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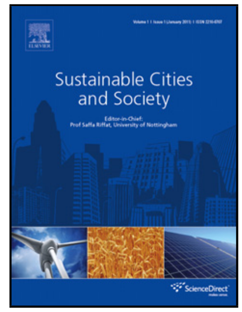

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PII: S2210-6707(21)00144-X

DOI: https://doi.org/10.1016/j.scs.2021.102854

Reference: SCS 102854

To appear in: *Sustainable Cities and Society*

Received Date: 22 July 2020

Revised Date: 28 January 2021

Accepted Date: 14 March 2021

Please cite this article as: Tong HY, Ng K, Development of Bus Driving Cycles using a Cost Effective Data Collection Approach, *Sustainable Cities and Society* (2021), doi: https://doi.org/10.1016/j.scs.2021.102854

Development of Bus Driving Cycles using a Cost Effective Data Collection Approach

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Highlights

- Developed driving cycles for a highly-utilized comprehensive fixed-route bus network
- Adopted a cost-effective data collection method to cover a wide range of bus route patterns
- Identified five bus driving patterns without prior cycle stratification criteria
- Bus driving in Hong Kong were aggressive with significantly longer idling
- The cycles are useful for traditional/electric bus emission and energy consumption estimation

Abstract

Driving cycles are important for vehicle performance evaluations including emissions and fuel/energy consumption estimations. The franchised bus services are currently being extensively used in Hong Kong, however, no driving cycle has been developed specifically for buses. Therefore, this study has developed a set of bus driving cycles using a cost effective data collection approach. On-road bus speed data were collected using the built-in GPS function of smartphones Based on an analysis of the structure of the franchised bus route network and the statistical properties of the collected bus speed data, five significantly different bus driving patterns in Hong Kong were identified. Separate driving cycles were then developed for each identified pattern namely Pattern I(a): Inter-districts; Pattern I(b): Within a District; Pattern II(a): Peaks; Pattern II(b) Off Peak (Day); and Pattern II(c): Off Peak (Night). These patterns indicated significantly longer idling and more aggressive acceleration/deceleration characteristics as compared to other international bus driving cycles. Bus operators and regulating authorities can select appropriate cycles for traditional/electric bus emission and/or energy consumption estimations under specific bus driving patterns. The developed cycles can also fill the knowledge gap in providing a representative platform for the bus emissions testing in Hong Kong.

Keywords: Bus Driving Patterns, Driving Cycles, Vehicle Specific Power (VSP), GPS Data Collection, Bus Driving Behaviours, Bus Driving Characteristics

1. Introduction

A driving cycle is a profile of vehicle speed versus time representative of the driving behaviours or driving characteristics under particular conditions. The development of driving cycles started in the 70s mainly in the US, European and Australian regions to provide a platform for vehicle emission and fuel consumption estimations. Due to the differences in driving characteristics under different driving conditions, driving cycles have been stratified according to vehicle types (e.g. motorcycles (MCs), light duty vehicles (LDVs), heavy duty vehicles (HDVs), buses as well as special purposes vehicles), time periods of a day (e.g. morning peak, evening peak, and off peaks), trip purposes (commuting or leisure), road types (e.g. highway, arterials and local roads) and areas of interests (e.g. urban or rural). In many developing economies without their own driving cycles, well-known cycles had been extensively used in the past. However, it is generally agreed that driving cycles developed specifically for these regions or areas are necessary due to the fact that driving characteristics are unique to a particular city. Therefore, on-road transient driving cycles have been developing rapidly in recent years, especially in the Asian and Middle East regions. Most of them are developed for understanding bus driving characteristics and vehicle performance evaluation purposes such as exhaust emissions and fuel/energy consumption estimations. More detailed analysis of these driving cycle studies would be given later in the literature review section.

Among the driving cycles developed in the past decade, a majority of them were for MCs, LDVs and HDVs. Driving cycles developed for public transport modes are not very common, even though there are still a number of cases around the world. In Hong Kong, the driving cycles developed in the past two decades were also for LDVs. In the Asian region, one of the first driving cycles based on real world driving data was developed in 1999 in Hong Kong for a single diesel powered LDV under urban driving conditions (Tong et al., 1999). The Hong Kong driving cycles were then further expanded as a set of driving cycles (covering urban, suburban and highway conditions) for LDVs using a much bigger set of on-road driving data (Hung, et al., 2007). In recent years, due to the fast developing and adoption of various electric vehicle technologies in the bus fleets around the world, Hong Kong has been undertaking various stages of electric bus trials. Another driving cycle was then constructed for one supercapacitor bus route (Tong, 2019).

