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Comparisons of Driving Characteristics between Electric and Diesel-Powered Bus Operations along Identical Bus Routes

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Abstract: The energy consumption profiles of conventional fuelled and electric vehicles are different due to the fundamental differences in the driving characteristics of these vehicles, which have been actively researched elsewhere but mostly on the basis of uncommon geographical contexts. This study, therefore, collected driving data on electric and conventional diesel buses running along exactly the same set of bus routes in Hong Kong during normal daily revenue operations. This enabled a fair comparison of driving characteristics for both types of bus under identical real-life, on-road driving conditions, which highlighted the originality and contributions of this study. A three-step approach was adopted to carry out detailed driving pattern analyses, which included key driving parameters, speed–acceleration probability distributions (SAPDs), and vehicle-specific power (VSP) distributions. Results found that route-based comparisons did highlight important differences in driving patterns between electric and diesel buses that might have been smoothed out by analyses with mixed-route datasets. In particular, the spread, intensity, and directions of these differences were found to be exaggerated at the route-based level. The differences in driving patterns varied across different routes, which has significant implications on vehicle energy consumption. Government agencies and/or bus operators should make references to these results in formulating electric bus deployment plans.

Keywords: bus driving patterns; speed–acceleration probability distributions; vehicle-specific powers; driving cycles; electric buses; vehicle energy consumption

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Citation: Ng, K.-W.; Tong, H.-Y. Comparisons of Driving Characteristics between Electric and Diesel-Powered Bus Operations along Identical Bus Routes. *Sustainability* **2024**, *16*, 4950. https://doi.org/10.3390/su16124950

Academic Editor: Marilisa Botte

Received: 30 April 2024
Revised: 31 May 2024
Accepted: 6 June 2024
Published: 9 June 2024

1. Introduction

Given the automotive industry's influence on air pollution and CO_2 emissions, effort have been made to mitigate these impacts [1]. The automotive sector has consistently worked to reduce fuel consumption and emissions over the years [2,3]. To combat global warming and achieve a reduction in greenhouse gas emissions from the automotive sector, more stringent global standards and regulations are being implemented, with a significant focus on transitioning to electric vehicles [4].

Public transportation plays a pivotal role and poses numerous challenges, with transportation contributing around 45% of greenhouse gas emissions [5]. Public buses make up more than 80% of global public transportation passenger journeys [6]. Diesel-powered buses have been a major source of vehicle emissions [7], impacting the urban quality of life. Consequently, the global shift towards bus electrification is rapidly growing. Electric buses are often superior to internal combustion vehicles in terms of energy consumption and emissions [8,9]. For estimating vehicle emissions and energy consumption, driving cycles have been developed [10]. Numerous studies highlight substantial distinctions between driving cycles for electric vehicles and conventional vehicles, including power characteristics, transmission efficiency, energy recovery braking systems, and more [11]. Nevertheless, there are limited published studies comparing driving cycles designed for electric buses and those for diesel-powered buses. Relying on driving cycles developed for conventional diesel-powered buses to evaluate the performance of electric buses could result in substantial inaccuracies [12].

Over the past few years, driving cycles specific to franchised bus services have been synthesized to discern their driving characteristics concerning bus route structure and traffic conditions in Hong Kong [13]. By the end of 2027, the government aim to introduce approximately 700 electric buses [14]. Given the escalating demand for electric buses, there is an urgent need for an investigation into the driving characteristics of electric buses as compared to conventional diesel-powered buses. In particular, previous trial programmes have highlighted that electric buses are different from conventional diesel buses in terms of vehicle operation and characteristics under the unique driving environment in Hong Kong (e.g., relatively high ambient temperature, congested traffic, and hilly and mountainous driving environment) [10], which reduces the actual driving range to become far lower than what is specified (primarily for other places) as well as the daily milage requirement of general public buses [15]. Therefore, government agencies bus operators and manufacturers have been exploring ways to identify routes with operational conditions that might be more suitable to couple with the characteristics of these electric buses. This study aimed to identify the differences in driving characteristics between electric buses and conventional diesel-powered buses operating along the same route during regular daily bus operations. The findings from this study are expected to offer valuable insights for government authorities and bus operators in devising strategies for the deployment of electric buses in Hong Kong and other comparable regions.

In short, the significance of the current study can be summarised as follows:

- Characterising the operational characteristics of diesel and electric buses under the same driving environment as reflected in the evaluation metrics adopted.
- Identifying how electric buses might differ from conventional diesel buses during normal bus operations along the same set of routes (which is rare in the literature).
- Evaluating the extent and direction of differences between electric and diesel buses derived for route-based datasets versus those derived from mixed-route datasets.
- Providing evidence and insight for government agencies and/or bus operators in terms of the impact of route-specific characteristics on the deployment of electric buses, which would be helpful when it comes to making the decision to deploy electric buses on specific routes.

2. Bus Electrification Status in Hong Kong

The exploration of electric bus technologies in Hong Kong began in 2010. The government set aside HKD 180 million to enable franchised bus companies to acquire 36 single-deck electric buses, comprising 28 battery electric buses and 8 supercapacitor buses. These buses were procured for trial purposes, aimed at evaluating their operational efficiency and performance within the specific local conditions [15].

The results from the trial program indicated that, apart from the average driving range constraint due to the additional load resulting from the high temperatures and hilly terrain in Hong Kong, battery electric buses performed quite similarly to conventional diesel buses. Electric bus technologies showed promise in reducing fuel costs. However, electric buses are different from conventional diesel buses in terms of vehicle operations and characteristics. Subsequent policy studies examined global electric bus experiences and identified the major challenges hindering the adoption of electric buses in Hong Kong, along with offering policy recommendations [16].

In March 2021, Hong Kong unveiled its inaugural Roadmap for the Proliferation of Electric Vehicles, outlining well-defined strategies to work toward the ultimate objective of eliminating vehicular emissions by 2035 or even sooner [17]. Notably, franchised bus companies are actively collaborating with the government to explore the viability of introducing new energy buses in Hong Kong. Kowloon Motor Bus (KMB) and CityBus (CTB), for instance, are slated to conduct trials of double-deck electric buses supported by the New Energy Transport Fund [18]. They intend to introduce additional single-deck and double-deck electric buses along with the necessary charging infrastructure to assess the operational efficiency and technical feasibility of electric buses. CTB will also partner with the government to investigate the potential use of other new-energy buses, including hydrogen fuel cell buses, in Hong Kong. In November 2023, the government set its sights on attaining the objective of introducing around 700 electric buses by the end of 2027 [14].

In alignment with government policy objectives and the uncertainties revealed by the trial programs, further investigations into the performance of various electric bus technologies under Hong Kong's unique driving conditions are essential before broader deployment. To achieve this, it is crucial to develop driving cycles that accurately represent the real and distinctive bus driving environments in Hong Kong, providing an alternative means to evaluate the performance of electric buses.

3. Literature Review

The environmental advantages of electric buses have prompted cities to transition from diesel to electric. An analysis of scientific production indicated a notable surge in studies within this field, exhibiting an average annual growth rate of 26% [19]. The research is primarily concentrated in China, the United States, and the European Union. From 2010 to 2016, the Chinese electric vehicle industry witnessed an impressive 360% growth in both sales and production [20,21]. Chinese cities are home to roughly 98% of the globally deployed electric buses [22]. In the United States, diverse programs, including financial incentives such as tax credits, exemptions, and subsidies, have been introduced to encourage research and production in the electric bus sector [23,24]. The European Parliament adopted new regulations in 2019 to encourage investment in clean buses [25]. The implementation of electric buses in Hong Kong remains relatively limited in scale.

Upon reviewing the literature on electric bus adoption, a substantial and growing body of literature was found focusing on (i) technical aspects; (ii) battery technology; and (iii) sustainability. Studies have explored operational constraints, including service optimisation and system performance [26–28]. Battery technology, encompassing issues related to energy content and storage, has also been investigated [29]. Other studies have delved into environmental and energy consumption models, exploring GHG emission reductions and energy efficiency from electric buses [30–34]. However, these studies primarily concentrate on the review of electric buses without a direct comparison with conventional diesel buses.

Several studies have undertaken comparisons between electric buses and conventional diesel buses. A summary of relevant articles comparing conventional buses and electric buses is provided in Table 1. Similarly, these comparisons predominantly focus on vehicle technology and life cycle reviews. Vehicle performance reviews have been undertaken in Canada, Singapore, and Taiwan [35,36]. The electric bus could emerge as the most viable alternative if the electric bus's cruising distance reaches an acceptable range. Studies comparing fuel consumption have been conducted in Germany, China, and the USA [37–39]. Electric buses are categorised as environmentally friendly and energy-saving transportation systems. They are locally emission-free due to electric drive, exhibit low noise, and are both gentle and powerful during start and stop. Evaluations of the life cycle assessment of electric buses and diesel buses have been explored in Spain, Macau, China, Finland, the USA, and Germany [29,40–44]. These studies examined crucial data regarding obstacles to the integration of electric buses on a global scale. Consequently, valuable information has been derived that can assist in decision-making for more secure planning in the adoption of e-buses. Comparisons of energy performances between electric buses and diesel buses have been studied in Argentina, Chile, and Brazil [45,46]. The findings indicated that among zero-emission vehicles, electric vehicle technology is the most efficient alternative for short ranges. Additionally, research on CO_2 emissions has been carried out in Singapore, China, and West Virginia [4,47,48]. The most significant reduction in CO_2 emissions enables a potential decrease of approximately 61% in annual emissions. Analysing the life cycle and optimising performance based on actual data play a crucial role in identifying factors for technological innovation and achieving further cost reductions for electric buses.

