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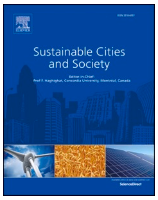

Developing electric bus driving cycles with significant road gradient changes: A case study in Hong Kong

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ABSTRACT

Battery electric buses have been increasingly being deployed to replace traditional diesel buses in providing urban public transport services. Accounted for over 30% of daily passenger trips, the franchised bus system in Hong Kong only retained a few battery electric buses after its trial programme. Under the unique bus driving environment in Hong Kong, more evaluations are anticipated for further deployment of electric buses. Driving cycle is a widely adopted platform for the assessment of vehicle fuel economy, energy consumption, emissions and driving range. Therefore, it is necessary to have a purposely developed driving cycle for battery electric buses. A comprehensive review of bus driving cycles developed elsewhere shows that the impacts of road gradients are seldom considered. Therefore, in this study, the only remaining battery electric bus route with significant gradient changes was selected for speed data collection and synthesis for a set of driving cycles. Results shown that driving characteristics of this route were comparable to urban bus cycles developed in other cities, but were slightly different from bus cycles developed for other conditions. It was also observed that battery electric buses appeared to be less responsive to drivers' acceleration activities than that of a supercapacitor bus.

1. Introduction

In recent years, driving cycles have been getting more attentions in developing economies. The major reason is that well-known overseas driving cycles have been widely recognised as unable to accurately reflect local driving characteristics. Therefore, driving cycles have been developed locally for estimating vehicle emission and fuel consumption (or energy consumption for electric vehicles). In particular, driving cycles have been increasingly being used for the assessment and optimization of various electric vehicle technologies (Anida et al., 2019; Kaymaz et al., 2019; Kivekas et al., 2018a, 2018b; Li et al, 2016; Shen et al., 2018). In the Asian region, special focus has been put on developing driving cycles for motorcycles (or rickshaws) and buses (Tong and Ng, 2021c). The first set of driving cycles developed in Hong Kong was for light duty vehicles under different driving conditions (Hung et al., 2007; Tong et al, 1999). In recent years, driving cycles for the heavily patronised franchised bus services were eveloped with an aim to identify their driving characteristics with respect to bus route architecture and traffic conditions in Hong Kong (Tong and Ng, 2021b).

Due to the popularity of electric bus technologies, public bus services have been incorporating them in replacing traditional buses. The public bus services have accounted for more than 30% of passenger journeys per day in Hong Kong. However, the use of electric buses is still at a trial stage. Even though the ultimate vision is to progressively replace the in-use traditional bus fleet with electric buses, the trial programmes have revealed some important obstacles for the further deployment of electric bus technologies under the unique hilly and mountainous driving environment in Hong Kong. As such, franchised bus operators have only maintained a few routes which are deemed to be relatively more suitable for deploying electric buses (Tong, 2019). For further evaluation and optimization of electric buses, a set of driving cycles developed specifically for electric buses under the unique driving conditions in Hong Kong are essential. Driving cycles enable a wide range of analytical tools that can influence decisions around the specific electric vehicle technology selection, based on indicators such as energy consumption, driving range and cost (Jin et al., 2020). There is a rich amount of research reporting that driving cycles for electric vehicles and traditional vehicles exhibit significant differences such as shorter driving ranges and faster acceleration / deceleration characteristics for electric vehicles (Das et al, 2021). These necessitate the development of driving cycles for electric vehicles to reflect their unique characteristics. Similarly, it also applies to the differences between electric buses and their

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Table 1
Comparison of reviewed bus driving cycles.

Location	Purpose	Stratification	Data Collection	Test Routes	Cycle Construction Method	Bus Type	Sources
Chennai, India	Understanding bus driving conditions	Time of a day	GPS	6 test routes selected by traffic density and time of a day	Random selection of micro-trips	Regular	Nesamania and Subramanian (2011)
Maharashtra, India	Highway bus route evaluation	Road type and time of a day	GPS Onboard	1 existing bus route on highway	Random selection of micro-trips	Regular	Maurya and Bokare (2012)
Delhi, India	Understanding bus driving conditions	Composite	GPS Onboard	1 test route selected by road types	Most representative single trip recorded	Regular	Kumar et al. (2013)
Beijing, China	Bus operation improvement	Route types	GPS Onboard	14 existing BRT routes	Selection of micro-trips according to VSP distribution	Regular	Lai et al. (2013)
Xi'an, China	Evaluation of EV bus performances	Traffic conditions	GPS Onboard	1 existing bus route	Random selection of micro-trips	Electric	Li et al. (2016)
Hanoi, Vietnam	Emission estimation	Urban	GPS Onboard	1 existing bus route	Markov chain with Transition Probability Matrix and SAFD	Regular	Nguyen et al. (2016)
Hamburg, Germany	Generation of driving cycle for public transport	Composite	GPS Onboard	Random travel in the city	Micro-trip selection model	Articulate	Gunther et al. (2017)
Hanoi, Vietnam	Emission estimation	Urban	GPS Onboard	5 existing bus routes	Markov Chain with Transition Probability Matrix, SAFD and VSP distribution	Regular	Nguyen et al. (2018)
Shanghai, China	Emissions, energy and fuel economy estimation	Inter-city bus route	Onboard	1 existing intra-city bus route	Random selection of segments with PCA and k-means clustering analysis	Hybrid	Shen et al. (2018)
Espoo, Finland	Energy consumption evaluation	Suburban	GPS Onboard	1 existing suburban bus route	Segment Based (between bus stops)	Electric	Kivekas et al. (2018a, 2018b)
Kuala Terengganu, Malaysia	Emission and Energy Estimation	Bus Route	GPS Onboard	1 existing bus route	Micro-trip Clustering	Hybrid	Anida et al. (2019)
Mexico City, Mexico	Compare DC Methods	Urban, Mountain, General	GPS Onboard	Existing bus routes in 4 regions	Micro-trip, Markov Chain, Fuel Based Approaches	Regular	Huertas et al. (2019)
Istanbul, Turkey	For EV Evaluation	BRT Lines	GPS Onboard	1 BRT route	Micro-trip Representative	Electric BRT	Kaymaz et al. (2019)
Kanchanaburi, Thailand	Bus accident analysis	Special bus route	GPS Onboard	1 existing bus route along hazardous areas	Micro-trip selection according to clustering results	Regular	Mongkonlerdmanee and Koetniyom (2019)
Fuzhou, China	Emission estimation	Urban	GPS Onboard	18 existing routes selected by station intensity	Random selection of micro-trips with PCA and k-means clustering analysis	Regular	Peng et al. (2019a)
Chennai, India	Emission and Certification	Bus Route	GPS Onboard	Several existing bus routes	Micro-trip Cluster	Regular Bus	Desineedi et al. (2020)
Shandong, China	Bus Driving Pattern	Urban	GPS Onboard	1 existing bus route	Markov Chain and Station Distance	Hybrid	Liu et al. (2020)
Zhangzhou, China	Energy Consumption	Bus Routes with BRT	GPS Onboard	2 existing bus routes (1 traditional and 1 BRT)	Markov Chain with Slope	Hybrid	Peng et al. (2020)
Mexico City, Mexico	Emission and Fuel Consumption	Urban	GPS Onboard	15 existing routes	Micro-trip selection	Regular	Quirama et al. (2020)
Isfahan, Iran	Emission and Fuel Estimation	Urban	GPS Onboard	5 selected test routes	Random Selection of Micro-trips	Regular	Ghaffarpasand et al (2021a, 2021b)
Kuala Terengganu, Malaysia	Emission and Fuel Estimation	Bus Routes	GPS Onboard	2 existing bus routes	Micro-trip Clustering	Regular	Norbakyah et al. (2021)
Mexico City, Mexico	Emission and Fuel Estimation	Urban	GPS Onboard	2 non-stop bus routes	Random Selection of Micro-trips	Regular	Quirama et al. (2021)
Debrecen, Hungry	Emission and Fuel Estimation	Composite	N/A	N/A	Micro-trips, Markov Chain	Regular	Vamosi et al. (2021)
Beijing, China	Fuel Consumption Estimation	Urban	GPS Onboard	Tour Bus	Micro-trip Clustering and Markov	Tour Bus	Yuan et al. (2021)

traditional counterparts. Their operations have significant differences in torque and power characteristics, transmission efficiency, powertrain, energy recovery braking system, etc. Use of traditional bus driving cycles for electric bus performance evaluations would contribute to significant errors (Wang et al., 2023).