As one of the most densely populated cities in the world, the public transport system accounted for more than 90% of the daily passenger trips in Hong Kong in 2018 (which equals to about 12.6 million daily passenger trips) and about 4.05 million of which were made through the franchised bus services (i.e. about 31.5% of the total daily passenger trips) (Transport Department, 2019). The major public bus service in Hong Kong is franchised. Rights are given to privately owned franchisees to operate different routes under the regulation of the government. Currently, there are 5 privately owned franchised bus companies operating 6 franchises with more than 600 routes across different districts in Hong Kong. While the franchised bus fleet represents only 1% of the total number of diesel commercial vehicles in Hong Kong, it contributes one-fifth of NO_x and 6% of PM_{10} emissions (Fung and Suen, 2014). It shows a disproportionately high share and thus is the focus of in-use diesel vehicle emissions control programme in Hong Kong. Within the framework of the emission control programme, the franchised buses are required to undergo emission tests during the annual roadworthiness inspection for license renewal. The emission tests administered by the Hong Kong Environmental Protection Department (HKEPD) are the free acceleration smoke test and the lug-down dynamometer test. Apart from the annual emission test, HKEPD also operates a smoky vehicle control programme where trained voluntary spotter would identify smoky in-use vehicles. Suspected vehicles are requested to go through a lug-down test at designated vehicle testing centres. However, these tests are mainly target for controlling smoky vehicles and do not check NO_x emissions (EPD, 2019). Given the fact that diesel franchised buses are a major source of PM and NO_x pollution in Hong Kong, other emission inspection are critically important. Driving cycles representing realistic on-road bus driving conditions are thus necessary. However, there is no driving cycle developed to characterise the special bus driving patterns in Hong Kong, except the one recently developed for a single supercapacitor bus route. Therefore, there is an urgent need to have a driving cycle for understanding various bus route driving patterns under the Hong Kong environment, conducting bus emission tests as well as evaluating bus driving performances in terms of exhaust emissions and energy consumption. A study was thus commissioned with an aim to (1) collect on-road bus speed data covering a wide range of daily bus travel patterns; (2) evaluate the driving patterns for the franchised bus transport mode in Hong Kong; and (3) develop a corresponding set of driving cycles representative of the characteristics of franchised bus transport in Hong Kong. As part of the activities under this study, a driving cycle for a supercapacitor bus route was developed and described in another paper (Tong, 2019). In the current paper, the major focuses are: (1) the adoption of a cost effective approach to collect on-road bus speed data; (2) to characterise and define bus driving patterns based on an analysis of the bus route network structure and the statistical properties of the collected data; and (3) to develop a set of bus driving cycles representative of the bus driving characteristics in Hong Kong. A flowchart is presented in Figure 1 showing the focuses of this paper together with the whole study methodology.

[Figure 1]

2. Literature Review on Bus Driving Cycles

Driving cycles for public transports have been getting relatively less attention in the literature but some driving cycle studies concerning buses can still be found. A comparison of reviewed bus driving cycle studies is summarised in Table 1. The review of these driving cycles highlighted a number of important observations. First of all, similar to driving cycles for other vehicle types, a majority of bus driving cycles are developed for densely populated cities in developing economies, including Beijing and Shanghai in China, Chennai and Delhi in India, and Thailand. This further affirms the necessity of a city to have their own driving cycles. Secondly, there is a very wide range of purposes for developing the bus driving cycles, including the traditional objectives of understanding bus driving conditions (Kumar, et al., 2013; Maurya and Bokare, 2012; Nesamani and Subramanian, 2011), emission and fuel consumption estimations (Nguyen, et al., 2016; Shen, et al., 2018) and bus operation evaluations (Lai, et al., 2013). Its application has also been extended to electric bus energy consumption estimations (Kivekas, et al., 2018a, 2018b) as well as accident analysis (Mongkonlerdmanee and Koetniyom, 2019). Due to the increasing uses of various electric vehicle technologies in the bus transportation sector, bus driving cycles have been developed not only for regular buses but also for different kinds of electric buses such as battery electric buses, hybrid buses, bus rapid transit (BRT), as well as articulated buses (Gunther, et al., 2017). These cycles were also stratified by different factors such as road types, time of a day, day of a week (i.e. weekdays vs weekends), traffic conditions (urban, suburban or highway), as well as different types of bus routes (e.g. BRT vs regular bus routes).