Direct comparisons of driving characteristics between electric buses and conventional diesel buses have been uncommon, especially in the Asian region, as highlighted in studies by Tong and Ng [13,49,50]. A study [51], closely aligned with our research question and methodology, pointed out that existing electric vehicle driving cycle studies lacked comparisons with internal combustion engine vehicle driving cycles in the same geographical locations. These comparisons provide supporting evidence for the electrification of public transportation, contributing to an overarching decrease in transportation emissions by advocating for the electrification of public transportation systems. Hence, this study seeks to bridge this gap by directly comparing electric buses and conventional buses deployed on the same routes during regular daily operations. This approach guarantees a comparison of driving characteristics under identical actual driving conditions.

Table 1. Summary of relevant articles in comparison between conventional buses and electric buses.

Ref.	Location	Main Topic	Objective
[4]	Singapore	Vehicle Technology Review	Focus on a comparative analysis between hydrogen and battery-powered buses, includes capital and operating costs, fuel consumption, and fuel cycle emissions.
[35]	Canada	Vehicle Technology Review	Conducts a comprehensive review of performance features across three electric bus categories: hybrid, fuel cell, and battery-powered.
[36]	Taiwan	Vehicle Technology Review	Performs a multiple attribute evaluation of alternative vehicles.
[37]	Germany	Vehicle Technology Review	Provides examples from both domestic and international contexts, illustrating how electric buses contribute to solving energy challenges in modern urban traffic.
[38]	China	Vehicle Technology Review	Undertakes a comparative study of two different powertrains for fuel cell hybrid buses.
[39]	United States	Vehicle Technology Review	Compares fuel consumption between diesel and hybrid buses under various driving conditions.
[40]	Spain	Life Cycle Analysis	Evaluates the overall life cycle of diverse powertrain technologies.
[41]	Macau	Life Cycle Analysis	Conducts a comparative life cycle assessment between conventional diesel public buses and electric public buses to assess actual greenhouse gas emissions.
[42]	China	Life Cycle Analysis	Assesses the benefits of electric buses compared to their diesel counterparts through a life cycle assessment, considering both upstream fuel production and operation stages.
[43]	United States	Life Cycle Analysis	Evaluates the environmental sustainability of electric buses and compares it to diesel buses.
[29]	Finland, California	Life Cycle Analysis	Conducts a life cycle cost and carbon dioxide emissions evaluation for different types of city buses.
[44]	Germany	Life Cycle Analysis	Compares the environmental footprint of diesel and electric buses across their entire life cycles.
[45]	Argentina, Chile, Brazil	Life Cycle Analysis	Carries out a comparative analysis of energy and environmental performances for four types of urban passenger bus powertrains within the well-to-wheel scope.

4. Data Collection

In Hong Kong, there are five franchised bus operators responsible for managing six franchises overseen by the Transport Bureau. The franchised bus network encompasses an extensive network comprising over 600 routes and a fleet of more than 6000 buses [52].

Kowloon Motor Bus (1933) Co., Ltd. (KMB) (Hong Kong), with a rich history as the longest-serving public bus service provider in Hong Kong, primarily operates routes in Kowloon Peninsula (Kln) and New Territories (NT). In contrast, City Bus (CTB) and New World First Bus (NWFB) are more focused on expanding their bus networks on Hong Kong Island (HKI). Additionally, New Lantau Bus (1973) Co., Ltd. (NLB) (Hong Kong), Long Win Bus Company (LWB) (Hong Kong), and the second franchise of CTB handle Tung Chung and airport routes. Tung Chung is a newly developed district situated on Lantau Island. This information underscores the complexity and comprehensiveness of the franchised bus network in Hong Kong. To accurately represent the characteristics of the electric bus network, it is essential to gather data covering various route structures.

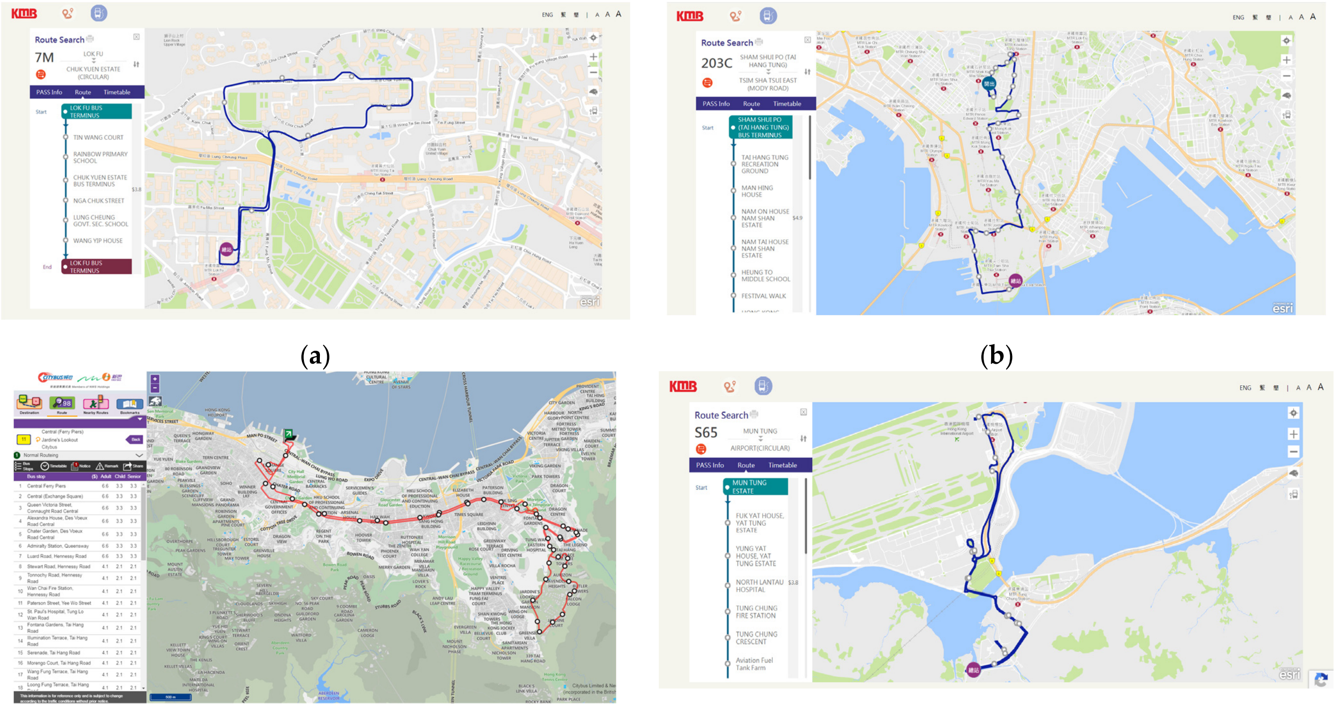
As a result of the previous electric bus trial programmes, only a few routes are retained for deployment with electric buses in daily operations [10]. This study conducted site visits to each of these routes to confirm the actual electric bus deployment status and schedules, and eventually identified four routes to carry out data collection. These routes were selected to ensure (i) a good coverage of different districts and typical driving conditions in Hong Kong; and (ii) a balanced mix of electric and diesel buses was deployed to operate the routes. The entire data collection campaign was conducted from January to June 2021 during normal daily bus operations. The bus drivers were not aware of the study, which made sure their driving would be impartial.

A total of 135 bus trip data points were finally collected, covering the four bus routes (7M, 203C, 11, and S65) by three franchised buses (KMB, LWB, and CTB) across different districts in Hong Kong. The maps of these four bus routes are shown in Figure 1. Route 7M and 203C operate in Kln. Route 7M is a circulatory route running between Wong Tai Sin and Chuk Yuen Estate with 10 stops. The total length and estimated travel time of this route are approximately 4.5 km and 20 min, respectively. Route 203C travels the crowded district from Sham Shui Po to Tsum Sha Tsui with 25 stops. The route's overall length spans around 8.8 km, with an estimated travel time of approximately 45 min. Route 11 and route S65 provide service on HKI and on Island, respectively. Route 11 is a circular route that operates between Central and Jardine. It covers a total of 32 stops and has the lengthiest travel time of 51 min, spanning 15.7 km. The final route, S65, connects Mun Tung and the airport, covering a substantial distance of 17 km with 21 stops and an approximate duration of 45 min (Table 2).

Table 2. Information collected on the bus routes.

Bus Route	Length (km)	Travel Time (mins)	Number of Stops	Origin	Destination	Districts	Circular	Operator
7M	4.5	20	10	Lok Fu	Chuk Yuen Estate	Kln	Yes	KMB
203C	8.8	45	25	Sham Shui Po	Tsim Sha Tsui East	Kln	No	KMB
11	15.7	51	32	Central	Jardine's Lookout	HKI	Yes	CTB
S65	17	45	21	Mun Tung Estate	Airport	Island	Yes	LWB

This study utilised battery electric buses primarily manufactured by BYD Auto Industry Company Limited (BYD), with the model being K9R. In contrast, the diesel bus used in this study was provided by Alexander Dennis. The physical characteristics, such as dimensions, weight, and passenger capacity, are comparable between these two bus types. BYD's batteries are environmentally friendly, non-toxic, and recyclable. A fully charged bus with a battery capacity of 324 kWh can sustain continuous travel for approximately 250 km. Detailed specifications for these two bus types can be found in Table 3.



(**a**) (**b**)

(**c**) (**d**)

Figure 1. Maps of bus routes for data collection. (**a**) Route 7M (a circular route); (**b**) Route 203C; (**c**) Route 11 (a circular route); and (**d**) Route S65 (a circular route).

