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Methodology to evaluate the operational suitability of electromobility systems for urban logistics operations

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Abstract

A methodology was developed to evaluate the operational suitability of electromobility concepts for last-mile delivery operations. Electromobility systems consisting of electric vehicles of ten weight classes and four mid-operation charging strategies were synthesized and evaluated using a hypothetical grocery outlet replenishment scenario. A system of operational suitability indicators was developed based on the amount of and efficiency of resources needed. The results highlight a strong trade-off between single-charge driving range, payload capacity, and the minimum fleet size needed. If operational performance similar to that of diesel vehicles is to be reached, mid-operation charging could be a reasonable alternative to "simply" having a bigger vehicle battery.

Keywords: Electromobility; Urban logistics; Last-mile delivery; Operational performance; Electric vehicle

1. Introduction

When considering the adoption of electric vehicles for goods transport, one is made aware of several operation-specific disadvantages in comparison to combustion engine vehicles: primarily the significantly less driving range, due in part to the technical and financial limitation of onboard energy storage, and the inconvenience of charging. Additionally, the heavy and large battery pack installed may reduce the payload capacity of the vehicle. The limited

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driving range and possibly reduced payload capacity are two technical constraints, which influence the operational capabilities of the vehicle. Nevertheless, technological advancement, such as fast charging and dynamic wireless charging, may reduce the disadvantages and remove barriers to adopting electric vehicles for logistics use.

Studies into the suitability of an electromobility[1]-based urban goods transport delve mostly into the economics of the vehicle purchase and the benefits to the environment (Davis, Figliozzi 2013; Feng, Figliozzi 2013; Lee et al. 2013). The exploration of how the vehicles would be used in the operation is secondary or assumed to be unchanged from how conventional vehicles would have been used. However, the aforesaid technical constraints may affect how the vehicles are being used; just as how range anxiety affects the distance a passenger vehicle would be driven (Moudrak 2013, p. 14). More research is required to understand how the technical specifications of the vehicles and chargers affect the operational capabilities of the goods transport system.

Real case studies of the electric vehicles could provide insight into the operational performance of the vehicles and the user acceptance (Jeeninga et al. 2002; Sustineo 2012). However, such an evaluation occurs at the product level, i.e. the purchased vehicles, and not at the conceptual level, which instead would allow the evaluation to be logically extended to other vehicles in the current (or future) market. The conceptual evaluation is especially appropriate for explorative studies in electromobility, where the technology still develops quickly. Accounting for the possible streams of development in the evaluation could aid the identification of the most suitable electromobility concepts for a given application; thus defining the emphasis future research should have. In particular, various charging strategies should be considered by the evaluation of concepts.

The research in this paper addresses the operational suitability of different electromobility concept variations for urban logistics operations. These concepts can vary in terms of the size of the vehicle, the desired single-charge driving range, and the type of charging infrastructure used. Wasson (2006, p. 50) defines operational suitability as the degree to which a system is "suited to a user's specific application in a given operating environment" and "integrates and performs within the user's existing system." The question of how well it performs is interpreted in this study as the efficient use of resources available for the movement of goods. An excellent review of operational freight transport efficiency, which is inextricably tied to performance, is found in Arvidsson's work, which develops a general definition of operational freight transport efficiency: "a set of utilisation measures of time, space, vehicle, fuel and driver in the movement of goods" (Arvidson 2011, p. 36). In this research paper, where the transport task is kept constant, an electromobility system's operational suitability is gauged based on the amount and the efficiency of allocated resources - time, space, vehicle, fuel, and driver. Note that the consideration of cost, such as total cost of ownership[2], is not included in the study, but could easily be added for further research.

Two aspects need to be considered for the evaluation. On one hand, the application context is important: the different urban structures; road network; size and type of the operation; amount and type of products shipped; and many other product-, operational- and city-specific characteristics drastically affect the transport system requirements. On the other hand, the diverse and still maturing electromobility technology may allow potential adopters to cope with the range and payload requirements of the operation. To account for these aspects, part of the study used methods to synthesize an electric vehicle fleet, simulate the daily driving schedule of each vehicle in the fleet for the given operation, and estimate the influence of using different charging strategies and systems. The variations implemented allow an analysis of the different trade-offs the use of one electromobility system has in place of another, in terms of battery capacity, fleet size, and charging power.

The paper is organized as follows. The methodology section reports different methods used in this study, from the creation of the scenario up to the evaluation of operational suitability. Then, the results are presented: the partial validation; a comparison with a conventional vehicle; and the evaluation of the operational suitability of the fleets. Finally, the study concludes with the major findings of the paper and several further research recommendations.