Therefore, a study was commissioned to (1) collect on road vehicle speed data for those battery electric bus routes maintained after the trial programmes; (2) evaluate the driving patterns of those battery electric bus routes; and (3) develop a set of driving cycles for battery electric bus routes in Hong Kong. Among those remained battery electric bus routes, only one covered road sections with significant road gradient changes. In Hong Kong, the landscape mainly consists of steep mountains and hills, which fall steeply to the coast (PD, 2005), and the upland landscape occupies around 60% of Hong Kong's land area. These characteristics are especially obvious on Hong Kong Island and Lantau Island where the bus network is landed on fairly hilly and mountainous terrains with frequent steep slopes. Whilst it is widely recognised that road gradient has significant impacts on the driving performances of electric vehicles (Hanzl et al, 2022; Liu et al., 2017; Prakash and Bodisco, 2019; Yang et al., 2023), it is worthwhile to separately investigate the

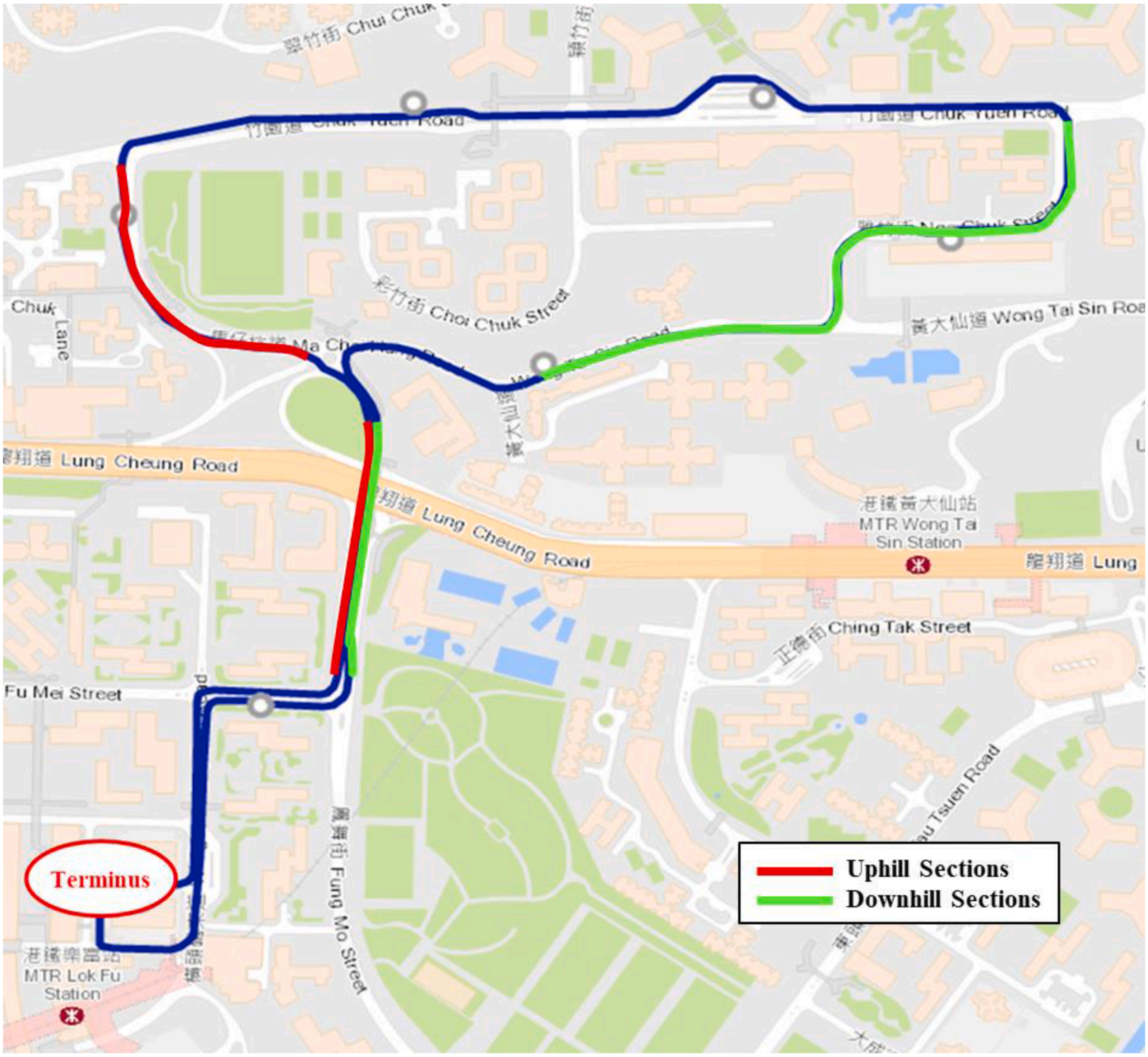


Fig. 1. Map of the Route 7M (a Circular Route).

Table 2
Details of the battery electric bus.

	Specifications
Bus Body:	Gemilang Coachworks bodywork 'EcoRange' aluminium bus body
Model:	K9R
Passenger Capacity:	31 seats and space for 35 standees
Dimensions:	11.6m (L) x 2.5m (W) x 3.25m (h)
Gross Weight:	19,000 kg
Curb Weight:	14,000 kg
Wheelbase:	6.25 m
Top Speed:	62.5 mph
Max Gradeability:	17%
Motor Type:	AC Synchronous
Max Power:	150 kW x 2
Max Torque:	550 N·m x 2
Battery Type:	Iron Phosphate
Battery Capacity:	324 kWh
Charging Capacity:	80 kW
Charging Time:	4 h
Longest travelling distance when fully charged:	250 km
Supplier:	BYD Auto Industry Company Limited (BYD)

characteristics of this hilly electric bus route. In particular, Salihu et al. (2023) reported that grades of the road significantly affect the behaviours of drivers which are necessary for micro-scale analysis. Driving cycles developed for different road grade classes exhibited significantly different acceleration and deceleration characteristics, and hence would affect vehicle emissions and energy consumption characteristics. Thus, this paper specifically selected this bus route, which covers roadways with significant road gradient changes, to synthesize a driving cycle. The developed cycle would therefore be able to reflect the bus driving characteristics under the unique hilly driving environment in Hong Kong, which can then be served as a more realistic platform for the evaluation and optimization of electric bus technologies to be adopted in Hong Kong.

In short, the motivations and contributions of this paper are to address the lack of real-world operational data that captures battery electric bus driving characteristics under the unique hilly driving environment in Hong Kong. Driving data was collected from real daily operation of the only battery electric bus route with significant road gradient changes. The first driving cycle for battery electric buses in Hong Kong was then developed with due consideration of the effect of road gradient changes. The developed cycle would be helpful to provide

Table 3
Driving characteristics for the speed data set.

(a) Weekdays Trips Collected for Battery Electric Buses

Micro-Trip Bin	P_{idle} (%)	P_{aece} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	RMS (m/s^2)	PKE (m/s^2)	a (m/s^2)	d (m/s^2)	v_1 (km/h)	v_2 (km/h)	c (s)	M (time)
Downhill	30.10	29.57	7.76	31.47	1.10	0.900	0.486	0.690	0.648	12.92	18.46	41.9	12.0
Flat	29.54	29.38	7.77	32.95	0.35	0.947	0.473	0.709	0.631	12.87	18.27	38.5	10.4
Uphill	42.32	23.52	5.41	27.47	1.29	0.966	0.475	0.735	0.625	10.66	18.45	32.8	9.0
Mean	33.99	27.49	6.98	30.63	0.91	0.938	0.478	0.711	0.635	12.15	18.39	37.75	10.47

(b) Weekend Trips Collected for Battery Electric Buses

Micro-Trip Bin	P_{idle} (%)	P_{aece} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	RMS (m/s^2)	PKE (m/s^2)	a (m/s^2)	d (m/s^2)	v_1 (km/h)	v_2 (km/h)	c (s)	M (time)
Downhill	29.53	30.27	8.21	31.74	0.25	0.909	0.470	0.695	0.663	14.70	20.86	48.0	12.8
Flat	36.40	26.38	7.10	30.01	0.12	0.947	0.484	0.731	0.642	11.52	18.11	35.4	10.0
Uphill	35.36	26.20	7.65	29.55	1.24	0.860	0.453	0.672	0.596	12.44	19.25	39.6	10.9
Mean	33.76	27.62	7.65	30.43	0.54	0.905	0.469	0.699	0.634	12.89	19.41	40.98	11.25

(c) Trips Collected for Traditional Diesel Buses

Micro-Trip Bin	P_{idle} (%)	P_{aece} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	RMS (m/s^2)	PKE (m/s^2)	a (m/s^2)	d (m/s^2)	v_1 (km/h)	v_2 (km/h)	c (s)	M (time)
Downhill	37.08	27.85	7.99	26.53	0.54	0.725	0.432	0.593	0.626	11.36	18.06	36.9	8.6
Flat	39.88	24.68	6.70	28.54	0.19	0.829	0.457	0.688	0.596	10.88	18.10	42.4	10.8
Uphill	43.82	23.77	4.12	26.83	1.46	0.769	0.432	0.628	0.582	10.22	18.19	30.0	8.1
Mean	40.26	25.43	6.27	27.30	0.73	0.774	0.440	0.636	0.601	10.82	18.12	36.4	9.2

a better understanding of battery electric bus operations under the hilly driving conditions in Hong Kong as well as offering a more realistic platform for the evaluation and optimization of electric buses in Hong Kong.

2. Trials and uses of electric buses in Hong Kong

Trial of electric bus technologies in Hong Kong was first initiated in 2010. The five franchised bus operators in Hong Kong were then fully subsidised to procure 36 electric buses under a trail programme. The primary aim was to evaluate the performances of these electric buses under the special bus operating environments in Hong Kong (LC Paper, 2017). In particular, the high temperature ambient condition and hilly driving environment in Hong Kong are significant factors affecting the performances of the electric buses. Results from the trail programme indicated that battery electric buses performed very similar to traditional diesel buses, except that the average driving range of electric buses (which was about 190 km) might be constrained by the additional vehicle load induced by the high ambient temperature and hilly driving environment in Hong Kong. However, electric bus technologies were observed to be helpful in reducing fuel costs. Another e-bus policy study commissioned afterwards had reviewed worldwide e-bus experiences and identified the major issues hindered the implementation of e-buses in Hong Kong together with some policy recommendations (Hung et al., 2016).

Until recently, a more ambitious policy has been released by the Hong Kong government aiming at achieving the ultimate goal of carbon neutrality by 2050. In 2021, one of the franchised bus operators, the Kowloon Motor Bus (KMB), announced that they will spend over hundred million dollars to purchase 42 electric buses from the Mainland China, US and Europe, with an aim to commence service in the second half of 2022. These e-buses will mainly cover routes along new development areas. The purchase of e-buses will be increased to 72 by the end of 2022 and then further expand to 500 in the next 5 years. The long term goal is replacing the whole 4000 bus fleet by electric buses by 2050.