Table 3. Specifications of bus types investigated.

Bus Type:	**Diesel**	**Electric**
Supplier:	Alexander Dennis	BYD Auto Industry Company Limited (BYD)
Model:	Enviro500	K9R
Passenger Capacity:	80	66
Dimensions:	11.3 m (L) × 2.5 m (W) × 4.1 m (H)	11.6 m (L) × 2.5 m (W) × 3.25 m (H)
Gross Weight:	19,000 kg	19,000 kg
Top Speed:	90 mph	62.5 mph
Motor Type:	Enviro500	AC Synchronous
Max Power:	180 kW	150 kW
Max Torque:	1200 N·m	550 N·m
Battery Type:	-	Iron Phosphate
Battery Capacity:	-	324 kWh
Charging Capacity:	-	80 kW

Data were gathered using an iTrail GPS Data Logger supplied by KJB Security, a company based in the United States. As outlined in the literature review, GPS devices have become the preferred method for collecting on-road data worldwide. In recent times, with the growing acceptance of electric vehicles as an alternative to conventional fuel-powered vehicles, GPS data loggers have found increased utility in developing driving patterns for electric vehicles [53–55]. This portable and waterproof iTrail GPS Data Logger provides tracking capabilities at no additional cost, capturing latitude, longitude, altitude, location, speed, and time information for each journey at 1 s intervals.

Upon installing the GPS logger on board the bus, the surveyors initiated the recording process as the bus commenced its journey from the starting point of the route. The recording ceased when the bus had completed the trip and arrived at a full stop at the terminal. Throughout the bus journey, the logger meticulously captured the previously mentioned data at the highest sensitivity setting. Concurrently, the surveyors manually noted the precise times for the initiation and conclusion of each trip, a step taken to facilitate cross-verification of actual stopping locations and time intervals. This methodology resulted in the collection of data from 110 journeys of battery electric buses and 25 journeys of conventional diesel buses (Table 4), covering different time periods of a day and days of a week. The resultant dataset consists of nearly 300,000 second-by-second on-road bus driving speed data points during the normal daily bus operations. It is important to note that, given the sizable sample obtained (i.e., a total of 135 bus trips) with a certain level of imbalanced split between electric and diesel buses, it is believed that this dataset will still be able to capture important bus driving characteristics because:

- The data collection campaign and methodology were consistent with the common practices that have been used in many other studies.
- The amount of data collected (in terms of the number of selected bus routes and the number of trips) was unarguably sizable when compared to many previous studies. In fact, many public transport driving cycle studies were based on data from only one or two routes, or just a few trips [13].
- The distribution of trips for diesel and electric buses collected was due to and thus reflected the actual split and bus deployment status during daily operations of those selected bus routes.
- Normally, only a few distinct drivers would be deployed to run a specific route to ensure that they are familiar with the features of the route. Given the relatively sizable number of trips collected for each route, variations across drivers deployed for a specific route should have been largely captured in the collected dataset.

Table 4. Bus journey data collection statistics.

Bus Route	Number of Trips (Electric)	Number of Trips (Diesel)	Total Number of Trips
7M	45 (33.33%)	4 (2.97%)	49 (36.30%)
203C	26 (19.26%)	13 (9.63%)	39 (28.89%)
11	14 (10.37%)	6 (4.44%)	20 (14.81%)
S65	25 (18.52%)	2 (1.48%)	27 (20.00%)
Total	110 (81.48%)	25 (18.52%)	135 (100.00%)

Therefore, this study collected bus driving data in the same city along the same set of bus routes, which largely eliminated the interference of different driving conditions, and could allow for a fair and direct comparison of driving characteristics between electric and conventional diesel buses under the same driving environment.

5. Data Analysis

To analyse the collected data, a three-step approach was adopted, i.e., driving parameters, speed–acceleration probability distribution (SAPD), and vehicle-specific power (VSP) distributions, to characterise and compare the driving characteristics in this study. Driving parameters have been widely used elsewhere and were derived for the survey data as shown in Table 5.

A total of 13 parameters were adopted for analysis in this study, including most of the commonly used quantitative driving indicators such as speed- and acceleration-related metrics and vehicle operating mode distributions. This list has been widely used in driving pattern descriptions [10,13,49,50]. In particular, the "Creep" mode is considered in the vehicle operating mode distribution analysis. This has been relatively uncommon, but is definitely useful for this study. The "Creep" mode is normally used to describe short acceleration and deceleration driving behaviours, which mostly occur in slow stop-and-go situations such as at urban junctions, under traffic congestions, or bus dwell activities. It helps to appropriately portray vehicle queuing behaviours, which is particularly useful in reflecting urban driving conditions.

Table 5. Definitions of the 13 driving parameters.

Abbr.	Name	Unit
v_1	Average speed of the entire driving cycle	km/h
v_2	Average running speed	km/h
a	Average acceleration of all acceleration phases	m/s^2
d	Average deceleration of all deceleration phases	m/s^2
RMS	Root mean square acceleration	m/s^2
PKE	Positive acceleration kinetic energy	m/s^2
c	Mean length of a micro-trip	sec
P_{idle}	Time proportions of idling modes	%
P_{acce}	Time proportions of acceleration modes	%
P_{cruise}	Time proportions of cruising modes	%
P_{dece}	Time proportions of deceleration modes	%
P_{creep}	Time proportions of creeping modes	%
M	Average number of acceleration/deceleration changes (and vice versa) within one micro-trip	number of times

In addition to these parameters, SAPDs were also used to illustrate the greater details of a bus trip's speed and acceleration characteristics. They are obtained by first dividing the speed and acceleration ranges into equal portions (called resolutions), and the data occurrence frequency and then probability for each combination of speed and acceleration are then computed. The resultant SAPD (also called the speed–acceleration map) can be shown in matrix form with each cell showing as a percentage frequency of occurrence. SAPD is useful for comparing driving characteristics between two trip-based speed datasets by finding the differences between the SAPDs derived from them. The smaller the differences across different cells, the more commonalities the two datasets share. This comparison has been widely employed elsewhere for vehicle dynamic analysis as well as driving cycle development activities [10,13,49,50].

To further enhance the analysis of vehicle operating characteristics, VSP distributions between datasets were also derived and compared. The formula for calculating VSP for buses (a type of heavy-duty vehicle) is as follows [56,57], where v is the speed (in m/s) and a is the acceleration (m/s^2).

$$\text{VSP} = v\,(1.1 \times a + 0.132) + 0.0000745\,v^3 \tag{1}$$

VSP is a very important variable for estimating vehicle emissions and energy consumption, as well as for evaluating eco-driving behaviours [58]. The VSP distribution is defined as the proportion of time spent in each VSP bin for a specific traffic condition. The USEPA defined 23 vehicle operating modes for energy consumption estimations based on different VSP ranges. Many studies have confirmed the close relationship of instantaneous vehicle emissions and energy (or fuel) consumption with VSP distributions [56,57,59]. Therefore, analysing bus driving VSP distributions would be of great interest to enhance understandings on the implication for bus tailpipe emissions and energy consumption characteristics.

Based on this three-step approach, the speed–time profiles of bus journeys were analysed first as a whole to characterise the overall battery electric bus driving characteristics as compared to those derived from conventional diesel buses. Then, the analyses looked at different groupings of bus journey data, such as route-based comparison, which is the primary objective of this study. This was able to provide solid evidence based upon a direct comparison of driving characteristics between battery electric buses and conventional diesel buses over the same geographical setup. Results from these analyses help to better highlight the key areas of differences between the electric and diesel buses, and possibly profile them.

6. Results and Findings

This section presents the results from analysis, including the findings on the set of driving parameters, SAPDs, and VSP distributions.

6.1. Overall Driving Patterns

This section starts by looking at the results, in terms of driving characteristics, derived for the entire set of 135 bus trips as well as separately for all diesel only (35 trips) and electric only (110 trips) bus journeys. The mean values of the 13 driving parameters for these three groupings of datasets are presented in Table 6. Mean values for different days of a week (i.e., weekdays versus weekends) and time periods (peaks vs. off-peaks) were also generated. Traffic conditions and bus operating patterns are the two observable factors affecting the variations.

Table 6. Driving pattern characterisation and comparison (overall).