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[1] Electromobility is a concept that refers to the usage of electrified road transport. An electromobility system should at the very least include the electric vehicle and the charging system.

[2] The total cost of ownership considers "all costs arising with the ownership of an automobile including costs of purchasing, operating and maintaining, charges and taxes as well as costs of recycling and disposal over a specified timeframe under consideration of opportunity costs." (Gass et al. 2014, p. 98)

2. Methodology

The overview of the methodology explained in the following sub-sections is presented in Fig. 1. It starts with (a) the description of the logistics case scenario. Next, (b) the energy consumption model, which calculates the electrical energy required by each vehicle during its operation, is presented. Then, the weight and battery parameters are defined in (c) the synthesis of electric vehicle fleets, followed by the simulation of the driving schedule of the fleet vehicles using the (d) vehicle routing and scheduling methods. Both steps (c) and (d) require the use of (b) the energy consumption model. Based on the results of the (c) and (d), the (e) chargers' parameters are calculated. In this step, it is also evaluated whether the tested charger strategy is relevant for the fleet. Finally, in (f) the operational suitability of the electromobility systems to the logistics operations are evaluated based on the results of both (d) and (e). The details of the methods used are explained in the following sub-sections.
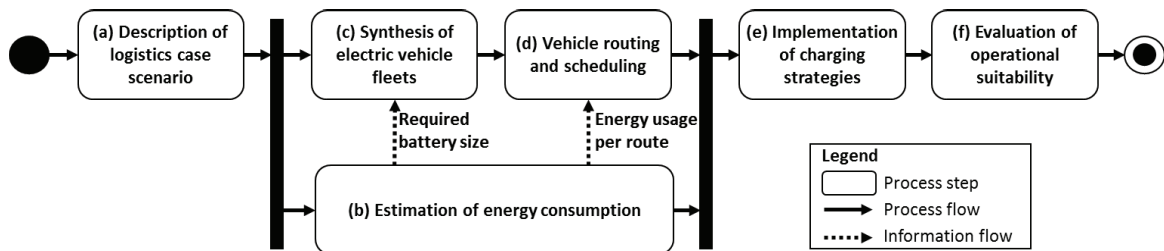

Fig. 1. Process diagram of methodology

2.1. Description of logistics case scenario

The hypothetical test case scenario is the replenishment of groceries of retail outlets from a centralized warehouse with refrigerated vehicles. The entire scenario occurs in Singapore. The locations of the stores and the warehouse are based on publicly available data on the website of a selected company, but the shipment demand is synthesized. The company transports cartons of groceries from its central warehouse to all the stores daily. The drivers work for nine hours and have an hour break sometime in between. Each outlet requests a number of cartons from the central warehouse, depending on the type of outlet. The volume per carton is assumed to be 0.025 m^3, and the average weight density of the shipment ρ_{goods} is assumed to be 360 kg.m^{-3}. As mentioned, in the routing methodology, the outlets are served by a homogeneous fleet. The full description of the case scenario based on these assumptions is shown in Table 1.

Table 1. Description of the case scenario with assumptions on the attributes of shipments

Type of outlet	Number of outlets (-)	Number of cartons (-)	Volume per outlet (m^3)	Weight per outlet (kg)
Convenience store	152	15	0.375	135
Premium supermarket	16	180	5	1,800
Supermarket	99	480	12.5	4,500
Hypermarket	7	1,200	30	10,800

2.2. Estimation of energy consumption

The energy consumption model considers the motion of the vehicle, auxiliary components of the vehicle, and the refrigeration of the cargo box. The motion and auxiliary energy consumption depend on the distance travelled, whereas the refrigeration depends on the duration of travel. The energy consumption in the route k, E^k, is calculated by equation (1) using: the average motive energy rate of leg j in route k, EM_j^k; distance of the leg, L_j; refrigeration

energy rate, ER^k; and route duration, D^k. The units of the variables E^k, EM^k_j, L_j, ER^k, and D^k are kWh, kWh.km^{-1}, km, kWh.h^{-1} and h respectively.

$$E^k = \sum_j (EM^k_j * L_j) + ER^k * D^k \tag{1}$$

The motive energy rate of the vehicle during leg j, EM^k_j is calculated taking into account two variables throughout the route: the weight and speed of the vehicle. An estimation model for EM^k_j, dependent on the weight of the vehicle at the time of motion, was created based on the simulation tool FASTSim[3]. The weight of the vehicle changes in each leg, due to the loading and unloading activities. The speed of the vehicle is accounted for in this tool using a driving cycle[4], the Urban Dynamometer Driving Schedule for Heavy Vehicles (Barlow et al. 2009, p. 39), which is a driving profile of goods vehicles in the urban areas. An estimation model for the refrigeration energy rate, ER^k dependent on the volumetric capacity of the cargo box was created based on the estimated rate of 3.6 kW per volume of 20' containers (Gesamtverband der Deutschen Versicherungswirtschaft e.V. 2003).

