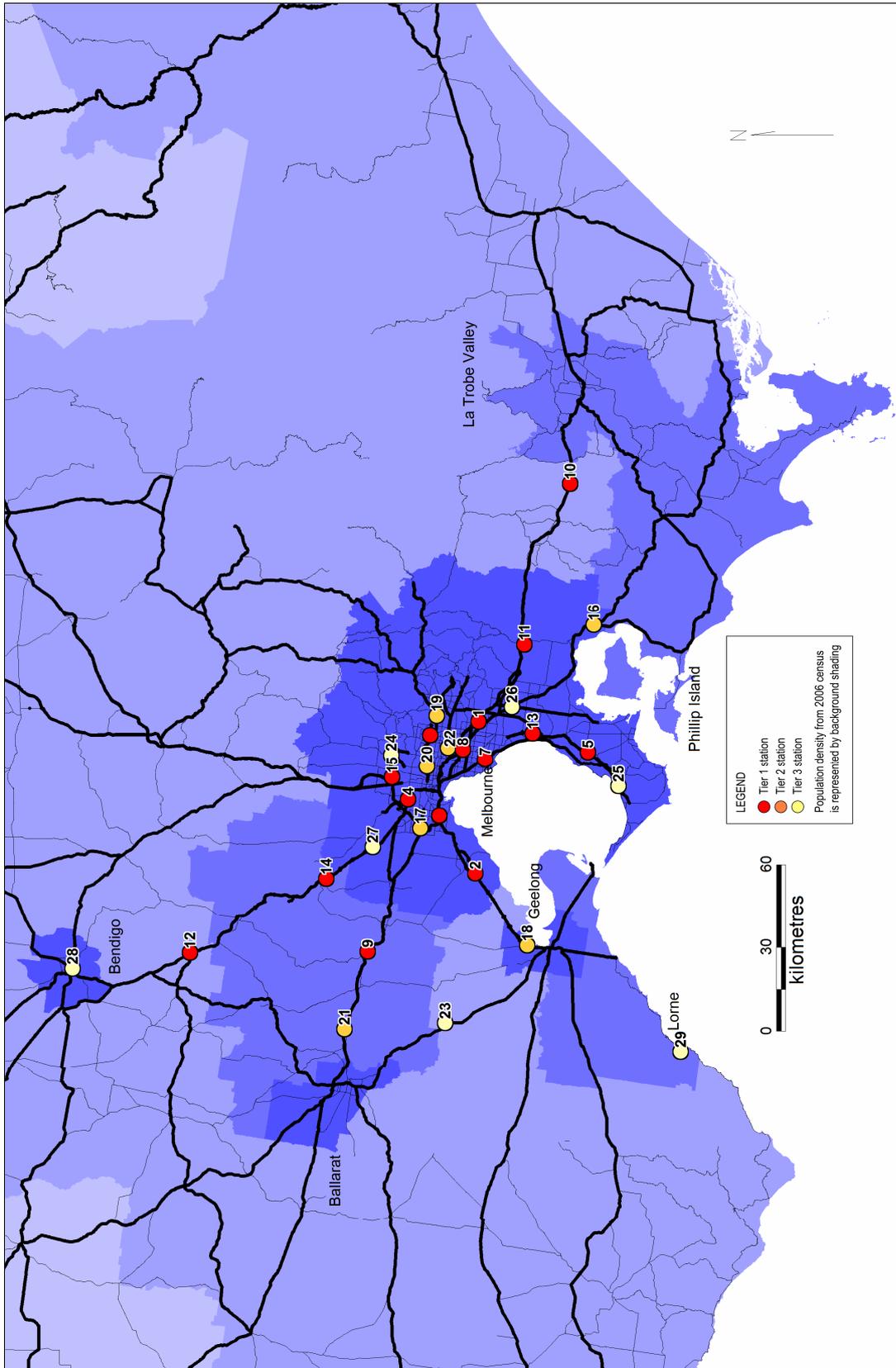
- **Tours and trips.** As explained earlier, tours and trips provide different bases for determining vehicle routes. Both were tested to determine the impact on station locations. Tours tended to produce a more compact configuration of stations than trips. This seems to be a logical outcome of the tour geometry: whereas trips are typically elongated linear journeys, tours tend to be more circuitous and localised.
- **Vehicle range.** This paper has assumed a typical EV range of 120km. However in hilly terrain or situations where the car's air-conditioner is in use, the range may be reduced. In addition, some drivers may become anxious when there is little charge remaining, and may choose to switch batteries at shorter intervals. A test of a shorter 80 km range produced a more compact configuration of stations, as might be expected. Vehicle range was the variable that had the largest effect on station layouts.
- **Detour distance.** It is not yet known how far EV drivers would be prepared to divert from their chosen routes in order to access a battery-switch station. A short (700 metre) detour resulted in slightly more clustering of stations as drivers were assumed to be less willing to deviate from their chosen routes. Stations were generally located directly adjacent to major routes. A long (2.5 kilometre) detour resulted in more widely-spaced stations, but in built-up areas the stations were sometimes located away from the major arterial roads. This was particularly apparent where there were two parallel routes (for example, a freeway and an adjacent arterial road). In these cases, a station was often located midway between the two roads.
- **Starting battery charge.** Kuby and Lim (2005) note that if drivers travel to a remote destination from a refuelling point, they must retain at least half a tank of fuel at the destination in order to return to the charging point. In most cases, therefore, it would be reasonable to assume that an electric vehicle will start a journey with at least a half-charged battery. This is less of an issue for tours, as tours are usually expected to start from a location where the battery is fully charged (e.g. home or workplace). However, drivers that do not have charging facilities at home (e.g. residences with no off-street parking) may need to start with a partially-depleted battery. Tests showed that the half-charge starting assumption resulted in a slightly smaller geographic area being covered by a set of stations, but the number and ranking of stations was relatively insensitive to the charging assumption.