(a) Overall (All Data)

		P_{idle}	P_{acce}	P_{cruise}	P_{dece}	P_{creep}	RMS	PKE	a	d	v_1	v_2	c	M
Overall	Weekday	33.85	27.86	7.44	29.83	1.02	0.910	0.482	0.709	0.655	13.91	20.39	44.85	12.36
Overall	Weekend	32.52	28.13	8.73	29.82	0.80	0.866	0.450	0.671	0.629	15.04	21.62	48.11	12.87
Overall	Off Peak	37.34	26.42	6.39	28.50	1.35	0.937	0.501	0.729	0.671	12.11	18.89	37.50	10.50
Overall	Peak	32.08	28.47	7.89	30.75	0.81	0.903	0.475	0.704	0.646	14.73	21.09	48.79	13.56
Overall	Mean	33.24	27.98	8.03	29.83	0.92	0.890	0.467	0.692	0.643	14.42	20.95	46.33	12.59

(b) Diesel

		P_{idle}	P_{acce}	P_{cruise}	P_{dece}	P_{creep}	RMS	PKE	a	d	v_1	v_2	c	M
Diesel	Weekday	35.35	27.59	7.30	28.84	0.92	0.909	0.500	0.725	0.678	13.70	20.56	42.13	10.72
Diesel	Weekend	37.41	26.44	6.99	28.03	1.13	0.835	0.450	0.658	0.622	11.08	17.65	37.05	10.17
Diesel	Off Peak	40.79	24.91	5.45	27.74	1.11	0.986	0.541	0.783	0.702	10.93	18.45	33.79	9.31
Diesel	Peak	38.66	25.63	5.95	28.66	1.10	0.963	0.538	0.769	0.688	11.40	18.57	33.59	9.25
Diesel	Mean	36.51	26.94	7.13	28.38	1.04	0.868	0.472	0.687	0.646	12.23	18.93	39.29	10.41

(c) Electric

		P_{idle}	P_{acce}	P_{cruise}	P_{dece}	P_{creep}	RMS	PKE	a	d	v_1	v_2	c	M
Electric	Weekday	33.58	27.91	7.46	30.00	1.04	0.910	0.479	0.706	0.651	13.94	20.37	45.34	12.66
Electric	Weekend	31.06	28.63	9.25	30.36	0.70	0.875	0.450	0.675	0.631	16.22	22.80	51.40	13.67
Electric	Off Peak	36.68	26.71	6.57	28.64	1.40	0.928	0.493	0.719	0.665	12.34	18.97	38.22	10.73
Electric	Peak	31.35	28.78	8.10	30.99	0.78	0.897	0.468	0.697	0.641	15.10	21.37	50.48	14.04
Electric	Mean	32.49	28.22	8.23	30.16	0.89	0.895	0.466	0.693	0.642	14.92	21.42	47.95	13.09

(d) Percentage Difference = ((c) — (b))/(b)

		P_{idle}	P_{acce}	P_{cruise}	P_{dece}	P_{creep}	RMS	PKE	a	d	v_1	v_2	c	M
Difference	Weekday	−5.0%	1.2%	2.2%	4.0%	12.6%	0.1%	−4.4%	−2.6%	−4.0%	1.7%	−0.9%	7.6%	18.1%
Difference	Weekend	−17.0%	8.3%	32.3%	8.3%	−38.3%	4.7%	0.0%	2.6%	1.5%	46.4%	29.2%	38.7%	34.4%
Difference	Off Peak	−10.1%	7.2%	20.6%	3.3%	25.7%	−5.9%	−8.9%	−8.2%	−5.4%	13.0%	2.8%	13.1%	15.3%
Difference	Peak	−18.9%	12.3%	36.3%	8.1%	−29.1%	−6.9%	−13.0%	−9.3%	−6.8%	32.4%	15.1%	50.3%	51.9%
Difference	Mean	−11.0%	4.8%	15.5%	6.2%	−14.2%	3.1%	−1.3%	0.8%	−0.6%	22.0%	13.1%	22.1%	25.8%

Generally, weekends exhibited smoother traffic conditions than weekdays, resulting in a shorter time spend idling (P_{idle}) and longer time spent cruising (P_{cruise}), longer micro-trips (the c value) and thus faster driving (higher v_1 and v_2) and less aggressive acceleration behaviours (smaller RMS, PKE, a, and d values). The time spent in acceleration and deceleration modes was similar between weekends and weekdays. Unexpectedly, the values of P_{creep} are insignificant, which indicate that creeping movements were not common along these selected bus routes. Comparing peaks and off-peaks, intuitively, driving during peak periods should be slower, with more idling and less cruising, and should experience more stop-and-go conditions due to traffic congestions. The reason for the generally opposite results observed in this study is most likely because of the bus operating characteristics. During off-peak periods, buses usually have spare capacities to carry passengers, and thus have to stop for every (or most of the) bus stop(s). However, during peak periods, buses may get fully loaded with passengers quickly and thus do not need to stop for passengers throughout the rest of the journey. The significantly longer micro-trip, as reflected in the value of the parameter c, was very strong evidence supporting this argument. This agreed well with the shorter time spent in idling mode but longer time spent cruising, as well as the relatively higher v_1 and v_2 values.

6.2. Differences in Overall Driving Characteristics between Electric and Diesel Buses

To analyse the differences in the overall driving patterns between the diesel and electric bus journeys, the mean values of the 13 driving parameters derived for diesel bus trips only (as well as for weekday, weekend, peak, and off-peak trips) were directly compared with their counterparts for electric bus trips only results. In short, the analysis procedure is described as follows:

1. Calculate the percentage differences for each parameter (as shown in Table 6d). A positive percentage means the electric bus has a higher value than the diesel bus counterpart.
2. Classify the percentage differences, according to its direction and magnitude, into three categories: above +5%, within ±5%, and below −5%.
3. Highlight the percentage differences in (i) Red (if above +5%); (ii) Yellow (if within ±5%); or (iii) Green (if below −5%).
4. Apply the same colour scheme (i.e., Red, Yellow, and Green) to both the percentage difference (Table 6d), and the electric bus trips only results (Table 6c).
5. Plot the percentage differences as a radar map (Figure 2) for visual interpretation.
6. Compute SAPDs for the electric and diesel bus datasets separately and then directly compare more detailed speed and acceleration characteristics (Figure 3).
7. Derive and compare the VSP distributions for the electric and diesel bus datasets (Figure 4).

6.2.1. Driving Parameters

This analysis was based on characteristics observed from Table 6c,d, and Figure 2. The purpose was to highlight the key differences in the overall traffic characteristics as reflected in the driving parameters. Driving patterns were interpreted with due considerations to not only the behaviour of individual parameter but also the collective effects across multiple inter-related parameters as well.

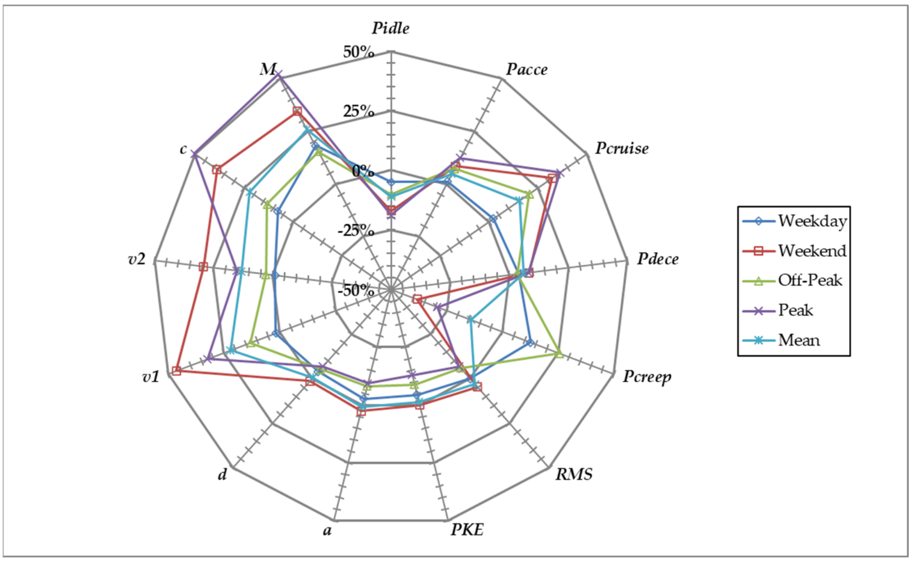
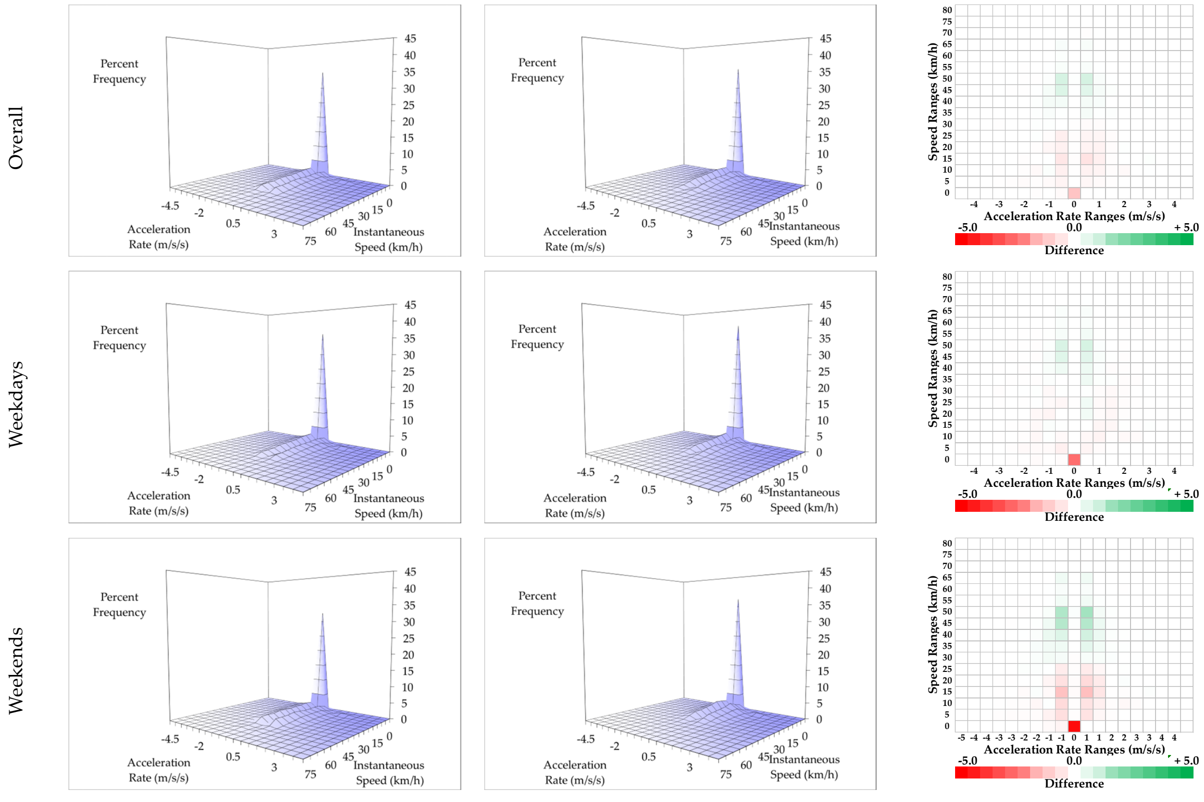


Figure 2. Radar map illustrating percentage differences between electric and diesel Buses.