Because of the obstacles identified in the trial programmes and studies, only a few electric buses were then retained for deployment in daily revenue generating operations. Among these retained routes, two third of them are shorter than 10 km in length and there is only one route covering road sections with significant road gradient changes (Tong and Ng, 2021c). This reflects the special driving characteristics when compared with their traditional diesel counterparts such as shorter driving range and less effective in climbing hill. Along with the government policy objectives and the identified uncertainties from the trail programmes, more investigations on the performances of different e-bus technologies under the unique Hong Kong driving environments are necessary before further deployment. Driving cycles reflecting the real and unique bus driving environments in Hong Kong are therefore essential to provide an alternative means of testing performances for electric buses.

3. Literature review

Development of driving cycles for buses or bus routes is uncommon until recent years, especially in the Asian region (Tong and Ng, 2021a, 2021b, 2021c). A summary of driving cycle studies related to buses is provided in Table 1. It indicates that there is a clear increasing trend in developing driving cycles for different types of buses, especially in China and India. It is also obvious that GPS has been unarguably becoming a predominant technology for on-road bus speed data collection. Among those reviewed studies, most of them were for traditional buses. Only a few of them were related to electric or hybrid buses including the suburban bus driving cycle for Espoo in Finland (Kivekas et al., 2018a, 2018b), the Xi'an EV bus driving cycle in China (Li et al, 2016), the driving cycle for an inter-city bus route in Shanghai (Shen et al., 2018), a hybrid bus driving cycle for Kuala Terengganu, Malaysia (Andia, et al., 2019), the Istanbul driving cycle for an electric bus rapid transit route in Turkey (Kaymaz, et al., 2019), the hybrid bus driving cycles in Shangdong (Liu, et al., 2020) and Zhengzhou (Peng, et al., 2020) as well as the Supercapacitor Bus Driving Cycle (SBDC) developed in Hong Kong (Tong, 2019). It demonstrated the importance of developing a local driving cycle for battery electric buses in Hong Kong.

For driving cycle construction methods, it can be broadly classified into three types, micro-trip based, Markov Chain based and other methods. As part of the large scale study, a comprehensive review of about 100 driving cycle studies covering over 190 driving cycles worldwide was conducted (Tong and Ng, 2021c). It is commonly agreed that each approach has its own advantages and disadvantages. The choice of a particular approach tends to be dependent on the preferences of individual study and researcher. In particular, the review also indicates that the micro-trip approach has been the most frequently used, no matter across all the 100 driving cycle studies reviewed (the micro-trip approach accounted for 59%), among developing economies

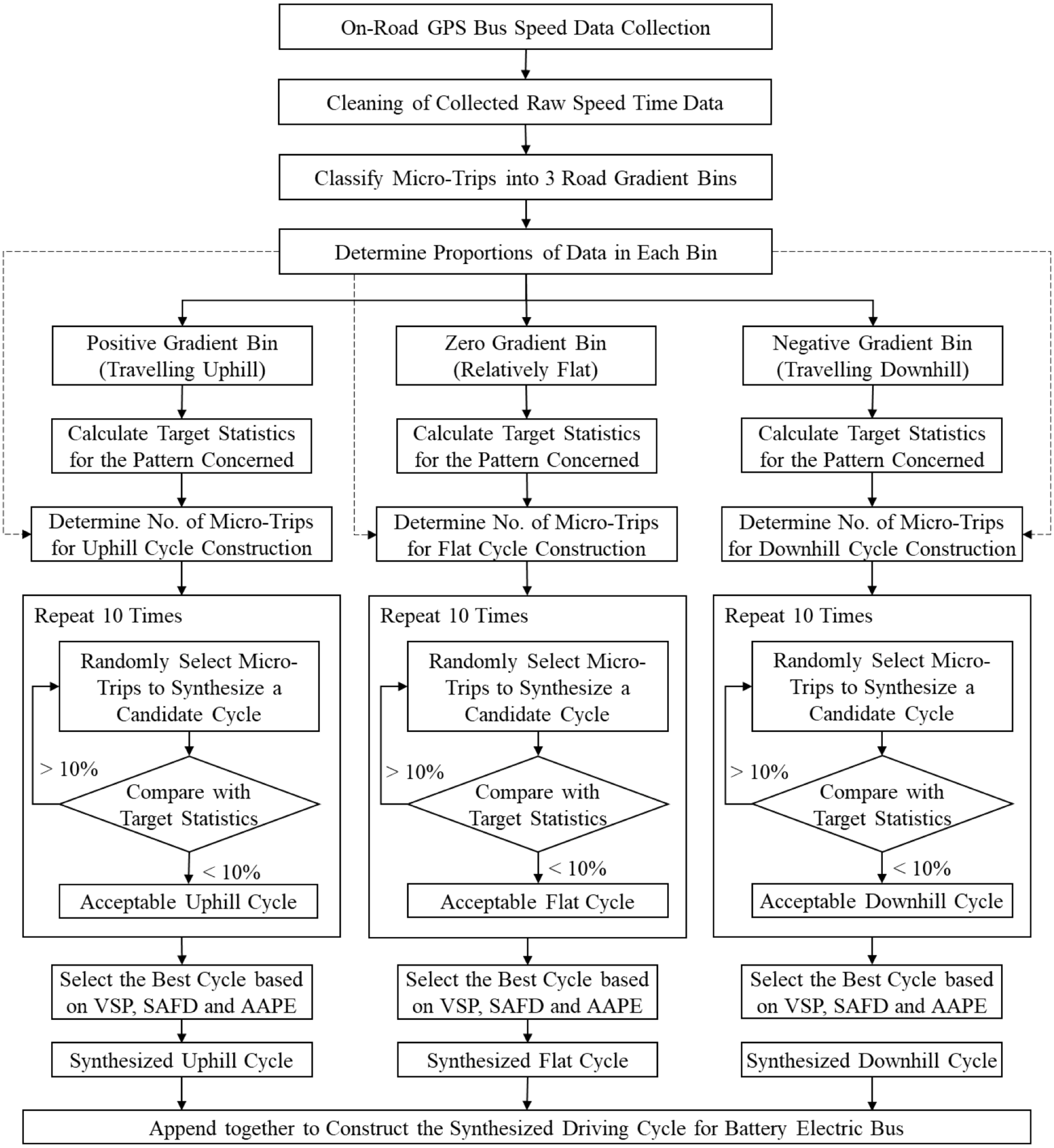


Fig. 2. Overall Approach of driving cycle development considering road gradients.

(64%), developed economies (56%), or for public transport and bus vehicles (80%). This approach has also been identified as more suitable for driving scenarios with frequent stop-and-go conditions (Tong and Hung, 2010b). The core element of this approach is the use of micro-trips as the fundamental building blocks for developing driving cycles, which has been adopted in Hong Kong since two decades ago, and then further extended and refined in recent years to cater for other cycle development scenarios and vehicle types. This long history of adoption has substantiated its appropriateness for the special driving environments in Hong Kong. Therefore, building upon this well-established foundation, the core micro-trip based approach is adopted, with appropriate refinement and adjustment considering road gradient changes, for the current study to develop driving cycles.

The literature review also pointed out that, no matter which particular cycle construction approach was adopted, most of the reviewed driving cycle studies did not consider the impact of road gradients except just a few of them (Tong and Ng, 2021c). Mongkonlerdmanee and Koetniyom (2019) employed a micro-trip based time clustering technique to develop a driving cycle for bus transportation in Thailand for accident analysis purposes. This cycle involved data collected from just one single bus route in the rural areas of North West Thailand. Even though this route was identified to be dangerous and hazardous because of a long deep gradient, narrow and continuous curve, the road gradient variable was still not incorporated into the analysis and development of the resultant driving cycle. At the same time, road gradient is known to be influential on vehicle dynamics and vehicle performances such as exhaust emissions, energy efficiency and driving range, especially for electric vehicles and buses (Liu et al., 2017; Prakash and Bodisco, 2019). Therefore, the impacts of road gradient changes should deliberately be considered in driving cycle analysis.

Bender and Sawodney (2015) developed a driving cycle for refuse trucks including not only speed time profile but also road grade and

Table 4
Results for the determination of number of micro-trips to be selected.

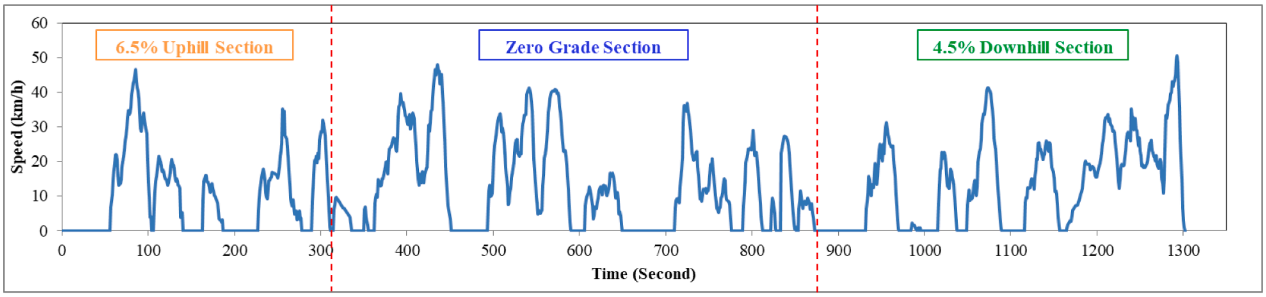
Micro-Trip Bin	Number of Micro-Trips	Cycle Duration (*s*)	Proportions of Data in each bin	P_{idle}	v_1 (km/h)	*c (s)*
(a) For Weekday Cycle						
Downhill	5	325	27.1%	30.10	12.92	41.9
Flat	10	567	47.2%	29.54	12.87	38.5
Uphill	5	308	25.7%	42.32	10.66	32.8
Total	20	1200	100%	–	–	–
(b) For Weekend Cycle						
Micro-Trip Bin	Number of Micro-Trips	Cycle Duration (*s*)	Proportions of Data in each bin	P_{idle}	v_1 (km/h)	*c (s)*
Downhill	5	316	26.3%	29.53	14.70	48.0
Flat	11	610	50.8%	36.40	11.52	35.4
Uphill	5	275	22.9%	35.36	12.44	39.6
Total	20	1200	100%	–	–	–