5.2 Case study: Greater Melbourne, Sydney and Brisbane

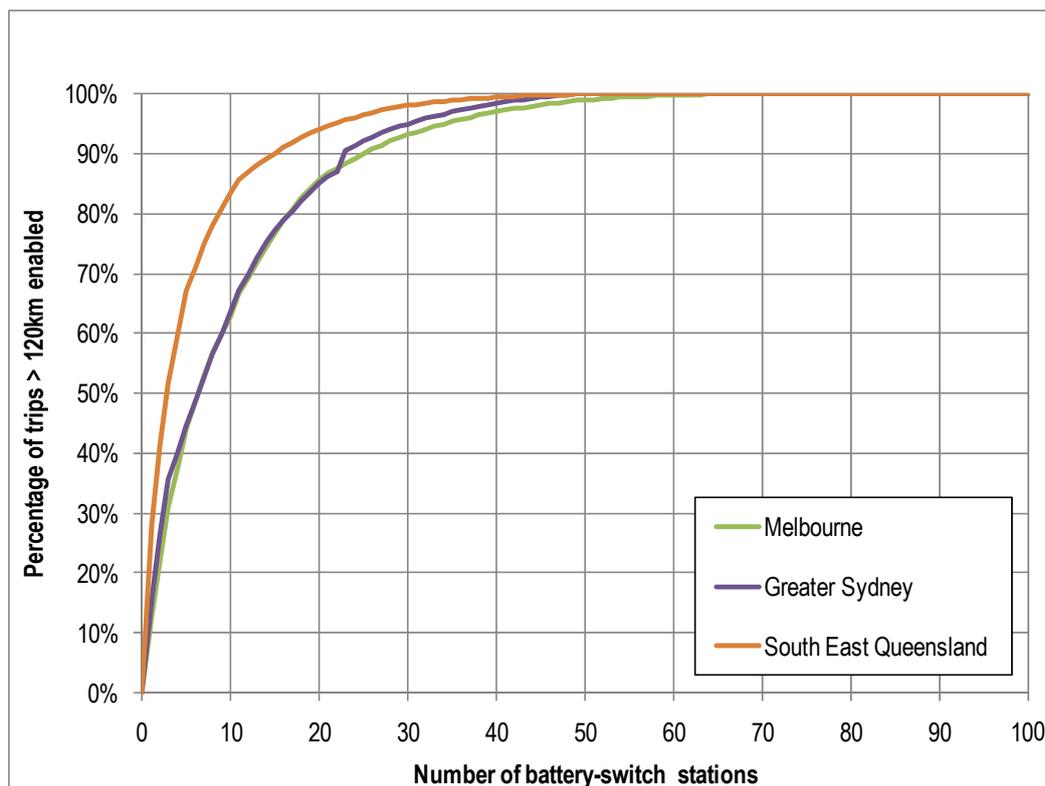
Figure 7 shows an example of optimised station locations for the Greater Melbourne area and nearby regional cities. The number attached to each station is its rank (i.e. stations with lower numbers have the greatest incremental effect). Stations were also classified into three tiers, as follows:

- Tier 1 - Locations considered essential for providing a basic network backbone.
- Tier 2 - "Infill" stations that provide more convenience for customers on key routes and in major population centres.
- Tier 3 - Strategic stations that will allow expansion into regional and tourist centres.

■ Figure 7: Example optimised station layout map for Greater Melbourne



■ **Figure 8: Percentage of vehicle tours greater than 120km served by number of stations⁵**



From the customer's point of view, the distribution of battery-switch stations should ideally be sufficient to cover all desired travel without excessive detours. A suitable measure of performance might be the proportion of trips (tours) that can be completed with a given network of stations.

The optimisation model produces statistics on the number of trips served by a given station layout and also the number of vehicle-kilometres. By successively measuring the performance of one station, then two stations, three stations and so on – until all possible trips are served – the model enables the incremental benefit of each additional station to be determined.

Figure 8 shows the proportion of tours greater than 120km that the model suggests will be covered by different numbers of stations in the Melbourne, Sydney and Brisbane regions.

The graph shows that most long tours are captured by the first ten stations, with the incremental benefit of each successive station slightly less than its predecessor.

The curve for south east Queensland rises more sharply than the Melbourne and Sydney curves, reflecting the more compact nature of the Brisbane arterial road network.

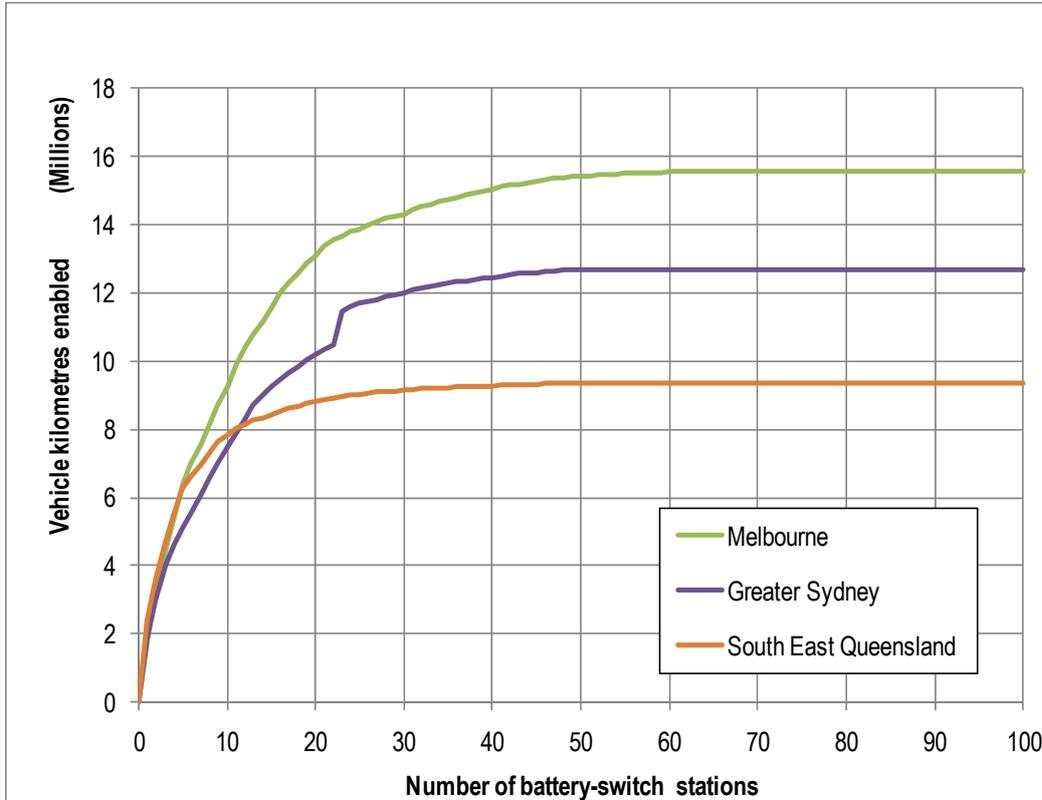
Figure 9 shows the total number of vehicle kilometres enabled by each successive station. The curves have a similar shape to those in Figure 8 – that is, the increment in vehicle kilometres provided by each successive station is slightly less than its predecessor.

While the shape of the curves is similar, Figure 9 shows that there are significant differences in total travel modelled for each region. These differences are mainly due to the size of the areas covered by the household travel surveys. The Victorian survey includes long trips to regional cities (an area of some 250x200 km), the Sydney survey covers the most heavily

⁵ The 'bump' on the Greater Sydney curve at the 23-station mark is due to station #23 opening up a corridor between a New South Wales regional city and the Sydney metropolitan area.