First, electric bus trips along the selected routes spent much shorter time in idling (a reduction of 5% to 19%) but more time in other modes. Creeping has been kept at a very low proportion. Secondly, electric buses operated significantly faster (up to 46.4%) than diesel buses along these routes, with much longer micro-trips (up to 50%). Thirdly, acceleration-related parameters were generally similar for both types of bus along the selected routes. However, when looking at peaks and off-peaks separately, electric buses appeared to have smaller values, reflecting relatively less aggressive and smoother driving behaviours even though the number of acceleration/deceleration changes (i.e., *M*) was higher. These observations were generally consistent across all the five scenarios studied (i.e., weekends, weekdays, peaks, and off-peaks, and mean). Relatively more significant differences could be observed for the weekend and the peak period bus operations.

6.2.2. Speed–Acceleration Probability Distributions (SAPDs)

The SAPD illustrates the speed and acceleration distributions of the bus journeys which complement the driving parameters discussed earlier. It is a probability distribution of the bus driving data obtained for each unique combination of speed and acceleration classes. Separate SAPDs were developed for the entire electric bus only and diesel bus only datasets (Figures 3a and 3b, respectively), as well as for the further subdivided weekday only and weekend only datasets. The SAPDs were obtained using a resolution of 5 km/h and 0.5 m/s^2 with speed that ranged from 0 to 80 km/h, whilst acceleration ranged from -3 m/s^2 to 3 m/s^2. Eventually, each cell in the SAPD (representing each combination of speed and acceleration ranges) carried a probability value (between 0 and 1, or 0% and 100%) reflecting its likelihood of occurrence throughout the entire bus trip. It provides additional driving pattern details focusing on the bus trips' speed and acceleration behaviours, such as the spread of speed and acceleration ranges, and the areas where there may be higher intensities, etc.



(**a**) (**b**) (**c**)

Figure 3. SAPDs for electric and diesel bus. (**a**) SAPD (electric); (**b**) SAPD (diesel); and (**c**) heat map of the differences.

To evaluate how the SAPDs developed for the two types of bus differ from each other, two measures were introduced. First, the differences between corresponding cells in the electric and diesel bus SAPDs were computed and then expressed in the form of a heat map showing the direction and intensity of differences at each cell (Figure 3c). It was found that these differences ranged roughly within ±5% (i.e., a difference in a cell probability of ±0.05), with slight variations across different groups of comparisons made. For consistency reasons, a common scale was employed (using the identified ±5% as the basis) for all the SAPD comparisons. As illustrated in the legend below each heat map, "Red" represents the electric bus SAPD value being smaller than the corresponding diesel bus counterpart, and vice versa for "Green". The darker the colour is, the bigger the magnitude of the difference is. "White" means no or just a very small difference was observed. These heat maps are very useful tools to visually present the areas where the two SAPDs have relatively bigger contrasts. In addition to this visual evaluation, the sum square differences (SSD) between the two SAPDs was also calculated. The SSD represents the overall similarity (or dissimilarity) between two matrices. Smaller SSD values imply that the two SAPDs are more similar to each other and vice versa.

The basic pattern identified for the SAPDs is fairly consistent across all three cases analysed in this section. First, the presence of an idle peak is very clear. A significantly large proportion of the time is in the speed range of 0 to 5 km/h (around 35% to 40% of the entire bus trip). The speed essentially ranges from 0 to around 50 km/h, which is reasonable for bus operations, whilst acceleration mainly fluctuates within ±2 m/s^2. When looking at the SSDs, weekends exhibit the biggest difference (SSD = 42.0) between the SAPDs developed for the two types of bus as compared to the weekdays counterpart (SSD = 11.2). The SSD obtained for the entire dataset is the smallest (SSD = 5.2), which may represent a potential smoothing effect of combining weekdays and weekends data as a whole. Taking a closer look at the heat maps, it can be consistently observed that the largest difference is due to the idle peak, and the differences for other cells were generally within 1% (as reflected in the intensity of the colours), spreading mainly across a narrow acceleration range between $-0.5\ m/s^2$ and $+0.5\ m/s^2$. Electric buses generally involve slightly more high-speed driving at around 40–55 km/h (i.e., the Green areas on the heat maps) and thus less low-speed driving (i.e., the Red areas on the heat maps), as well as a clearly smaller idle peak. The pattern is even more obvious in the case of the weekend.

6.2.3. VSP Distributions

VSP provides an estimate of the power mass unit considering vehicle dynamic conditions such as speed, acceleration, and road grades. It is commonly used for conventional vehicle emission and energy consumption estimation according to a set of well-defined VSP modes. For electric vehicles' energy consumption estimation, the VSP modes have been further modified to improve the estimation accuracy [60]. For the case of battery electric vehicles, there is a strong positive correlation between energy consumption and VSP [60]. Higher energy consumption is expected for higher VSP modes. Using distributions to describe power data is crucial for electric buses' energy consumption estimation [61]. Therefore, the purpose of this analysis was to get a better understanding about electric buses' power distribution and how it compared with that of the diesel buses.

The VSP derived for the electric and diesel buses are shown in Figure 4. The green line in the middle shows the differences in bin frequencies between the VSPs developed for the two types of bus. A negative difference here means the electric bus has a lower frequency. Figure 4 indicates that the VSP for both types of bus varied mainly within ±10 kW/ton. The buses run more in the positive than negative VSP intervals for both types of bus, indicating that the buses have more running time within low acceleration ranges but less running time under deceleration conditions. The observed pattern echoes the findings from Section 6.2.2, where there is a peak at the zero VSP bin. This pattern is also consistent across both types of bus, except that the electric buses appear to have a lower peak at the zero VSP bin and a slightly flatter distribution than that of the diesel buses.

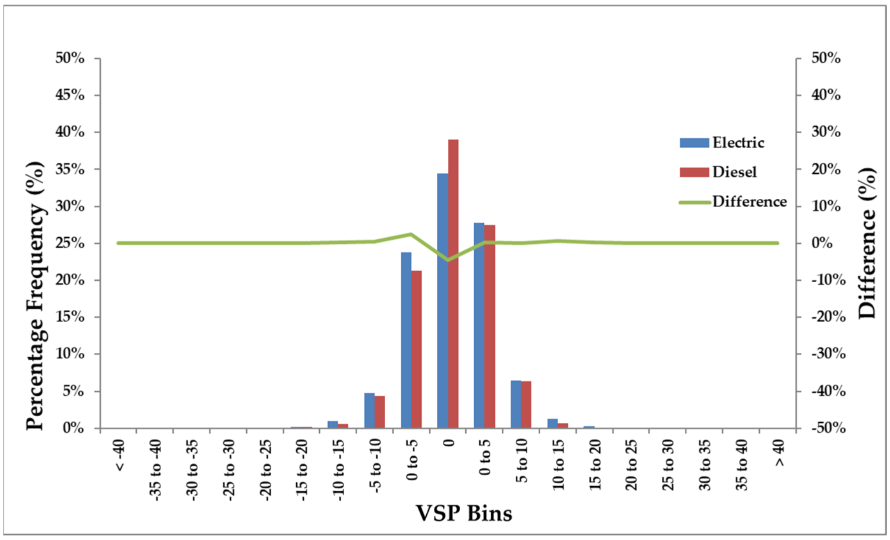


Figure 4. VSP distributions for electric and diesel buses (all data).

6.3. Route-Based Comparison

This section looks at route-based assessment of bus driving patterns. It starts by investigating the overall driving patterns for each selected route, disregarding the effect of bus types. This will be achieved by visually examining the idle vs. average speed plot, as shown in Figure 5. Each data point in Figure 5 represents one trip classified according to one of the four selected routes. The purpose of this analysis is to get a better understanding about any route-specific features in profiling bus driving characteristics.

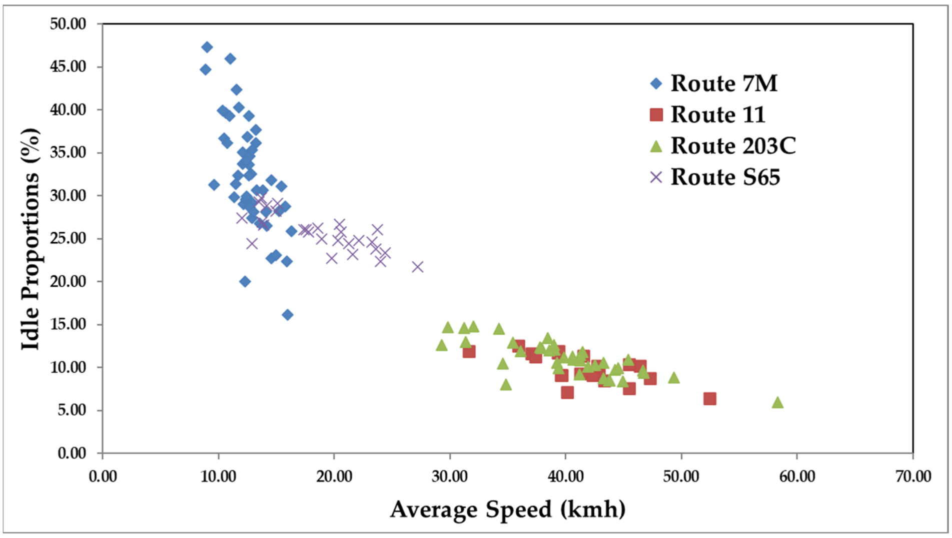


Figure 5. Average speed vs. idle proportions plot characterising bus route characteristics.