vehicle mass information. To develop the final driving cycle, a window algorithm incorporating a continuous sequence of micro-trips was employed to ensure the smooth transition between micro-trips in terms of the road grade and vehicle mass. Liu et al. (2020) developed a city bus driving cycle using data from a single hybrid electric bus (HEB) route to address the problem of ignoring the passenger load and road grade information in the course of a driving cycle synthesis. Peng et al. (2020) also developed a driving cycle for HEB in Zhengzhou with due consideration of road slope information for electric vehicle design and energy consumption optimization. They used bus speed and road slope information from a Bus Rapid Transit (BRT) route to generate a ZhengZhou Urban Driving Cycle. Han et al. (2012) developed a methodology for deriving a driving cycle with considerations of the effects of road gradients, which would eventually affect fuel consumption estimations. Based on data from 16 test routes, a micro-trip based method was employed to determine the final driving cycle using two fuel consumption and road grade related parameters as target criteria. Bishop et al. (2012) developed a driving cycle for electric scooters in Oxford using road grade information. Jia et al. (2021) developed bus driving cycles for three distinct driving conditions (urban, suburban and highway) considering road slopes in the city of Zhangjiakou in China, which aimed at vehicle powertrain optimization. This study employed a segment-based approach (similar to micro-trip based approach) to incorporate speed and road slope information into the same driving cycle. Bhatti et al. (2021) developed a driving cycle representative of the urban areas of Islamabad by incorporating the road slope profile, for the evaluation of electric vehicle powertrain simulation. Road slope profiles were derived with the collected altitude data. The ultimate driving cycle was weighted according to the proportions of different road types considering road grade information.

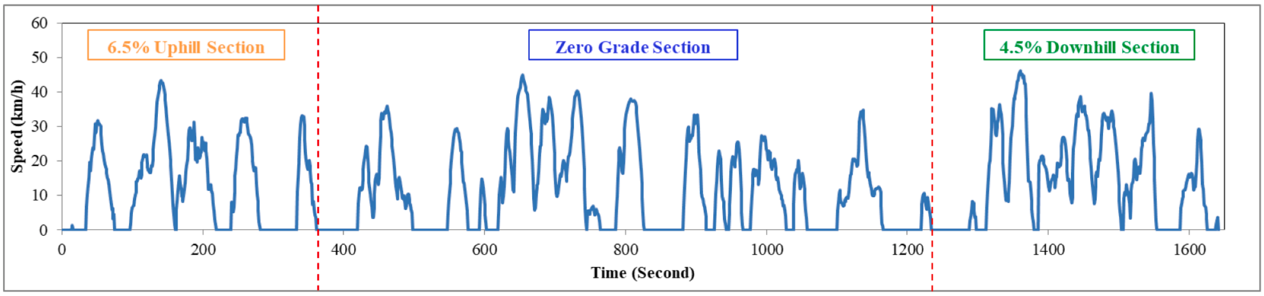
Based on the above review, it is clear that driving cycles incorporating road grade information were developed mainly for the evaluation of vehicle driving performances (especially for buses or heavy vehicles) towards road gradients (Bender and Sawodney, 2015; Liu et al., 2020; Salihu et al., 2023), electric vehicle design and energy consumption optimization (Peng et al., 2020), fuel consumption estimation (Han, et al., 2012), as well as electric heavy duty vehicle powertrain

Table 5
Assessment criteria of the EBDCRG weekday and weekend cycles.

	v_1 (km/h)	v_2 (km/h)	*a* (m/s^2)	*d* (m/s^2)	P_{idle} (%)	P_{aece} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	*RMS* (m/s^2)	*PKE* (m/s^2)	*c (s)*	*M (time)*	*AAPE*	*SSD*
Weekday Cycle	12.22	18.34	0.691	0.642	33.35	28.36	6.99	30.43	0.84	0.925	0.484	39.40	10.90	35.32	6.59
Weekday Mean	12.15	18.39	0.711	0.635	33.99	27.49	6.98	30.63	0.91	0.938	0.478	37.75	10.47		
Weekend Cycle	12.34	19.27	0.678	0.594	35.91	26.58	7.07	30.24	0.18	0.876	0.464	42.03	10.03	75.40	8.23
Weekend Mean	12.89	19.41	0.699	0.634	33.76	27.62	7.65	30.43	0.54	0.905	0.469	40.98	11.25		

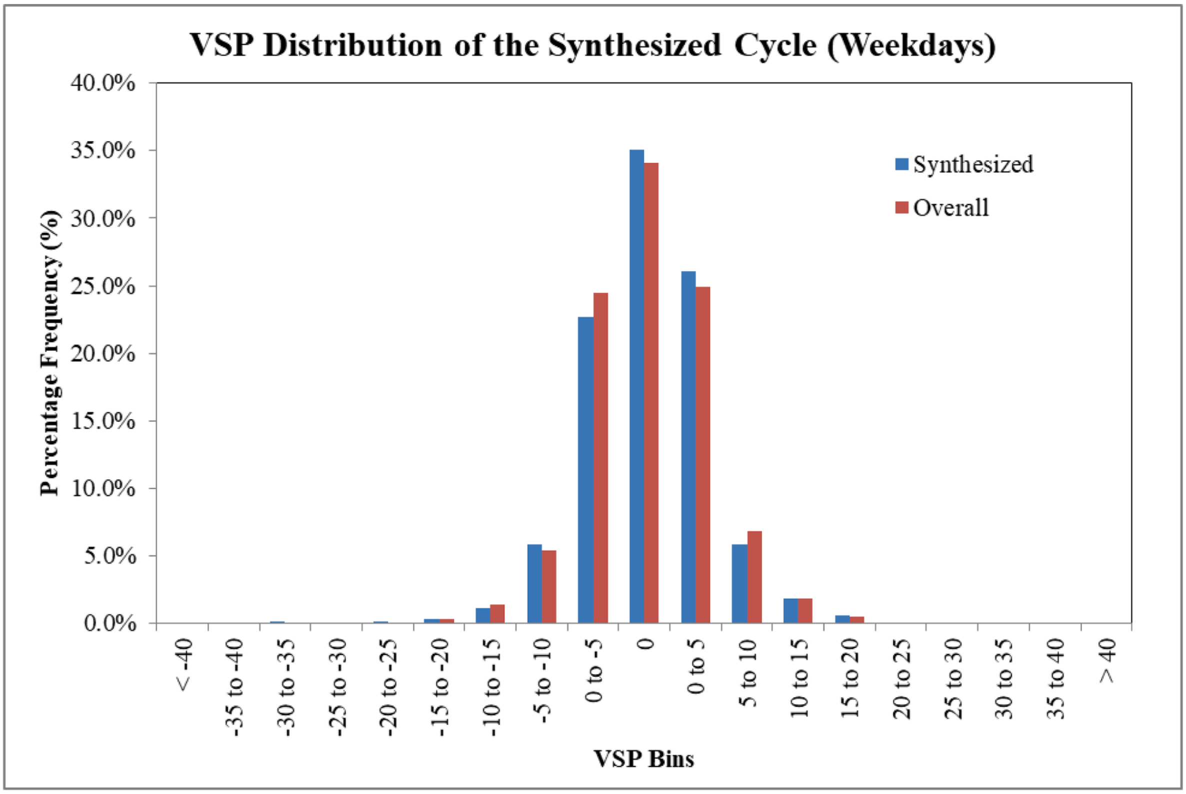


(a) EBDCRG Weekday Driving Cycle

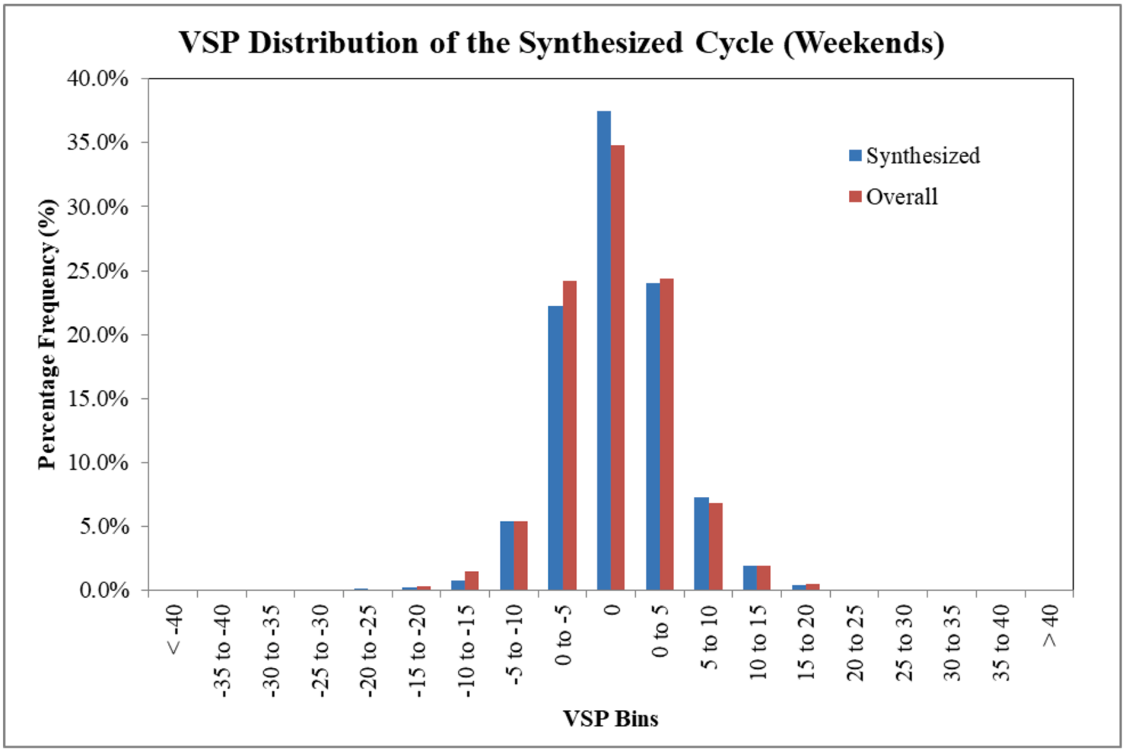


(b) EBDCRG Weekend Driving Cycle

Fig. 3. The Electric Bus Driving Cycles with Road Gradient Changes (EBDCRG).