2.3. Synthesis of electric vehicle fleets

The number of goods electric vehicle models available in the market is few compared to internal combustion engine vehicles (Electrification Coalition 2013, p. 10). Rather than depending on existing electric vehicles, the study uses a quick method to create a representative electric vehicle model (indexed with i) for each vehicle weight class, W^i_{class}, based on the physical parameters of conventional combustion engine vehicles. The method here defines the following key parameters for each vehicle class: the weight of the battery, W^i_{batt}; the volumetric capacity, V^i_{cap}; and the effective payload capacity, W^i_{effcap}.

Ten models are created ($i=\{1,\ldots,10\}$). The vehicle is not permitted to be loaded, such that the weight of the vehicle exceeds the weight class designation. In the study, the current weight of the vehicle, W^i_{veh}, is the sum of the current weight of the payload, W^i_{pay}, and of the unladen weight of the vehicle, W^i_{empty}. The maximum W^i_{pay} allowed is termed the payload capacity, W^i_{cap}. The unladen weight of the vehicle, W^i_{empty} must be defined for each vehicle model I and is the sum of the weight of the vehicle body, W^i_{body}, and the weight of the battery, W^i_{batt}.

The1 weight of the vehicle body refers to the weight of the cab, the chassis, and the powertrain (minus the battery). Using a database containing the weights and size dimensions of 80 diesel vehicles, such as from manufacturers Nissan, Isuzu, Mitsubishi, Toyota and MAN, a regression model for the kerb weight ratio was created. This kerb weight ratio (dependent on the vehicle weight class) is then used in equation (2) to calculate the weight of the vehicle body for the different vehicles i.

$$W^i_{body} = W^i_{class} * (\text{Kerb weight ratio}) \tag{2}$$

The sizing of the battery capacity, E^i_{cap} in kWh is rounded up to the next ten based on the required energy for a vehicle to travel a given driving range, L^i_{range}, when loaded up to γ_{util} of the payload capacity of the vehicle, W^i_{cap}. Depending on the size of the vehicle, L^i_{range} is given as either 100 or 150 km. Here, it the route payload utilization γ_{util} is taken as 70%.

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[3] FASTSim stands for Future Automotive Systems Technology Simulator. FASTSim is an Excel-based energy consumption simulator, which was created to compare the performance of different vehicle powertrains by the National Renewable Energy Laboratory (2014).

[4] The driving cycle is a "vehicle speed and gear selection as a function of time", used as a means to measure emissions and energy consumption "under reproducible conditions" according to to Barlow et al. (2009, p. 2).

$$E_{cap}^{i} = \left\lceil EM\left(W_{empty}^{i} + \gamma_{util} * W_{cap}^{i}\right) * L_{range}^{i} / 10 \right\rceil * 10 \tag{3}$$

The weight of the battery is calculated based on a standard value of the specific energy of a lithium ion battery pack, ρ_{batt}, which is 0.11 kWh.kg^{-1}.

$$W_{batt}^{i} = \frac{E_{cap}^{i}}{\rho_{batt}} \tag{4}$$

The maximum payload of the vehicle should also consider the volumetric capacity of the vehicle. The deck dimensions were calculated using linear regression on the same vehicle database used for equation (2). The deck dimensions, deck length, l_{dl}^{i}, deck width, l_{dw}^{i}, and deck height, l_{dh}^{i}, were then used to determine the volumetric capacity of the vehicle, V_{cap}^{i}.

$$V_{cap}^{i} = l_{dl}^{i} * l_{dw}^{i} * l_{dh}^{i} \tag{5}$$

Depending on the average weight density, ρ_{goods}, of the transported goods, either the payload capacity, W_{cap}^{i} or volumetric capacity, V_{cap}^{i} would limit the vehicle loading. The effective payload capacity, W_{effcap}^{i} is calculated using equation (6).

$$W_{effcap}^{i} = \min\left(W_{cap}^{i}, V_{cap}^{i} * \rho_{goods}\right) \tag{6}$$

2.4. Vehicle routing and scheduling

The vehicle routing and scheduling model simulates the daily driving behaviour of the vehicles selected in the previous step. The vehicle routing model aims to fulfil the shipment orders, using a homogeneous fleet of vehicles synthesized in the previous section. The routing was conducted using the XCargo logistics software by LOCOM GmbH. The software provides distances routed on a GIS platform by Map&Guide in the Singapore network map.