First, the trip pattern looks reasonable where idle proportion and trip average speed are negatively correlated. From Figure 5, it is clear that Route 7M is the slowest route, with an average operating speed generally well below 20 km/h. Route S65 is also a slow route, but relatively faster than Route 7M, and can be up to nearly 30 km/h. On the other hand, Routes 11 and 203C look very similar, with average speed ranging from around 30 km/h to above 50 km/h. To summarise, these four routes differ significantly in terms of driving patterns, and thus necessitate the need for a route-based analysis of bus driving data to uncover more details about the differences between electric and diesel bus driving activities. This analysis also demonstrates that the collected dataset has captured a wide range of driving characteristics, as reflected in the key driving parameters presented in Figure 5. This serves as a reliable basis for the route-based analysis in the next sections.

6.3.1. Route-Based Driving Parameters

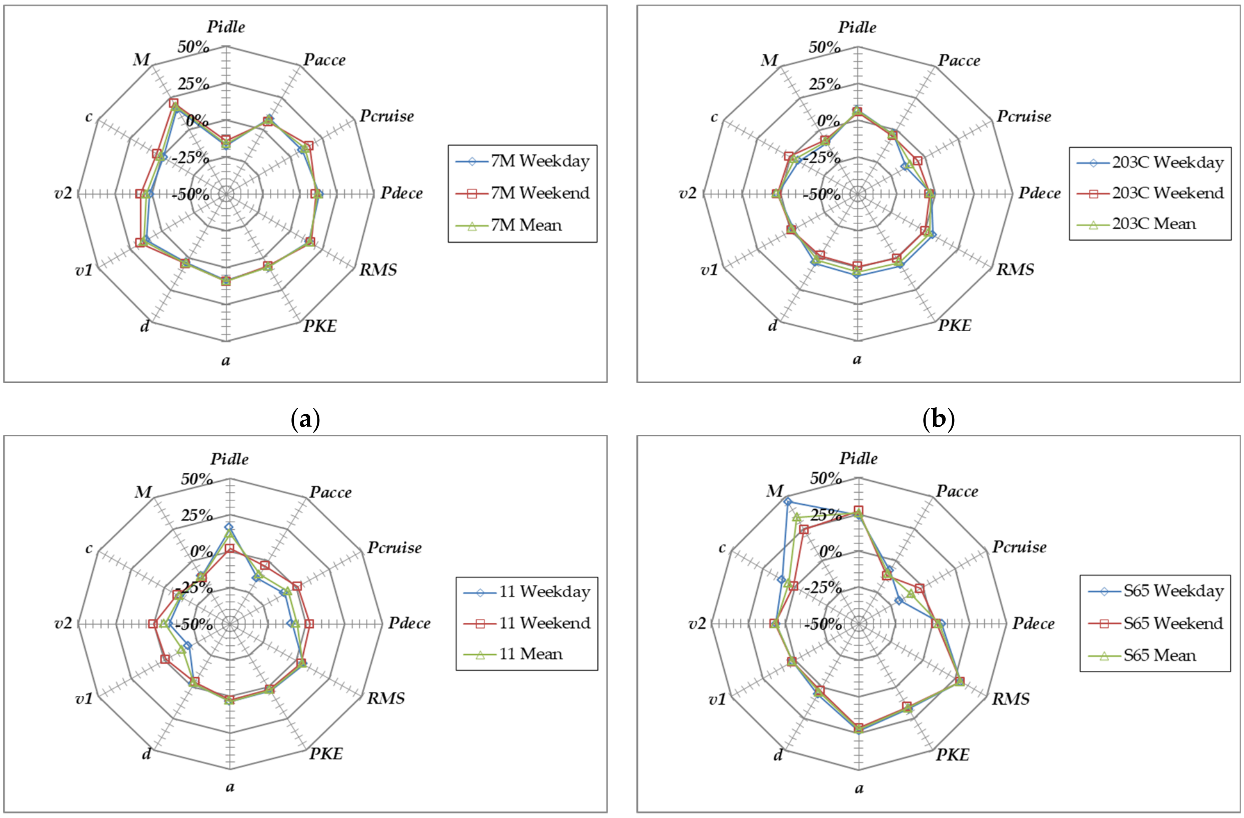
The route-based analysis first classified the collected bus driving data by the four selected routes. Then, the same three-step approach was applied to each of the four route-specific datasets. The detailed analysis procedure was basically the same as described in Section 6.1. Mean values of the 13 driving parameters were first derived for each route, but separately for electric and diesel buses. However, the selected routes were mainly served by electric buses. Conventional diesel buses were only scheduled for operation at a few specific timeslots, which limited the variety of data collected. Therefore, separate calculation of driving parameters for weekdays and weekends was not possible for diesel buses, and thus only overall averages for each route were computed in this case. For the electric bus cases, averages of the driving parameters for each route were derived for the whole dataset as well as for weekdays and weekends. These route-based driving parameter results are summarised in Table 7. Shaded in light blue are the diesel bus parameters which served as the baseline for comparison across all cases (i.e., overall mean, weekdays, and weekends) in the electric bus datasets. The same (Red, Yellow, and Green) colour scheme as described in Section 6.1 was adopted to highlight the magnitude and direction of differences for each electric bus driving parameters as compared to the baseline. Radar maps were also derived for each route as shown in Figure 6, which enabled an easier visual assessment of the differences. The purpose for the analysis in this section is two-fold. (1) To conduct a fair and direct comparison of route-specific differences in driving parameters between the two types of bus using data collected over exactly the same geographical setup; and (2) to investigate how these route-specific differences compare to the results obtained using mixed route datasets as described in Section 6.2. These analyses have been rare in the literature, as discussed earlier in the introduction and literature review sections, and thus highlight the originality and contributions of this study.

Table 7. Driving pattern characterisation and comparison (route-based).

	7M	P_{idle}	P_{acce}	P_{cruise}	P_{dece}	P_{creep}	RMS	PKE	a	d	v_1	v_2	c	M
Diesel	Mean	37.98	26.44	6.80	27.95	0.84	0.779	0.442	0.641	0.609	11.25	18.12	41.08	9.59
Electric	Weekda	31.34	28.75	7.42	31.55	0.94	0.894	0.474	0.695	0.633	12.65	18.41	40.66	11.14
Electric	Weeker	32.63	28.12	7.81	30.85	0.60	0.904	0.471	0.701	0.638	13.14	19.51	42.66	11.57
Electric	Mean	31.86	28.49	7.58	31.27	0.80	0.898	0.473	0.698	0.635	12.85	18.86	41.48	11.32
	11	P_{idle}	P_{acce}	P_{cruise}	P_{dece}	P_{creep}	RMS	PKE	a	d	v_1	v_2	c	M
Diesel	Mean	38.39	26.33	5.35	28.14	1.80	0.998	0.559	0.788	0.738	10.96	17.75	31.35	9.31
Electric	Weekda	44.45	22.63	4.89	25.50	2.54	1.055	0.575	0.816	0.723	8.89	16.00	27.35	8.15
Electric	Weeker	39.03	25.27	5.41	28.77	1.53	1.039	0.570	0.809	0.710	10.85	17.83	28.24	8.05
Electric	Mean	42.90	23.38	5.04	26.43	2.25	1.051	0.574	0.814	0.719	9.45	16.52	27.61	8.12
	203C	P_{idle}	P_{acce}	P_{cruise}	P_{dece}	P_{creep}	RMS	PKE	a	d	v_1	v_2	c	M
Diesel	Mean	38.47	25.65	6.90	28.09	0.90	0.875	0.465	0.685	0.623	11.12	18.05	36.13	10.13
Electric	Weekda	41.09	24.78	5.93	27.47	0.74	0.930	0.494	0.722	0.650	10.91	18.40	34.04	9.13
Electric	Weeker	40.60	24.50	6.54	27.08	1.28	0.876	0.467	0.680	0.613	11.04	18.43	36.48	9.34
Electric	Mean	40.88	24.66	6.19	27.30	0.97	0.907	0.482	0.704	0.635	10.96	18.41	35.07	9.22
	S65	P_{idle}	P_{acce}	P_{cruise}	P_{dece}	P_{creep}	RMS	PKE	a	d	v_1	v_2	c	M
Diesel	Mean	15.15	38.19	14.65	31.93	0.10	0.609	0.324	0.494	0.596	25.26	29.82	80.06	17.20
Electric	Weekda	18.79	35.02	11.98	33.91	0.30	0.789	0.381	0.609	0.629	25.74	31.65	88.15	25.14
Electric	Weeker	19.26	33.51	14.34	32.76	0.13	0.789	0.376	0.600	0.612	25.78	31.91	80.97	21.38
Electric	Mean	19.06	34.17	13.30	33.26	0.20	0.789	0.378	0.604	0.620	25.76	31.79	84.13	23.04

As can be seen from Table 7 and Figure 6, the two types of bus exhibited more distinguished patterns when they were operating on Routes 7M and S65, whilst their operations along Routes 203C and 11 were relatively stable and similar. In the cases of Route 7M, nearly all parameters exhibited notable differences, except for the deceleration rates (d) and length of a driving cycle (c). The electric bus operations were faster (v_1 and v_2)

and more aggressive (larger *RMS*, *PKE*, *M* and *a*), with a significant shift from time spent idling to other modes. In the cases of Routes 11 and 203C, the driving parameters of both types of bus did not differ a lot. The more obvious difference observed between electric and diesel buses was more time spent in idling than other modes and thus slower driving (v_1 and v_2). In the case of S65, there were significant increases in acceleration activities and their aggressiveness (*RMS*, *PKE*, *a*, *d*, and *M*). This observation particularly stood out in Figure 6. There were also considerable increases in the time spent in idling mode. These differences were obviously due to the route-specific features as described in Section 4 (Figure 1 and Table 2).