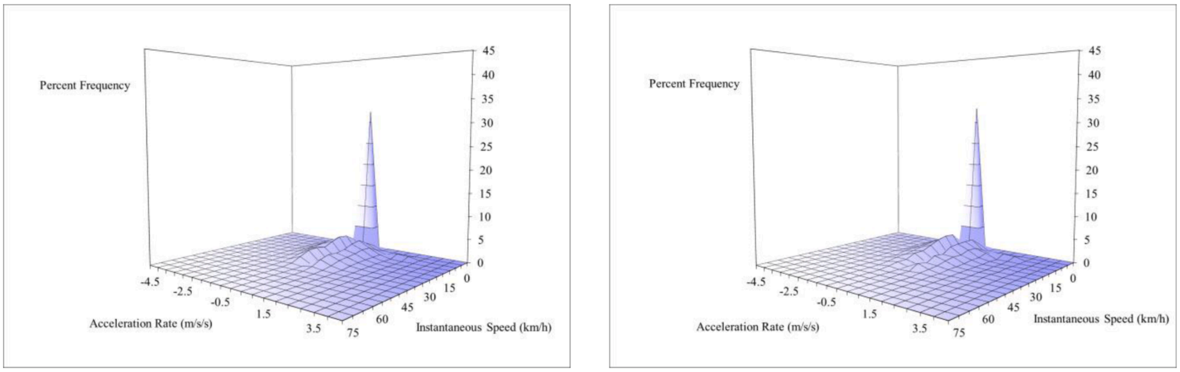


(a) EBDCRG Weekday

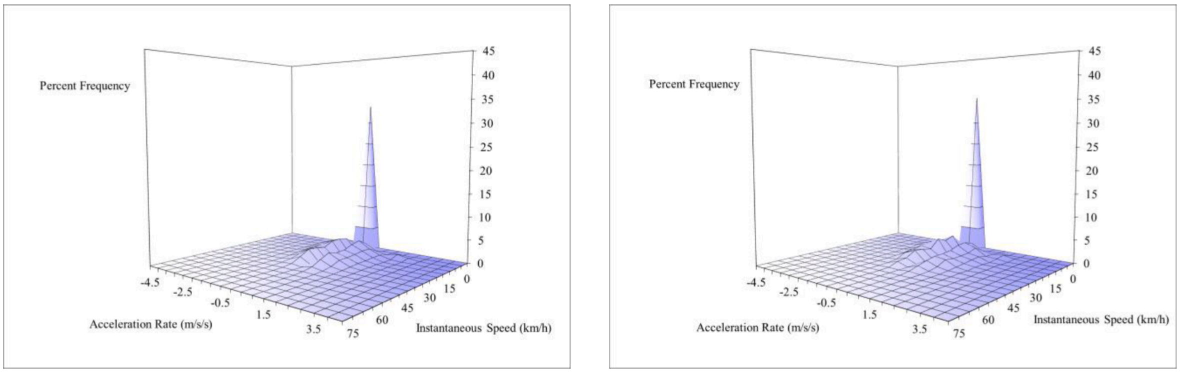


(b) EBDCRG Weekends

Fig. 4. VSP Distributions for the EBDCRCs and the whole dataset.



(a) SAPD for the Whole Weekday Dataset **(b) SAPD for EBDCRG Weekday**



(c) SAPD for the Whole Weekend Dataset **(d) SAPD for EBDCRG Weekend**

Fig. 5. SAPDs for the EBDCRGs and the whole datasets.

optimization (Bhatti et al., 2021; Jia et al., 2021). These are well aligned with the objective of the current study in addressing the need for incorporating road gradient information in driving cycle development. For cycle construction, the micro-trip based approach was again appeared to be more popular.

To summarise, the review highlighted the following important findings and knowledge gap:

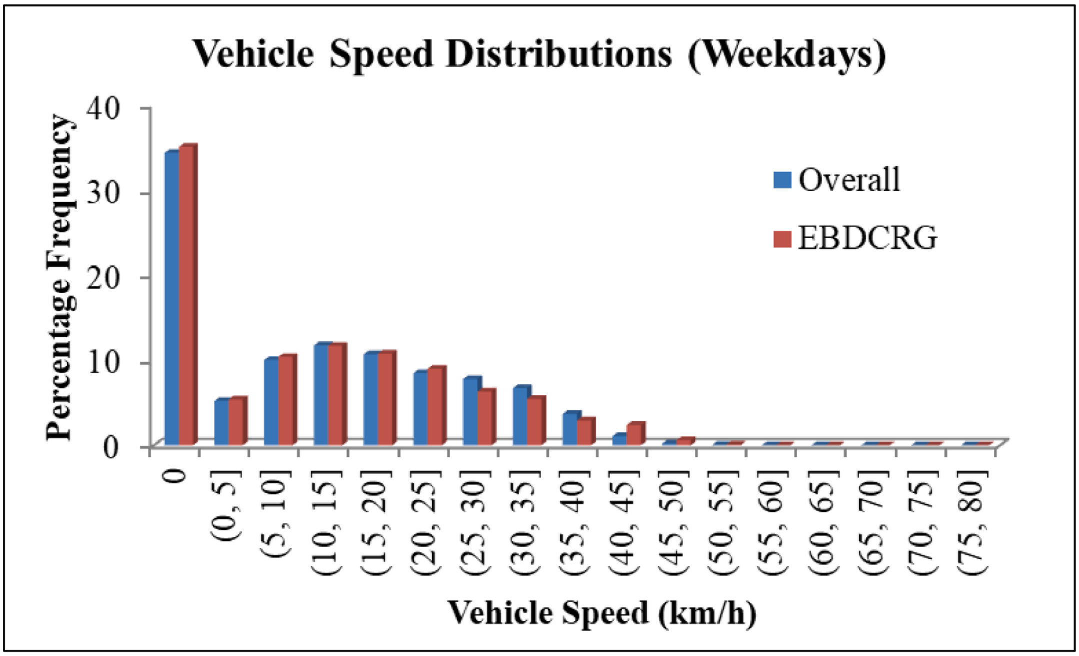
(1) There are significant differences in operational characteristics between regular and electric buses (e.g. shorter driving range);
(2) Driving cycles developed specifically for electric buses are uncommon;
(3) There are solid evidences that road grade information has significant impacts on operating performance of electric buses;
(4) Under the unique hilly and mountainous driving environment in Hong Kong, there is a clear need for developing a driving cycle for electric bus routes in Hong Kong with due consideration of road gradient changes.
(5) The micro-trip based cycle construction method appears to be more popular and suitable for the frequent stop-and-go driving characteristics in Hong Kong

4. Data sampling

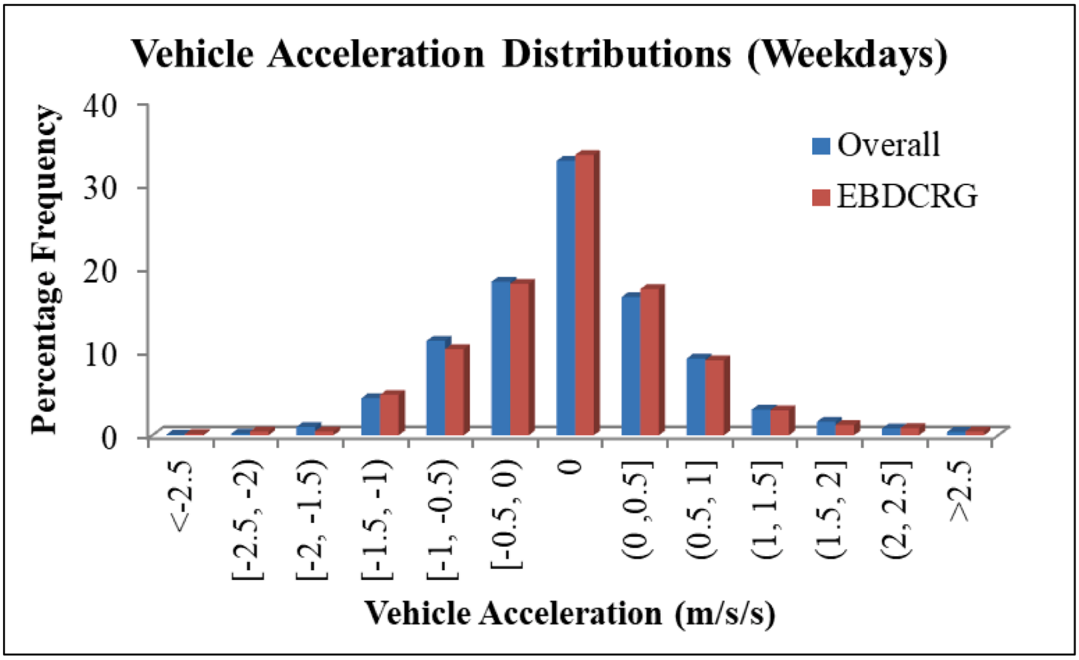
The battery electric bus route 7M was selected for data collection and driving cycle development. This route is a circulatory route running between Wong Tai Sin and Chuk Yuen Estate with 10 stops. Those areas are typical residential areas with moderate traffic and passenger flows. The total length and estimated travel time of this route are approximately 4.5 km and 20 min, respectively. This route travels along local roads with two sections of going uphill (about +4.5% road gradient) and downhill (about –6.5% road gradient). Details of the route 7M are shown in Fig. 1. Uphill and downhill portions take up about 15% and 23% of the whole route, respectively. The reason for selecting this route is that it is currently the only battery electric bus route covering roadways with significant road gradient changes after the e-bus trial programme mentioned earlier. Conversely, it reflects the typical scenario that is more suitable for deploying electric buses for actual daily revenue making operation in Hong Kong. Hence, the driving cycles generated based on data obtained from this route would be representative of the typical driving environment that is suitable for electric bus operation.