The use of vehicle routing with the consideration of time-windows (i.e. customer-imposed delivery times) is common in transport planning, especially for home deliveries. However, in the research, this was neglected for two reasons. Firstly, the selected scenario did not demand it. Secondly, for this ex-ante evaluation, adding more complexity to modelling would not necessarily add more value to the work, specifically when the scenario was a hypothetical one. Nevertheless, for future research, the influence of time-windows could be included, such as done by Kunze (2004) and others.

For each vehicle type i, the set of routes **R** found by the routing algorithm serves as the input for the scheduling algorithm to be assigned to vehicle p. The algorithm ensures that the workload in terms of duration is similarly distributed to all the vehicles in the fleet, and the number of vehicles needed is minimized. The algorithm follows the steps and equations below:

1. The minimum number of vehicles needed, N is calculated based on equation (7). This gives the average working hours for each vehicle to be less than or equal to the work shift duration.

$$N = \left\lceil \frac{\text{Sum of Route Duration}}{\text{Duration per work shift}} \right\rceil = \left\lceil \frac{\sum_{k \in K} D^{k}}{S} \right\rceil \tag{7}$$

2. For each vehicle p, a route k is assigned to it. Each of these routes belongs to the longest N routes in terms of work duration. The set of routes assigned to vehicle p is denoted by $\mathbf{R_p}$, where $p \in \{1,\cdots,N\}$.

3. The total duration of the routes assigned to vehicle p is denoted with T_p.

$$T_p = \sum_{k \in R_p} D^k \tag{8}$$

4. The vehicle with the shortest work duration, T_p, is denoted with p_s.

$$p_s : T_{p_s} = \min_{p \in \{1...N\}} T_p \tag{9}$$

5. The next unassigned route with the longest duration, D^k, is denoted with k_h.

$$k_h : D^{k_h} = \max_{k \notin R_p, p \in \{1,...,N\}} D^k \tag{10}$$

6. If $T_{p_s} + D^{k_h} > S$, then the set of vehicle $p \in \{1,\cdots,N\}$ is expanded to include a new vehicle, p_x, and the route k_h is assigned to it using equation (11), else the route is assigned to vehicle p_s using equation (12).

$$R_{p_x} = \{k_h\} \tag{11}$$

$$R_{p_s} = R_{p_s} \cup \{k_h\} \tag{12}$$

7. Steps 3 to 7 are repeated until all routes are assigned.

Table 2. Inputs and outputs of the routing and scheduling method

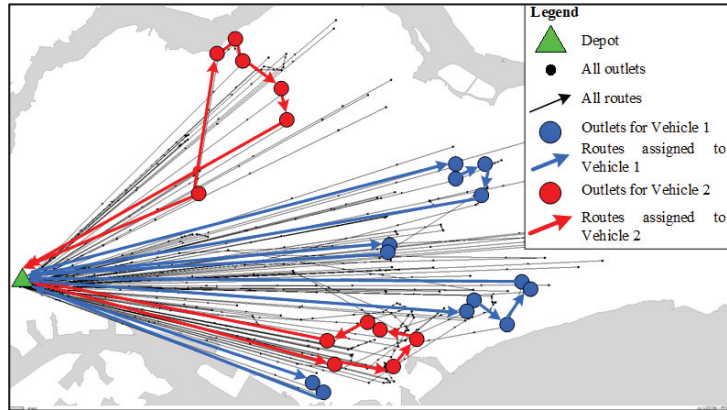| Procedure	Inputs	Outputs
Routing	• Order details (Depot Locations, Customer Locations, Weight of Shipment) • Vehicle (Effective payload capacity, W^i_{effcap}) • Route parameters (Loading time, unloading time, maximum route duration)	• Route information (Weight payload in leg j, W^i_{pay}, Distance travelled in leg j, Route duration, D^k) • Calculated energy consumption, E^k
Scheduling	• Route details of set $\mathbf{K}$ (Energy consumption E^k Route duration, D^k) • Duration per work shift, S	• Number of vehicles, N • Driving schedule of day (Set of assigned routes $\mathbf{R_p}$, Distance travelled, Energy consumption, Duration of work T_p)

Fig. 2. Illustration of all routes (in black) produced by the routing algorithm and the example of an assignment of routes to two vehicles by the scheduling algorithm.