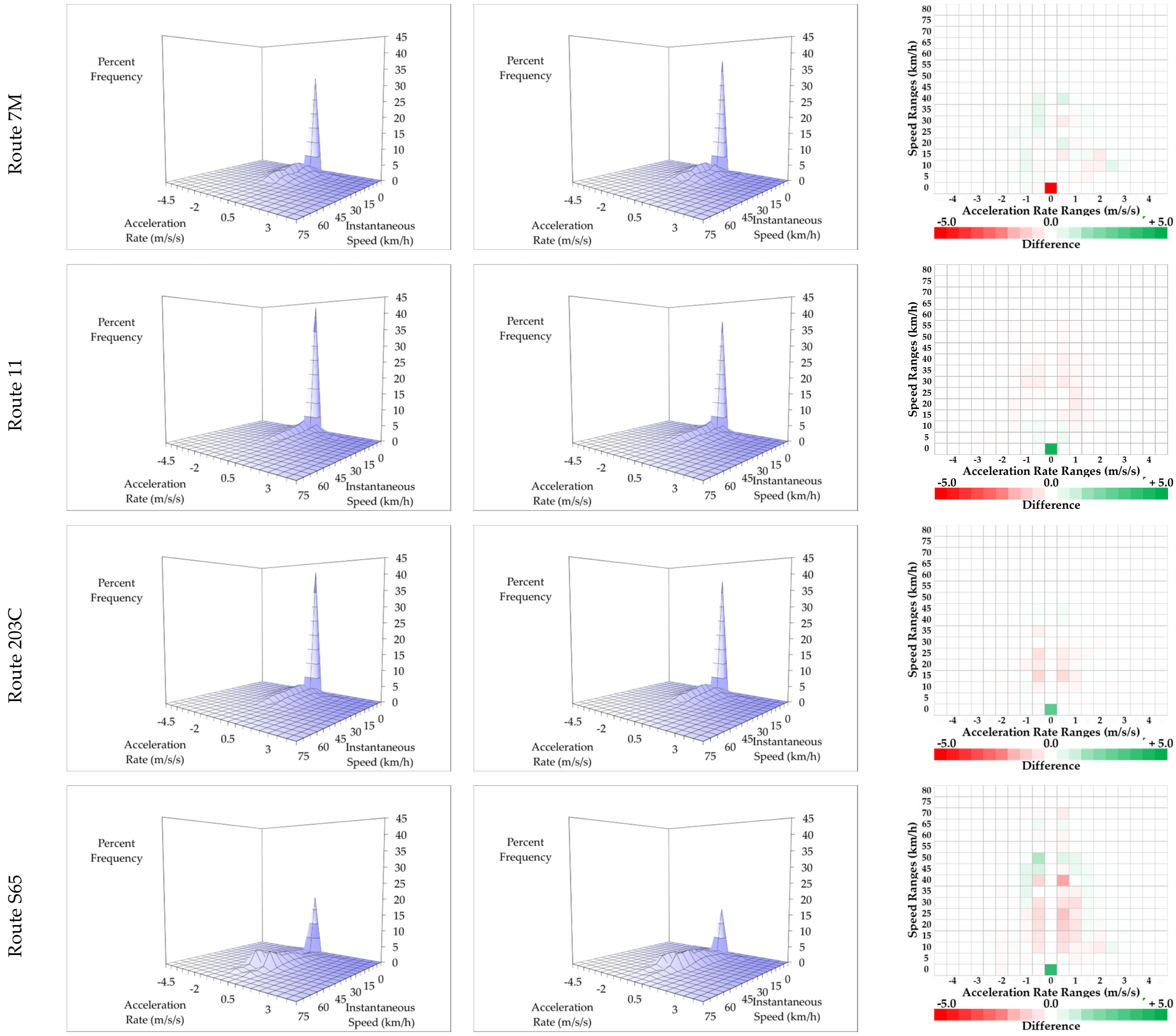
(**a**) (**b**)

(**c**) (**d**)

Figure 6. Radar map illustrating the route-based percentage differences in driving parameters for electric buses as compared to the conventional diesel bus counterparts. (**a**) Route 7M (a circular route); (**b**) Route 203C; (**c**) Route 11 (a circular route); (**d**) Route S65 (a circular route).

6.3.2. Route-Based Speed–Acceleration Probability Distributions

As for the SAPDs, the basic pattern is also consistent with the pattern observed in Section 6.2.2, where there is a significant idle peak. However, in some cases (Route S65, for example), the idle peak is much lower, and more time is observed spreading through to higher speed ranges. From the heat maps (Figure 7), more significant and varied differences are observed along Route S65 than any other route. The possible reason is that Route S65 serves a relatively newly developed district on Lantau Island of Hong Kong, where traffic conditions are less busy than the regions served by the other three selected routes. This presents more room for Route S65 to accommodate improved and more efficient driving behaviours using electric buses. The acceleration classes for which more notable differences can be observed between the electric and diesel SAPDs are also spread a bit wider (roughly from -2.0 m/s^2 to $+2.0$ m/s^2) than in the mixed-route analysis in Section 6.2.2 (-0.5 m/s^2 to $+0.5$ m/s^2). The intensities of the route-based differences between electric and diesel buses are also stronger (for example a bigger difference can easily be identified for the idle peak than in the mixed-route analysis from Section 6.2.2). The SSDs derived for comparing electric and diesel SAPDs are 41.6, 24.4, 12.8, and 33.3, respectively, for routes 7M, 11, 203C, and S65, which indicate generally bigger differences than in the mixed-route cases.



(**a**) (**b**) (**c**)

Figure 7. SAPDs for electric and diesel buses (route-based). (**a**) SAPD (electric); (**b**) SAPD (diesel); and (**c**) heat map of the differences.

6.3.3. Route-Based VSP Distributions

The differences between electric and diesel buses also can be observed from the comparisons of VSP distributions in Figure 8 as well. These differences vary quite a lot across different routes. One important observation is that there is a general decreasing trend in frequencies across the positive VSP bins for the electric bus operations, which essentially implies reductions in vehicle energy consumption. Similar to the route-based SAPD analysis, the differences between electric and diesel VSP distributions for routes 11 and 203C are small, with an increase in frequency in the zero VSP bin shifting from other bins. For Route 7M, the zero VSP bin has a drop in frequency which moves towards the negative VSP bins. The pattern of VSP distributions for Route S65 is again very distinct from other routes, where the 0–5 kW/ton bin records the highest frequency, and the distribution for electric buses is also flatter than the diesel buses. Again, these differences can be attributed to the route-specific features.

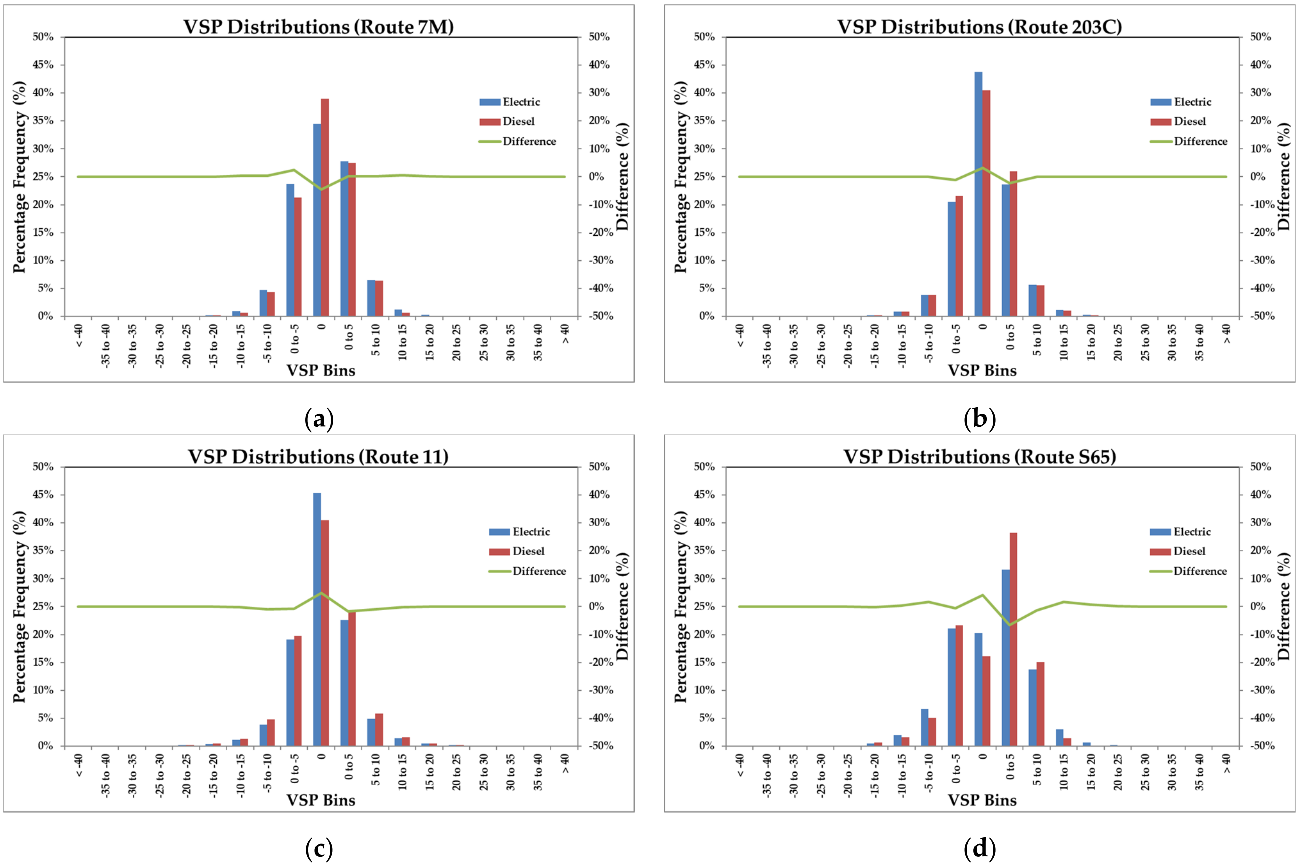


Figure 8. VSP distributions (route-based) for electric buses as compared to the conventional diesel bus counterparts. (**a**) Route 7M (a circular route); (**b**) Route 203C; (**c**) Route 11 (a circular route); (**d**) Route S65 (a circular route).