The major manufacturer of the deployed battery electric buses (Model: K9R) was BYD Auto Industry Company Limited (BYD). K9R is a single-decker air-conditioned bus with 31 seats and spaces for 35 standees. The dimensions and the gross weight of the K9R bus are 11.6m (L) x 2.5m (W) x 3.25m (h) and 13,500kg, respectively. K9R bus uses iron-phosphate batteries to drive electric motors to achieve zero tailpipe emission. According to BYD, its batteries are environmentally-friendly, non-toxic and can be recycled. A fully charged bus (about 4 h) with battery capacity of 324kWh can travel continuously for about 250 km. When the bus is slowing down or braking, the electric motor can act as an electric generator to maximise energy efficiency by converting kinetic energy to recharge the battery. The specifications of the K9R bus are listed in Table 2.

Data collection was performed with one of the iTrail GPS Data Logger, KJB Security, United States. As suggested in the literature review, GPS devices have been dominantly used around the world for on-road data collection. Recently, with the promotion in using electric vehicles as alternative fuel vehicles, GPS data logger was used to develop the driving cycle of electric vehicle (Mansour et al., 2011; Panchal et al., 2017; Wang et al., 2014). This portable and water-resistant iTrail GPS Data Logger provides tracking at no additional cost. It records the latitude, longitude, altitude, location, speed, and the time for each journey at 1-second interval.



(a) Comparison of Vehicle Speed Distributions (Weekdays)



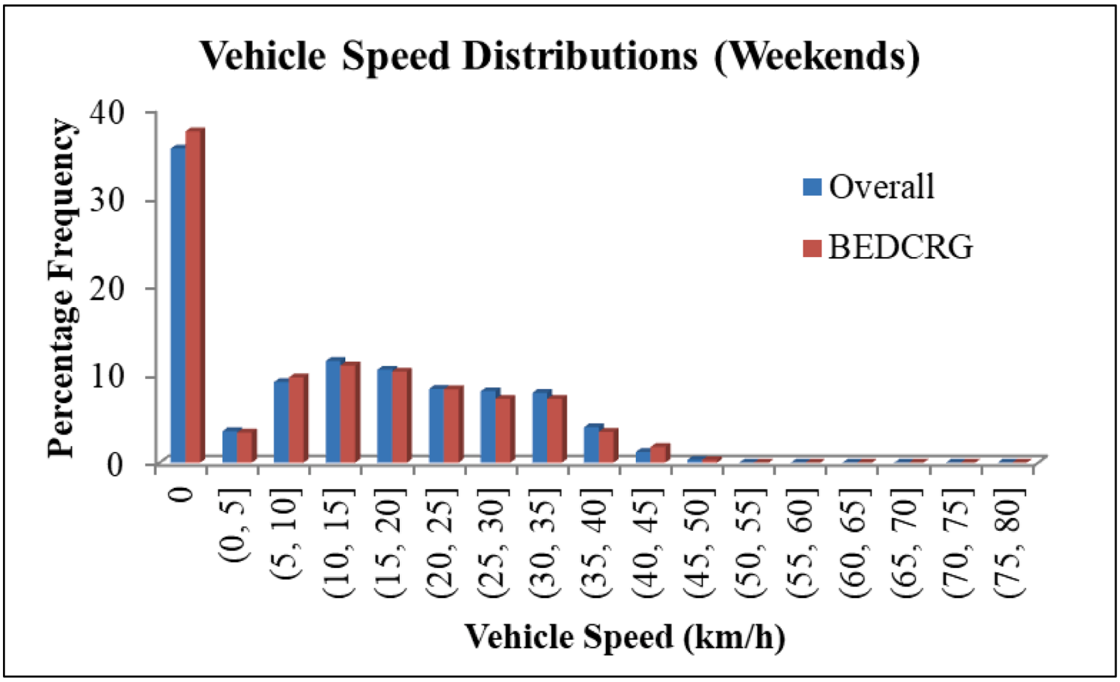
(b) Comparison of Vehicle Acceleration Distributions (Weekdays)

Fig. 6. Comparisons of speed distributions and acceleration distributions for the EBDCRG weekdays and the whole weekdays datasets.

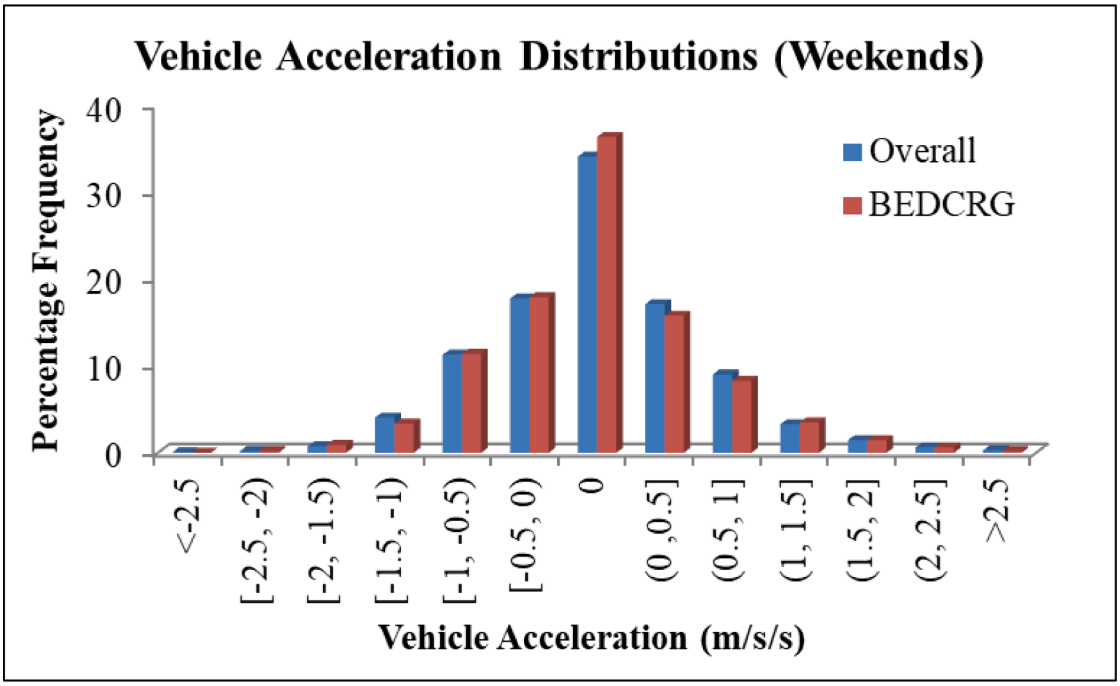
The data collection campaign was conducted in March 2021. With the GPS logger taken on-board of the bus, the surveyors started recording once the bus departed from the origin of the route. The recording was then ended when the bus had completed the journey and came to a complete stop back at the terminus. During the bus journey, the logger recorded the above mentioned information at the most sensitive mode. For the sections of going uphill and downhill, the surveyors on the bus recorded the corresponding times. The recorded times were then used as additional references for confirming the segregation of “downhill”, “uphill” and relatively “stable altitude” sections. The corresponding time for each start and stop activity were also manually recorded as well. This information was for cross-checking in determining the actual stopping location and time periods. Eventually, 45 trips of battery electric bus journeys and 4 trips of traditional diesel bus journeys were collected for the route 7M. For the 45 battery electric buses trips, 27 were collected on weekdays and 18 were collected during weekends.

5. Data analysis

The data screening process started by manual examination of each collected trip data to isolate any abnormalities and possible errors,



(a) Comparison of Vehicle Speed Distributions (Weekdays)



(b) Comparison of Vehicle Acceleration Distributions (Weekdays)

Fig. 7. Comparisons of speed distributions and acceleration distributions for the EBDCRG weekends and the whole weekends dataset.

which included repeated time records, sudden exceptionally high or low speed as well as short time gap (within 3 s). After going through these screening steps, the trip data were then further checked for extreme acceleration and deceleration rates beyond the physical limit of buses (i. e. +3.0 m/s^2 and –3.0 m/s^2), and then substituted by linearly interpolated values. Detailed procedures of the data cleaning process can be found in other papers by the authors (Tong 2019, Tong and Ng, 2021a, 2021b).