The inputs and outputs of the routing and scheduling procedure are given in Table 2. The output of the routing and scheduling model is illustrated in Fig. 2. In Fig. 2, four routes are assigned to the Vehicle 1 (see blue lines), whereas two routes are assigned to Vehicle 2 (see red lines).

2.5. Implementation of charging strategies

In this section, several charging strategies are evaluated to ensure the logistics operations can be completed and to improve its performance. If the charging strategy is acceptable, the number of units and the power rating of the necessary charging infrastructure is calculated. Additionally, any changes to the size of the battery (either positive or negative) will be estimated, along with the consequent changes in fleet size. Details on how the charging strategies were implemented in this study are presented in the subsections below.

2.5.1. Overnight charging

Overnight charging is the basic charging mode and is done for each vehicle at the end of every day, regardless of the mid-operation charging strategy. It ensures that the vehicle is fully charged at the beginning of each working shift. The power is determined based on a charging duration of 12 hours and the battery capacity of the vehicle. Each vehicle in the fleet requires one charger.

It is possible that none of the other charging systems is used if the battery capacity of the vehicle exceeds the total daily energy consumption of the vehicle. Hence, it would be more meaningful first to check if the battery could be expanded, such that mid-operation charging is not required. However, since the total weight of the vehicle is constrained, resizing the battery reduces the payload capacity of the vehicle, which would affect the operational suitability of the vehicle. The limits to how much this is allowed to affect the operations should be considered.

2.5.2. Break time charging

Break time charging occurs during the one hour break during the work shift. Assuming only one break is allowed, the vehicle can only be charged once a day. It is assumed that one charger, each with a rating of 100 kW, is shared between two vehicles in the fleet. The ratio of one charger to two vehicles is an assumption, which to the author's opinion would only require a minimal degree of coordination between drivers for the usage of chargers. The battery should be resized (either expanded or reduced), such that the vehicle has just enough energy to complete the daily routine.

2.5.3. Charging during loading and unloading time

During urban goods distribution operations, a significant amount of time is spent stationary, to load or unload the vehicle, which could be used to charge the vehicle. Similar to break time charging, the power rating is also assumed to be 100 kW, which provides about 42 kWh during each loading stop of 25 minutes and 25 kWh during each unloading stop of 15 minutes. These two charging strategies also offer the possibility of reducing the battery capacity. For the loading charging strategy, the minimum battery capacity considers the maximum energy usage of a route, whereas for the unloading charging strategy, the minimum battery capacity considers the maximum energy usage for trips between customers. For charging equipment installation, it would either be at each loading bay, or at each retail outlet with a dedicated unloading bay, depending on the strategy used.

2.5.4. Charging on the highways

The technology for charging on highways using catenary systems or inductive chargers embedded in the road already exist for bus systems. In this paper, the inductive system is considered since it could accommodate all types of vehicles; compared to the catenary system, which only supports vehicles of a minimum height. Also, while in an ideal case only the major road sections or intersections needs to be fitted with the chargers, in this paper the entire highway length (one lane in each direction) is assumed to be "electrified". The pickup power for each vehicle was selected to be 100 kW (Huh, Rim 2011, p. 1). The charging power to be installed depends on the number of vehicles assumed to be using the system, the average speed of travel, and the total lane-kilometre electrified. For this scenario, it is assumed that the all of Singapore's highways are electrified, which amounts to 328 lane-km (Land Transport Authority 2015).

2.6. Evaluation of operational suitability

The operational suitability indicators were selected based on the aim of showing the difference in transport operation performance when different electric vehicle variations are used. As mentioned before, the resource categories that need to be considered for operational efficiency are time, space, vehicles, fuel and driver. Here, the driver as a resource is covered under the vehicle or the time category. The selected indicators are shown in Table 3. Note that the study assumes that the vehicle does not have any unplanned downtime, such as due to insufficient energy or a breakdown, i.e. it is always available. Although this is an important consideration, the unplanned downtime depends more on the reliability of the vehicle as a product; it would be better evaluated in a test trial, rather than in a conceptual evaluation.

Table 3. Operational suitability indicators according to resource category

Time	Space	Vehicles	Fuel
• Driven hours per vehicle (h) • Customers served per working hour (h)	• Total parking area (m^2) • Number of loading bays (-)	• Number of vehicles (-) • Effective payload (%) • Empty vehicle distance (%)	• Fleet charging power (kW) • Fleet battery capacity (kWh) • Distance driven per customer (km) • Energy usage per tonne-km ($kWh.t\text{-}km^{-1}$) • Energy usage per km ($kWh.km^{-1}$)

3. Results and Discussions

The results section comprises of five main analyses: a comparison of selected outputs of the energy consumption model and the daily driving schedule, an overview of vehicles created by the vehicle model, a comparison with a conventional truck, the operational performance indicators of the different fleets, and the influence of the charging strategy on the fleet.