urbanised coastal regions (100x200 km) and the Queensland survey covers the Brisbane, Sunshine Coast and Gold Coast areas (50x200 km).

■ **Figure 9: Total vehicle kilometres served for tours greater than 120km by station count**



Despite the different geographic bases, it is notable that the first ten stations in each city appear to serve approximately the same amount of travel (8-9 million vehicle kilometres). Later stations expand the geographic range (which is largest in the case of Melbourne and smallest in the case of Brisbane).

6. Conclusion

Electric vehicles have the potential to revolutionise the private vehicle transport industry. An important hurdle in the uptake of electric vehicles will be their ability to make long continuous journeys similar to vehicles with internal combustion engines. A carefully-planned network of battery-switch stations is one promising solution that will allow the range of electric vehicles to be extended without undue inconvenience to drivers.

This paper has shown how principles from Kuby and Lim’s (2005) flow refuelling model can be adapted to plan such a network of stations. The model was tested with different sources of origin-destination data and it was found that daily tour data provided the best indication of vehicle journeys between overnight charges. In this study, household travel surveys were the primary source of this daily vehicle tour information.

A set of behavioural assumptions about how EV drivers may use battery-switch stations was developed in conjunction with Better Place Australia. Sensitivity testing was used to determine the impact of these assumptions on the distribution of stations, with the vehicle range assumption shown to have the largest effect on station layouts. In the future, the modelling process outlined in this paper may benefit from the findings of the various EV trials

being conducted in Australia and New Zealand. Observations from the trials may help to validate or improve the main behavioural assumptions underpinning the model.

Encouragingly, the modelling discussed in this paper shows that the number of stations required to enable longer vehicle trips is relatively low. The model suggests that Melbourne and Sydney would require about 10 stations to capture over 60% of long trips and 20 stations to capture over 85%. Brisbane, being a more compact city, is likely to require even fewer stations.

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