Preliminary analysis of the filtered speed data showed that quite clear separations of "downhill", "uphill" and relatively "stable altitude" travelling periods can be identified from the speed and altitude versus time profiles. Therefore, in order to incorporate the road gradient information in the driving cycle development process, the micro-trips were first classified into three bins with positive gradient (i.e. travelling uphill), negative gradient (i.e. travelling downhill) and (relatively) zero gradient (i.e. travelling on flat land). The properties for each bin were then characterised by a set of assessment parameters. Literature revealed that different assessment parameters have been employed for

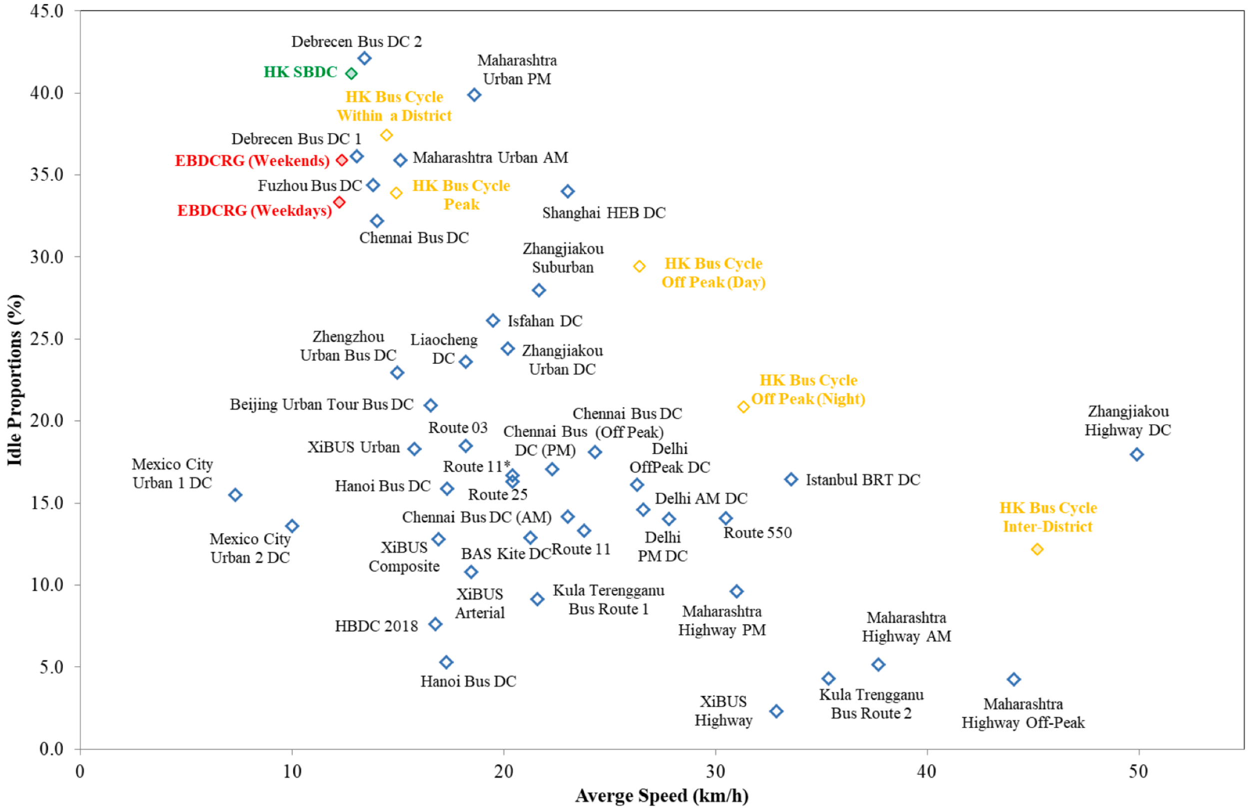


Fig. 8. Comparison with international bus driving cycles.

various reasons. The currently adopted set of parameters has been compiled for adoption under the Hong Kong environment and at the same time widely utilised by numerous driving cycle studies around the world (Tong and Hung, 2008, 2010a, 2010b). These parameters included average speed (v_1), average running speed (v_2), average acceleration (a) and deceleration (d), root mean square acceleration (*RMS*), positive kinetic energy (*PKE*), percentage of time spent on the five operating modes (P_{idle}, P_{acce}, P_{cruise}, P_{creep}, and P_{dece}), average length of a driving period (C), and average number of acceleration/deceleration changes within a driving period (M).

The average values of these 13 assessment parameters as well as some basic statistics for each bin are summarised in Table 3. For comparison purposes, data collected on weekends and weekdays for battery electric buses were separately analyzed and then compared with the data collected for traditional diesel buses.

6. Driving cycle construction

Driving cycle construction methods have been well researched and reviewed (Tong and Hung, 2010b; Tong, 2019; Tong and Ng, 2021a, 2021b, 2021c). For the development of a driving cycle for route 7M, the micro-trip based random selection approach was employed (Fig. 2). For each bin of micro-trips, a separate driving cycle were first developed using the basic approach of micro-trip random selection. These developed driving cycles for each bin would be treated as sub-cycles and then combined together to become the overall driving cycle for Route 7M. While details of this micro-trip random selection approach could be found in the literature (Tong et al., 1999; Hung et al., 2007; Tong and Hung, 2010b; Tong 2019; Tong and Ng, 2021a, 2021b), the key steps of the method are briefly outlined below.

Similar to cycles previously developed for Hong Kong, a driving cycle of about 20 min would be developed for this study. This cycle duration is also similar to the estimated travel time of Route 7M. As indicated in Table 3, weekday and weekend trips exhibited different driving patterns. Hence, weekday and weekend trip data were separated into two databases to develop the corresponding weekday and weekend driving cycles. The approach for developing these two driving cycles were exactly the same but just based on two different databases. First, micro-trips were randomly selected from each bin and then concatenated together with the idling periods come immediately before the micro-trip until the designated cycle length for that particular bin was achieved. Statistical analysis showed that proportions of data in the negative, zero and positive gradient bins were about 27%, 47% and 26% respectively. Considering (1) the proportions of data in each bin; (2) average length of micro-trips for each bin; and (3) the idling proportions for micro-trips in each bin, the number of micro-trips to be selected for each road gradient bin was determined. For a cycle of around 20 min, the number of micro-trips for the negative, zero and positive gradient bins candidate cycles were determined to be 5, 10 and 5 respectively for the weekday driving cycle. The results are summarised in Table 4.

For example, for a cycle of 20 min, the duration for the negative gradient section (i.e. travelling downhill) should be around 325 s (i.e. (1200)(27.1%) ≈ 325 s). Since the idling proportion for micro-trips along downhill sections is about 30.1%, the total length of the downhill cycle (excluding idling) should be around 227 s (i.e. (325)(69.9%) ≈ 227 s). Eventually, given that the average length of a micro-trip for downhill sections is 41.9 s, the number of micro-trips to be selected for the downhill cycle should be 5 (i.e. 227 / 41.9 ≈ 5). The numbers of micro-trips to be selected for synthesizing the uphill cycle and zero gradient cycle, as well as for the sub-cycles of weekend driving cycle were determined in the same way.

Values of the 13 parameters were then computed for the candidate cycle and matched with the target statistics for that particular bin. The cycle would then be regarded as acceptable if all assessment parameters were within 10% of the target. Otherwise, another cycle was compiled and evaluated using the same procedures. Eventually, these steps repeated 10 times and the 10 resultant cycles were then ranked by the average absolute percentage error (AAPE) across all the 13 assessment

Table 6
Comparison of international bus driving cycle characteristics.