[Table 1]

Regarding the technical details of the development of these bus driving cycles, a number of important issues could also be highlighted in terms of data collection, test route selection and cycle construction. First, nearly all the reviewed bus cycles have employed GPS technologies in bus driving data collection and it has become a dominating trend in on-road driving tests. For test route selection, most of the reviewed studies adopted existing bus route(s) as the test route(s). However, only a few routes were selected for on-road testing. The largest number of routes involved about 18 routes (Peng, et al., 2019a) which were selected based on a station intensity index reflecting how busy were the stations along the selected bus routes. In Chennai's study, 6 test routes were selected according to different traffic density, time of a day and day of a week (Nesamani and Subramanian, 2011). However, many other studies collected data for only one single bus route (Kivekas, et al., 2018a; Li, 2016; Nguyen, et al., 2020) even though some of these routes were selected for a special purpose such as intercity bus routes (Maurya and Bokare, 2012; Shen, et al., 2018;) and hazardous bus routes (Mongkonlerdmanee and Koetniyom, 2019). This might, to certain extend, affect the representativeness of the collected data and thus the resultant bus driving cycle. For cycle construction methods adopted for developing bus driving cycles, the micro-trip based selection method appeared to be a more popular approach (i.e. 12 out of the 14 bus driving cycle studies reviewed). However, the method of selecting the micro-trips varied across different studies, including random selection, selection based on clustering results or even selection based on a transition probability matrix. Markov Chain together with transition probability matrices was the next more commonly used approach (i.e. 2 out of the 14 bus driving cycle studies reviewed). Some of these studies also considered the characteristics of bus operations (i.e. the dwell times at bus stop as well as the stop-and-go characteristics between bus stops) as a special feature in developing their bus driving cycles.

When taking a closer look at the cycle construction methods for other vehicle types, the same trend can also be observed. This paper has reviewed 62 driving cycle studies (covering over 130 driving cycles developed in the past 10 years) for MCs, LDVs, HDVs as well as buses, at developing economies (e.g. Argentina, China, India, Iran, Lebanon, Mexico, and Sir Lanka) and developed economies[1] (e.g. Canada, England, France Germany, Korea, Singapore, Sweden and US) across different continents around the world (Table 2). Among these reviewed studies, 36 employed micro-trip based methods, 13 adopted Markov Chain based methods, and the other 13 made use of other methods such as segment based, pattern recognition or single most representative trip based methods. It indicated that the micro-trip based method was the more popular method. Some other driving cycle review studies also revealed the same finding (Galgamuwa, et al., 2015; Heurtas, et al., 2019; Quirama, et al., 2020; Tong and Hung, 2010a; 2010b). These studies generally agree that each approach has its own advantages and disadvantages and there is no standard or unified method for constructing a driving cycle. The micro-trip based method has the definite advantage of low resources requirement and easy to use, and is more suitable for areas with frequent stop-and-go conditions. However, its performance depends on the parameters being used for assessing the candidate driving cycles or selecting the most representative driving cycles (Quirama, et al., 2020). The driving cycles obtained by using the micro-trip based method are more suitable for emission estimation purposes. On the other hand, Markov Chain based method is more suitable for areas with less stop-and-go conditions but is more data demanding. In

[1] Classification of developing and developed economies is based on the International Monetary Fund's World Economic Outlook (IMF, 2018).

particular, Heurtas et al., (2019) concluded from their study that the micro-trip based method performed better than the Markov Chain based method in obtaining a driving cycle that was representative of the driving patterns, fuel consumption and emissions from vehicles.

[Table 2]

To sum up the review, GPS devices have been undoubtedly becoming the major tool for on-road vehicle testing. This provides an easier and more convenient alternative for collecting vehicle speed data. Secondly, existing bus routes (usually only one route or just a few routes) were commonly used for on-road driving tests instead of designing specific test route(s). The limited number of bus routes adopted in previous studies might be compromised with the required equipment costs and/or the difficulties in hiring more buses. This implies that on-road driving tests need to strike a balance between these two contradicting requirements (i.e. route coverage versus costs required). Also, separate driving cycles should be developed to reflect the differences in driving patterns under different driving conditions. Given the issues revealed above, this study would devise a methodology to develop a set of bus driving cycles that could address these concerns.