3.1. Comparison of selected outputs of the energy consumption model and the daily driving schedule

Two key outputs are compared to check the validity (or strength) of the methodology. The first relates to the accuracy of the energy estimation model, whereas the second relates to the characteristic of the logistics scenario simulated using the vehicle routing and scheduling procedure. Admittedly, the data available for comparison is limited, however for the level of precision required by this study, the comparisons presented below would suffice.

For the validation of the energy consumption model, the driving range in kilometres and the battery capacity in kilowatt-hours of several electric vehicles[5] based on their specification sheets were compared with the vehicle models created. The energy consumption estimated in the study was higher by about 0.21 kWh.km^{-1} on average compared to those shown in the manufacturer's fact sheets and research literature, even if refrigeration power was included. This difference could be attributed to the different driving cycle more commonly used to estimate the range, such as the New European Driving Cycle or Urban Dynamometer Driving Schedule. Furthermore, the research considers power usage while the vehicle is stationary, such as during loading or unloading time, which is not a typical feature of driving cycles.

For the validation of the routing and scheduling procedure, the latest publicly available road freight study in Singapore (Luk 2002) was used as a comparison. According to the study, for vehicles exceeding 3.5 tonnes (termed by them HGV), the average distance travelled per vehicle per day is 209 km, the average distance between stops is 15.5 km and the average number of stops per vehicle per day is 13.6. In comparison, the results of the study presented here (for the vehicles exceeding 3.5 tonnes) is 245 km, 24.9 km, and 10.4, respectively. The deviations might be explained by two factors. Overall, the modelling results show a slightly higher distance travelled (of 36 km), though with fewer stops per day. It is concluded that the "normative" vehicle routing and scheduling procedure used in the study is applicable for the research purpose.

Table 4. Description of the synthesized electric vehicles in the fleet

Weight of class [kg]	Battery capacity [kWh]	Effective Payload Capacity [kg]	Average energy usage rate [kWh/km]	Average driving range [km]	Number of vehicles [-]	Number of loading bays [-]
1,500	40	170	0.35	115	539	225
2,000	50	280	0.41	122	326	136
3,000	80	460	0.52	153	202	85
5,000	110	1,240	0.69	159	86	36
7,000	130	2,330	0.83	157	48	20
9,000	150	3,640	0.96	156	35	15
11,000	160	5,240	1.05	153	28	12
13,000	180	6,630	1.12	161	26	11
15,000	190	7,810	1.20	158	25	11
17,000	210	8,900	1.37	154	21	9

3.2. Overview of the vehicles and resources required

The ten electric vehicles created by the model and used for the evaluation are shown in Table 4. For the logistics operation outlined in the scenario, the number of vehicles was estimated using the procedure outlined in the

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[5] The vehicles considered are the Mercedes E-Vito 3.1t, Iveco Daily 3.5t and 5.0t, Renault Kangoo ZE 2.2t , Smith Edison 3.5t and 4.6t, Smith Newton 7.5t , the converted UPS P80 7.5t , Ford Transit Azure 2.3t , Nissan e-NV200 2.2t, Toyota RAV4 EV 2.3t, and the EMOSS CM1212, CM1612, and CM1816 . Although other electric trucks are also available on the market, such as from manufacturers Balqon and Terberg, their literature either did not state their vehicle's range, battery capacity or total vehicle weight.

methodology section. However, it was found that the battery capacity was insufficient for all the vehicles in each fleet to complete their assigned driving schedule. Hence, it would be important to consider battery resizing or mid-operation charging to compensate for this insufficiency.

3.3. Comparison of electric vehicles with a diesel vehicle

A conventional diesel vehicle was also used to represent the current system. The vehicle parameters were taken from observation at the retail outlets and by checking the vehicle specification sheet provided by the manufacturer. The vehicle is an 11 tonne Isuzu truck, with an effective payload capacity of 6,700 kilogrammes. According to the vehicle routing and scheduling procedure, the fleet size would be 26 vehicles with a total fleet energy consumed of 17.7 MWh. The operational indicators are comparable to that for the fleet of the 13-tonne electric vehicles, also with a fleet size of 26 vehicles, but with only almost 40% of its total fleet energy consumed, 6.9 MWh.