7. Discussions and Implications on Vehicle Energy Consumption

It is well researched that electric vehicles' energy consumption heavily depends on driving characteristics. However, direct comparison of driving characteristics between electric and diesel buses have been rare in the literature, and thus their differences in driving characteristics have not been fully pursued. Results from this study, as summarised in Table 8, have uncovered important findings that previously were unclear. This provides important references for electric bus energy consumption estimation and vehicle optimisation, as well as bus deployment plans. Section 6.1 characterised the basic driving patterns of the selected routes. It was found that weekend driving was smoother and faster, but less aggressive (i.e., more stable) than on weekdays. Off-peak driving was surprisingly slower than during peak periods due to the routes' normal passenger demand characteristics.

Table 8. Summary of analyses and key findings from this study.

Section	Metrics	Dataset	Purpose	Results
Mixed-Route Analysis				
Section 6.1	Driving parameters: Table 6a	All Data (Mixed-Route; Mixed bus types)	• Describing overall driving patterns for the whole dataset	• Weekend driving is smoother, faster, and less aggressive than weekdays. • Off-peak is slower, with more stops for passenger-loading activities. • Peak has longer micro-trip length due to early full-load and thus the bus does not need to stop frequently for passengers.
Section 6.2.1	Driving parameters: Table 6b–d; Figure 2	Electric Only; Diesel Only; (Mixed-Route)	• Comparing the differences in overall driving characteristics between electric and diesel bus operations	• Notable differences identified. • Electric bus driving was faster and smoother, and had longer micro-trip lengths.
Section 6.2.2	SAPDs Figure 3a–c and SSD	All Data; Electric Only; Diesel Only; (Mixed-Route)	• Comparing the differences in overall speed and acceleration characteristics between electric and diesel bus operations	• Large difference at idle peak—smaller for electric buses. • Small differences identified across a narrow range of acceleration rates (±0.5 m/s^2). • More obvious differences on weekends. • Combined (weekday and weekend) dataset potentially smoothed out the differences.
Section 6.2.3	VSPs Figure 4	Electric Only; Diesel Only; (Mixed-Route)	• Comparing the differences in power distributions between electric and diesel bus operations	• Positive VSPs more than negative VSPs within a VSP range of ±10 kW/ton. • Electric buses had a lower peak at zero VSP bin and a flatter VSP distribution.
Route-Based Analysis				
Section 6.3	Key driving parameters Figure 5	Route-based data	• Describing overall route-based driving patterns	• Covered a wide range of driving characteristics (e.g., for average speed and idle proportions). • Distinct characteristics for each route.
Section 6.3.1	Route-based Driving Parameters Table 7; Figure 6	Route-based Electric Only; Route-based Diesel Only	• Comparing route-specific differences in driving characteristics between electric and diesel buses • Comparing the direction and magnitude of the differences between non-route-based and route-based analysis	• Notable differences for most of the driving parameters for each route. • Two of the routes exhibited significant differences for most of the driving parameters—electric buses were more aggressive. • The other two routes exhibited relatively stable pattern between electric and diesel buses.
Section 6.3.2	Route-based SAPDs Figure 7 and SSD	Route-based Electric Only; Route-based Diesel Only	• Comparing route-specific differences in speed and acceleration between electric and diesel buses • Comparing the direction and magnitude of the differences between non-route-based and route-based analysis	• Basic pattern consistent with Section 6.2.2, but some routes exhibit a much smaller peak. • Differences between electric and diesel buses were much more obvious than for mixed-route analysis. • Differences were observed across a wider spread than in mixed-route analysis. • Intensity of the differences were much stronger than in mixed-route analysis.
Section 6.3.3	Route-based VSP Figure 8	Route-based Electric Only; Route-based Diesel Only;	• Comparing route-specific differences in VSP distributions between electric and diesel buses • Comparing the direction and magnitude of the differences between non-route-based and route-based analysis	• VSP differences varied a lot for different routes. • VSP differences between electric and diesel buses were much more obvious than for mixed-route analysis.

Section 6.2 performed a mixed-route analysis to identify the key differences between electric and diesel buses, considering primarily the collective effect across all the selected routes. Notable differences between the two types of buses were observed, where electric buses were faster and smoother, with longer micro-trip lengths. The difference was the most significant around the idle periods, and small differences were observed across a relatively narrow acceleration rate of $\pm 0.5\ \mathrm{m/s^2}$. These differences were more obvious during weekends, which uncovered strong evidence that combined (weekend and weekdays) analysis would possibly smooth out the differences. Differences in VSP distributions were similar to this pattern as well.

Section 6.3 investigated the intensity and direction of these differences at a route-based level. Results from this kind of analysis have been rare and are thus crucial to the literature. In general, the differences between electric and diesel buses became more obvious at the route-based level, spread across a wider speed and acceleration range, and the intensities and directions of these differences varied across different routes according to their route-specific features. In particular, electric buses were found to be generally more aggressive than diesel buses. This implies that route-based consideration is important for a better and more accurate electric bus deployment. These route-based analysis results were consistent with other studies such as Ye et al. [51], which contributed to the significant differences between driving distances and energy usage of electric buses following different driving cycles.

However, Ye et al.'s study was based on only one single test route, which might potentially smooth out the impact of route-based characteristics on the variations in driving characteristics. It is clear from our results that route-based analysis of bus driving characteristics has highlighted even greater variations in the direction and intensity of differences between electric and diesel buses across different bus routes, which might be related to the route-specific features and background traffic conditions. This could have significant implication on electric buses' energy consumption levels [62,63]. Therefore, electric bus trial, optimisation, and deployment programmes should consider the route-specific driving conditions in which the bus is expected to be deployed. This is particularly important under the unique driving and background traffic conditions in Hong Kong.

8. Conclusions

This work carried out a fair and reasonable comparison of driving patterns between electric and conventional diesel buses under identical traffic conditions during normal daily bus operations. A three-step approach was employed to study and profile the driving characteristics along four selected routes in Hong Kong, covering different temporal and geographical features. This approach involved using the collected bus operating speed data to derive (i) a comprehensive set of driving parameters; (ii) speed–acceleration probability distributions; and (iii) vehicle-specific power distributions. Whilst the nature of this study is investigative and observational (instead of using complicated modelling), the approach adopted for data collection and analysis have been widely used and are consistent with similar studies in the literature. This approach of analysis and the metrics employed are standard and well accepted in the field, and have been widely used in similar studies. The sample size obtained (i.e., a total of 135 bus trips) was also considered sizable when compared to many previous similar studies, which substantiated the reliability of the collected dataset.

The significance of the current study lies in the investigation of driving characteristics in electric and conventional diesel buses under the same driving environment, as reflected in their operations along exactly the same set of bus routes. This provides solid evidence and insight on how electric buses might differ from conventional diesel buses during normal bus operations. This fair and reasonable comparison has been rare in the literature, which helps uncover important characteristics and differences between the operations of the two types of buses. The results obtained could be good references for government agencies and/or bus operators when it comes to making the decision to deploy electric buses on routes bearing specific driving characteristics.

The results of this study demonstrated significant differences in driving characteristics between electric buses and conventional diesel buses. Electric buses can generally operate faster and smoother than diesel buses, with a relatively longer duration of micro-trips and shorter time spent in idling mode. The patterns and intensities of these differences in driving characteristics are even more exaggerated when it comes to route-specific analysis. It highlights the fact that pooling mixed-route speed data together can potentially smooth out the differences and distinct patterns specific to a particular bus route. Therefore, there is a concrete need to consider route-specific features in determining electric bus evaluation and deployment strategies.

Author Contributions: Conceptualization, K.-W.N. and H.-Y.T.; methodology, K.-W.N. and H.-Y.T.; software, K.-W.N. and H.-Y.T.; validation, K.-W.N. and H.-Y.T.; formal analysis, H.-Y.T.; investigation, K.-W.N. and H.-Y.T.; resources, K.-W.N. and H.-Y.T.; data curation, K.-W.N.; writing—original draft preparation, K.-W.N. and H.-Y.T.; writing—review and editing, K.-W.N. and H.-Y.T.; visualization, K.-W.N. and H.-Y.T.; supervision, K.-W.N. and H.-Y.T.; project administration, K.-W.N. and H.-Y.T.; funding acquisition, H.-Y.T. and K.-W.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The driving speed data will be available upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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