Location	v_1 (km/h)	a (m/s^2)	d (m/s^2)	P_{idle} (%)	P_{aece} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	Source
EBDCRG (Weekdays)	12.2	0.691	0.642	33.4	28.4	7.0	30.4	0.8	This Study
EBDCRG (Weekends)	12.3	0.678	0.594	35.9	26.6	7.1	30.2	0.2	This Study
SBDC (Hong Kong)	13.4	0.931	0.980	42.1	27.6	2.7	26.2	1.4	Tong (2019)
HK Bus Cycle (Inter District)	45.2	0.807	0.818	12.2	40.1	7.4	39.5	0.72	Tong and Ng (2021b)
HK Bus Cycle (Within a District)	14.45	0.877	0.897	37.4	29.1	3.7	28.3	1.38	Tong and Ng (2021b)
HK Bus Cycle (Peak)	14.91	0.909	0.909	33.9	30.5	4.1	30.2	1.42	Tong and Ng (2021b)
HK Bus Cycle (Off Peak Day)	26.4	0.809	0.817	29.4	32.5	5.1	32.2	1.14	Tong and Ng (2021b)
HK Bus Cycle (Off Peak Night)	31.32	0.856	0.898	20.9	37.5	5.2	35.7	0.74	Tong and Ng (2021b)
Chennai Bus DC	14.0	0.650	0.710	32.2	29.8	3.5	29.6	4.9	Nesamania, et al. (2011)
Maharashtra Highway AM	37.7	0.280	0.370	5.2	26.0	46.6	21.5	-	Maurya and Bokare (2012)
Maharashtra Highway Off-Peak	44.1	0.330	0.310	4.3	27.0	53.5	15.5	-	Maurya and Bokare (2012)
Maharashtra Highway PM	31.0	0.280	0.600	9.6	38.2	38.5	18.5	-	Maurya and Bokare (2012)
Maharashtra Urban AM	15.1	0.500	0.470	35.9	28.3	-	27.4	-	Maurya and Bokare (2012)
Maharashtra Urban PM	18.6	0.600	1.500	39.9	29.2	-	29.3	-	Maurya and Bokare (2012)
Delhi AM DC	26.6	-	-	14.6	39.9	8.1	37.4	-	Kumar et al. (2013)
Delhi OffPeak DC	26.3	-	-	16.1	39.2	8.4	36.3	-	Kumar et al. (2013)
Delhi PM DC	27.8	-	-	14.0	39.7	9.7	36.6	-	Kumar et al. (2013)
Hanoi Bus DC	17.3	0.480	0.510	5.3	34.5	-	32.4	-	Nguyen et al. (2016)
XiBUS Arterial	18.4	0.509	0.504	10.8	40.3	16.8	32.3	-	Li et al. (2016)
XiBUS Composite	16.9	0.420	0.460	12.8	38.2	15.7	32.9	-	Li et al. (2016)
XiBUS Urban	15.8	0.404	0.580	18.3	35.5	22.0	24.3	-	Li et al. (2016)
XiBUS Highway	32.9	0.422	0.590	2.3	45.8	15.0	37.0	-	Li et al. (2016)
Route 11	20.4	0.540	0.510	16.7	32.4	15.1	34.4	1.5	Kivekas et al. (2018a)
Route 11	23.8	0.380	0.390	13.3	-	22.2	-	0.1	Kivekas et al. (2018b)
Route 24	17.3	0.680	0.730	15.9	-	9.3	-	0.1	Kivekas et al. (2018b)
Route 550	30.5	0.500	0.500	14.1	-	16.8	-	0.1	Kivekas et al. (2018b)
Route 03	18.2	0.650	0.680	18.5	-	10.6	-	0.3	Kivekas et al. (2018b)
Route 25	20.4	0.710	0.770	16.3	-	8.9	-	0.2	Kivekas et al. (2018b)
HBDC 2018	16.8	0.500	0.520	7.6	34.2	14.1	32.7	11.4	Nguyen et al. (2018)
Shanghai HEB DC	23.0	0.710	0.830	34.0	33.0	5.0	28.0	-	Shen et al. (2018)
BAS KITe DC	21.3	0.420	0.470	12.9	45.7	40.8	0.6	-	Anida et al. (2019)
Fuzhou Bus DC	13.8	0.740	-	34.4	27.0	15.5	23.1	-	Peng et al. (2019a)
Istanbul BRT DC	33.6	1.470	1.700	16.4	-	-	83.6	-	Kaymaz et al. (2019)
Kanchanaburi DC	-	-	-	-	52.1	1.8	46.2	-	Mongkonlerdmanee (2019)
Xi'an Bus DC	18.2	-	-	23.6	27.8	25.3	23.3	-	Liu et al. (2020)
Chennai Bus DC (AM)	23.0	0.360	0.660	14.2	36.6	23.5	25.3	0.3	Desineedi et al. (2020)
Chennai Bus DC (PM)	22.3	0.350	0.570	17.1	34.7	24.6	23.2	0.5	Desineedi et al. (2020)
Chennai Bus DC (Off)	24.3	0.380	0.580	18.1	35.7	25.1	20.8	0.3	Desineedi et al. (2020)
LiaoCheng Bus DC	18.2	-	-	23.6	27.8	25.3	23.5	-	Liu et al. (2020)
Mexico City Urban 1 DC	7.30	0.500	0.500	15.5	32.9	22.7	29.3	-	Quirama et al. (2020)
Mexico City Urban 2 DC	10.0	0.400	0.500	13.6	33.8	25.9	29.1	-	Quirama et al. (2020)
Zhengzhou Urban Bus DC	15.0	-	-	22.9	33.3	28.8	15.0	-	Peng et al. (2020)
Isfahan, Iran	19.5	0.840	0.820	26.1	32.0	9.0	33.5	-	Ghaffarpasand et al. (2021)
Beijing Urban Tour Bus DC	16.6	-	-	21.0	29.0	31.0	19.1	-	Yuan et al. (2021)
Kula Terengganu Bus Route 1	21.6	0.480	0.560	9.2	46.5	2.1	42.3	-	Norbakyah et al. (2021)
Kula Terengganu Bus Route 2	35.3	0.600	0.610	4.3	48.1	0.4	47.2	-	Norbakyah et al. (2021)
Debrecen Bus DC 1	13.0	0.295	0.314	36.1	-	-	-	-	Vamosi et al. (2021)
Debrecen Bus DC 2	12.8	0.817	0.651	41.2	-	-	-	-	Vamosi et al. (2021)
Zhangjiakou Urban	20.2	0.500	0.500	24.4	25.1	24.9	25.6	-	Jia et al. (2021)
Zhangjiakou Suburban	21.7	0.400	0.500	28.0	30.1	20.4	21.5	-	Jia et al. (2021)
Zhangjiakou Highway	49.9	0.400	0.400	18.0	22.3	19.2	40.5	-	Jia et al. (2021)

parameters. Speed, acceleration and vehicle specific power (VSP) distributions of the acceptable cycles were then reviewed and utilised as criteria for selecting the final best cycle. Sum Squared Differences (SSD) between the Speed Acceleration Probability Distributions (SAPD) derived from the acceptable cycle and the whole dataset were also derived as another useful quantitative assessment indicator. The formula widely used for determining VSP is as follows (i.e. Eq, (1)). This version of the formula has specifically included the effect of road gradient changes (Duarte et al., 2015, 2016; Pouresmaeili et al., 2018; Wu et al., 2015; Yao et al., 2013).

$$VSP = v\left(1.1xa + 9.81tan^{-1}\left(sin(grade)\right)\right) + 0.132\right) + 0.000302v^3 \quad (1)$$

where v is the speed (in m/s), a is the acceleration (m/s^2), and grade is the road gradient (in %). As mentioned earlier, the +4.5% and –6.5% road gradients were adopted for uphill and downhill sections respectively.

7. Results and interpretation

7.1. Driving characteristics of the battery electric bus routes

The mean values of the 13 assessment parameters (i.e. target statistics) for the battery electric bus as well as for the traditional diesel bus datasets are shown in Table 3 for comparison purposes. Since all the data collected for traditional diesel buses were on weekends, they were therefore compared with the mean values for battery electric buses collected for weekend trips only. It shows that the two types of bus exhibit slightly different features. Battery electric buses were observed to have faster average speeds, longer micro-trip lengths and larger values for acceleration related indicators (i.e. acceleration and deceleration rates, root mean square acceleration and PKE). Differences in the physical capabilities between the two types of bus might be the possible reason for these observations. When comparing the characteristics between weekday and weekend trips collected for the battery electric buses, the patterns were quite similar.

7.2. Electric Bus Driving Cycles with Road Gradient Changes (EBDCRG)

The Electric Bus Driving Cycle with Road Gradient Changes (EBDCRG) utilised all the datasets collected for the electric buses. The synthesized EBDCRG for weekday and weekend trips are shown in Table 5 and Fig. 3, with cycle durations of 1300s and 1640s, average speeds of 12.22 km/h and 12.34 km/h, respectively. Whilst the basic characteristics of the two cycles are generally similar, some key differences can still be spotted. First, the weekday cycle is relatively shorter than the weekend cycle. The weekday cycle exhibits slightly more aggressive acceleration and deceleration characteristics. Values of all the acceleration and deceleration related parameters for the weekday cycle are higher than those for the weekend cycle. This reflects the operational features of daily commuting traffic during weekdays. Fig. 3 also shows similar characteristics that sharper acceleration and deceleration changes.

To further assess more characteristics of the developed EBDCRGs, their SAPD and VSP distributions were also compared with those derived from the whole dataset for weekday and weekend trips (Figs. 4 and 5). The SAPD and VSP distributions generated for the weekday and weekend datasets matched very well with the corresponding distributions derived for the synthesized cycles. In Fig. 6, the speed and acceleration distributions of the EBDCRGs are compared side-by-side with those for the whole datasets. Very good agreements were also observed (Figs 7 and 8.

7.3. Comparisons with other bus cycles

The major parameters of EBDCRGs together with more than 40 other bus driving cycles are summarised in Table 6. The cycles developed for the Hong Kong franchised bus network (Tong and Ng, 2021b) were also included in the comparison to highlight the difference in driving characteristics between double decked traditional diesel buses and single decked battery electric buses. To compare the characteristics between the two electric bus technologies under the trial programme, the SBDC (Tong, 2019) was also included in the comparison as well.

The comparison with international bus cycles indicates that the EBDCRGs are comparable to other urban bus driving cycles but differ from bus cycles developed for other driving conditions. First, the average speed and idle proportion of EBDCRGs are quite close to the Dehrecen DC 1 cycle, the Fuzhou bus cycle, the Maharashtta Urban AM cycle and the Chennai bus driving cycle. In particular, the EBDCRGs exhibit very similar characteristics with the Chennai bus driving cycles in terms of not only the average speed, but also the acceleration and deceleration rates, as well as for the proportions for each of the five driving modes.

Comparing EBDCRGs with the SBDC, the average speeds are very close to each other. However, the average acceleration and deceleration rates of EBDCRGs are significantly smaller than those of the SBDC. This reflects that the supercapacitor bus adopted in Hong Kong may be more responsive to the drivers' acceleration and deceleration activities than that of the battery electric bus. Moreover, the road gradient changes for the EBDCRGs might also constraint the acceleration and deceleration activities to a lower level relative to those exhibited in SBDC. When comparing it with the five bus cycles developed for the whole bus network in Hong Kong, the EBDCRGs are consistent with the characteristics of the "Peak" and the "Within a District" cycles.

8. Conclusions

In this study, driving cycles for a circulatory battery electric bus route with significant road gradient changes were developed for the first time (EBDCRGs) in Hong Kong. Actual bus speed and location information were acquired by surveyors during normal bus service operations. Data were first examined to summarise the distinct driving characteristics. The EBDCRGs were then developed with due considerations of road gradient changes. Speed, acceleration and VSP distributions were also investigated to substantiate representativeness of the EBDCRG cycles. With the inclusion of road gradient change information, the use of EBDCRG cycles would become more realistic in reflecting the impact of the unique driving environment in Hong Kong.

The developed driving cycles indicated distinct driving characteristics for this selected battery electric bus route. Even though the developed EBDCRG cycles are based on the selected battery electric bus route only, however, it is still possible to pinpoint some distinctive characteristics for electric bus driving in Hong Kong with significant road gradient changes. First, the developed EBDCRGs were consistent with the urban driving cycles developed for the whole bus network in Hong Kong. Through the comparison with the Hong Kong SBDC, some differences in the driving characteristics between the two types of electric bus technologies adopted in Hong Kong were also observed. Battery electric buses appeared to be less responsive to acceleration activities than that of a supercapacitor bus.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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