The results in the following sections disregards the results for the vehicles of weight classes 1,500 to 7,000 (see Table 4), which require a fleet size more than 36 (which is 10 more than needed for the diesel vehicle fleet). Neglecting those results will let the focus be on the fleets which are more similar to the conventional fleet operation-wise.

3.4. Operational performance indicators

The selected performance indicators are displayed in Table 5. Except for weight class 15,000, the heavier vehicles show better use of resources, in terms of driven hours, served customer rate and distance driven per customer. The exception of weight class 15,000 could perhaps be due to the suboptimal routing and scheduling, which could also occur in real situations. The results are not invalidated due to this, but rather show that choosing the right vehicle for evaluation should include as many variations as possible. The performance characterized by these indicators is most influenced by the number of vehicles in the fleet. In the next section, the influence of the different charging strategies on the size of the fleet is shown.

Table 5. Comparison of the performance indicators according to weight class

Weight of class [kg]	Area needed for parking [m²]	Number of driven hours per vehicle [h]	Served customers rate [1/h]	Distance driven per customer [km]	Share of empty vehicle distance [%]	Route payload capacity utilization [%]	Energy per transported tonne-km [kWh/t-km]
9,000	981	4.00	0.91	31.40	46%	49%	0.54
11,000	888	3.85	1.19	24.15	45%	44%	0.46
13,000	891	3.89	1.25	22.53	45%	37%	0.46
15,000	920	3.87	1.30	21.22	44%	33%	0.46
17,000	827	3.52	1.57	15.14	42%	42%	0.36

3.5. Resources required for different charging systems

As mentioned, none of the fleets was able to sufficiently complete their driving schedule assigned, without changing the battery capacity or employing a mid-operation charging strategy. Here, the expected change (in comparison to that in Table 4), ceteris paribus, to the battery as well as to the fleet size will be presented. Additionally, the amount of resources associated with the electrification of goods transport is shown, which includes the total fleet battery capacity and the fleet charging power. The fleet's charging power could be differentiated by the type: the overnight chargers and the additional chargers. The results are presented in Table 6.

It was found that for the vehicles of class 9,000, the enlarged battery and break time charging strategy cannot be used without significantly affecting the operational performance of the fleet. In both strategies, the addition of the 113% and 47% of the current battery size reduces the payload capacity such that additional vehicles (more than 36) are required to service the routes.

3.5.1. Overnight charging and increased battery size.

A proper battery sizing, which could make use of modular battery systems could be used to adapt the vehicles specifically to needs of the operation or even to the individual daily requirements. Table 6 shows that the strategy would effect a maximum number of vehicles increase of 24% (disregarding class 9,000 for reasons mentioned above). If there could be flexibility in the battery capacity of the vehicles, in terms of the vehicle availability, as well as the operational planning, not every vehicle would need a greater battery size. In general, a vehicle independent from using additional chargers during operations would be beneficial for the simplicity of the operations. However, if costs of the vehicle are considered and the battery remains its largest cost component, it might prove to be very expensive. Nevertheless, a proper total cost of ownership analysis, which considers the costs for charging, energy usage, battery life and maintenance, would provide a more conclusive answer.

3.5.2. Fast charging during break time, loading and unloading.

A comparison of the three fast charging strategies (see Table 6) show how using the same technology at different locations and at different times during the schedule of the driver could yield different results. Although each charger is rated 100 kW, each strategy offers some advantage over the other. In general, considering the effect the strategy has on reducing the fleet size, the unloading time charging is the best. However, using the strategy will require a significant investment of altogether 12.2 MW for the chargers to be borne by the building owners. Compared to the other two fast charging strategies, break time charging required both the increase in battery size, the increase in fleet size and the additional investment for the charging stations. In the absence of alternatives and if necessary, the strategy would work for the fleet classes 11,000 to 17,000. Charging during loading may not reduce the fleet size significantly, but it balances out a reduction in the fleet battery capacity while keeping the fleet fast charging power also low, in comparison to the other strategies.

Table 6. Overview of energy-related resources and vehicles, according to charging strategies

Strategy	Vehicle class	9,000	11,000	13,000	15,000	17,000
Enlarged battery	Battery change [%]	113%	94%	89%	74%	57%
	Number of vehicles change [%]	63%	21%	12%	8%	24%
	Fleet battery capacity [MWh]	18.24	10.54	9.86	8.91	8.58
	Fleet overnight charger power [MW]	1.52	0.88	0.82	0.74	0.72
Break time charging	Battery change [%]	47%	31%	33%	21%	10%
	Number of vehicles change [%]	20%	7%	4%	4%	5%
	Fleet battery capacity [MWh]	9.24	6.30	6.48	5.98	5.06
	Fleet overnight charger power [MW]	0.77	0.53	0.54	0.50	0.42
	Fleet fast charging power [MW]	2.10	1.50	1.35	1.30	1.10
Loading time charging	Battery change [%]	-7%	-13%	-11%	-16%	-14%
	Number of vehicles change [%]	0%	0%	0%	-4%	-5%
	Fleet battery capacity [MWh]	4.90	3.92	4.16	3.84	3.60
	Fleet overnight charger power [MW]	0.41	0.33	0.35	0.32	0.30
	Fleet fast charging power [MW]	1.50	1.20	1.10	1.10	0.90
Unloading time charging	Battery change [%]	-53%	-38%	-39%	-58%	-67%
	Number of vehicles change [%]	-9%	0%	0%	-12%	-19%
	Fleet battery capacity [MWh]	2.24	2.80	2.86	1.76	1.19
	Fleet overnight charger power [MW]	0.19	0.23	0.24	0.15	0.10
	Fleet fast charging power [MW]	12.20	12.20	12.20	12.20	12.20
Electrified highway	Battery change [%]	-73%	-75%	-78%	-74%	-76%
	Number of vehicles change [%]	-11%	-4%	-4%	-16%	-24%
	Fleet battery capacity [MWh]	1.24	1.08	1.00	1.05	0.80
	Fleet overnight charger power [MW]	0.10	0.09	0.08	0.09	0.07
	Electrified highway power [MW]	539.49	532.31	526.31	519.88	513.48

3.5.3. Charging on the highways.

Dynamic charging using inductive technology still requires research, even though there are implemented projects, such as for trams and buses. In terms of the logistics operation, the number of vehicles could be reduced by up to 24%, which is a significant efficiency increase. On one hand, as Table 6 shows, the strategy benefits the vehicle owners a lot, such that the battery capacity could be shrunk by up to 78%. On the other hand, according to this estimate, the charging infrastructure if fully utilized would increase the total energy consumed in the transport industry in Singapore per day by 8%[6]. Furthermore, this strategy may only become relevant when a critical mass of electric vehicles is gained, which can justify the policy decision to electrify the highways. Since the infrastructure is located on the publicly-owned roads, consideration must be given to all stakeholders of the road, including private and public passenger vehicles. This is beyond the scope of this study, but could be done using an agent-based simulation to identify correctly the roads or lanes to be electrified, while considering all the vehicles in the city, as well as the required battery size as it was done for private vehicles (Ul Abedin and Waraich, 2014).

4. Conclusion

The paper explored the operational performance of electric vehicles in a set scenario under different charging strategies. A method was developed to "synthesize" electric vehicle models, which have not yet appeared on the market. These vehicles, unfortunately, could not meet the high requirements, in terms of energy capacity, required by the logistics operation. Nevertheless, if the insufficient energy capacity could be overcome, the vehicles could show comparable operational efficiency and far greater energy efficiency than a diesel vehicle.

The paper showed how coping with the limited driving range of the vehicles could be handled: by increasing the battery capacity, using opportunity charging during break, loading or unloading time, or using dynamic inductive charging on highways. For the case of commercial transport, the operational needs add another dimension to the question of choosing the right charger. As shown in the comparison between the break, loading and unloading time strategies, the question is not only, what and how many chargers to install, but when (and where) should the charger be used. The appropriate strategy could be identified by understanding the daily driving schedule of the driver by and pairing suitable technology to each charging opportunity.

A well-designed and reliable electromobility system (vehicle and charger) would be operationally competitive with the current conventional vehicles. More research is encouraged, particularly to improve the feasibility and viability of wireless charging. Static wireless charging could be well suited for commercial vehicles, during unloading and loading activities. Dynamic wireless charging could make use of the long duration spent on the road.

The paper also showed that there is a good reason to design electric vehicles with modular battery systems, such that could be expanded to fit the high, medium and low energy demands of different vehicles in the same fleet. Research in this area, besides research to improve the energy density of the battery, would also significantly increase the suitability of electromobility for goods transport.

Further research needs to be done on developing a more holistic evaluation framework, which would tie in economic, environmental and social impact factors, at the level of the company as well as the society. This framework would then be able to advise public agencies regarding policy to support the long-term development of the suitable electromobility concepts.

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[6] The transport sector consumed 2370 GWh in 2013 according to Singapore's Energy Market Authority 2014, which is 6.49 GWh per day.

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