3. Franchised Bus Transports in Hong Kong

As of September 2019, the public transport system in Hong Kong is carrying over 12 million passenger trips per day. It accounts for over 90% of total daily passenger trips which is the highest in the world (Transport and Housing Bureau, 2017). Apart from the railway service, the public bus service in Hong Kong can be roughly divided into 3 types, Franchised bus, Non-Franchised bus (NLB) and Public light bus (PLB). While the heavy rail lines being the backbone of the public transport system, the franchised bus services are (i) serving as a mass carrier for areas with no direct railway access; and (ii) providing feeder services to the railway network. There are a total of five franchised bus operators operating more than 600 routes with a fleet of 6139 buses in which 5843 are double decker buses (Transport Department, 2019). The carrying capacity of a double decker bus in Hong Kong ranges around 100 to 150 passengers. As of 2019, over 95% of the franchised buses are Euro IV or above. They serve nearly 4.1 million trips each day which has been kept fairly stable in the past decade. This accounts for around 33% of the total public transport patronage. The franchised bus network basically covers the three major districts in Hong Kong, namely the Kowloon Peninsular (Kln), the Hong Kong Island (HKI), as well as the New Territories and Lautau Island (NT and Island). One the other hand, PLBs are 16-seat or 19-seat low capacity public transport providing supplementary feeder service and serving areas with relatively lower passenger demand. It accounts for about 15% of total public transport patronage. NLBs are mainly residential bus services. They are also operated by private companies and playing a role of relieving the demand for franchised bus and PLB services during peak hours as well as providing services for districts where the operation of franchised buses and PLBs are not cost-effective. It accounts for around 1.9% of public transport patronage (Transport and Housing Bureau, 2017).

It is important to note that the target of this study is the franchised bus services. The basic territorial architecture has been one of the major factors affecting the design and evolution of the current franchised bus route networks in Hong Kong. In accordance to this structure, the bus routes can be broadly classified into two major types, (1) routes running within a district; and (2) routes running between districts. The first type of routes mainly travels within any one of the above mentioned three districts to serve the local mobility needs within that district. The characteristics of these routes are having relatively short station spacing so as to fulfil passenger demands distributed across the whole densely developed district, no matter it is an urban (e.g. Mongkok in Kln and Central on HKI) or a suburban district (e.g. Tuen Mun in NT and Tung Chung on Lantau Island). Therefore, frequent stop-and-go activities are expected. For routes travelling between districts, a significant portion of the routes would be on highways with limited stops. Typical examples of this type are those daily home-to-work (or home-to-school) commuting routes travelling from suburban residential areas via highways to urban areas for work or school, and vice versa. Therefore, frequent stop-and-go driving conditions are also expected at each end of the highway travelling section to pick-up and drop-off passengers in individual districts.

4. Data Collection

This study adopted a cost effective approach that was capable of collecting a significant amount of reliable and representative bus speed-time data within a relatively low budget. Literature review indicated that the car chasing technique and the on-board measurement method were the two major approaches for conducting an on-road driving test. In early years, the car chasing technique had been more commonly used primarily due to its low resources requirements while the on-board measurement method was mainly employed by large scale studies. In the current study, the target is to cover driving patterns of different bus routes. Data collection would be conducted on-board of the target buses along the specific bus routes, therefore the on-board measurement method would be more appropriate. In recent years, with the evolvement of positioning technologies, GPS devices have been widely used for collecting vehicle activity data. To apply in this study, however, more GPS devices are needed in order to cover more routes within a limited timeframe. It makes the data collection process to become more costly (i.e. more GPS devices might be required if the study targets for a large number of bus routes), more time consuming (i.e. more time might be required to cover more bus routes if fewer GPS devices are available), or restricted to within a smaller route coverage (i.e. fewer GPS devices are available to collect data within a limited timeframe). This might be one of the reasons constrained the number of routes employed for bus driving data collection in the literature (Kivekas, et al., 2018a; Li, 2016; Nguyen, et al., 2016).

Smartphones with built-in GPS or any other positioning technologies are becoming very popular in recent years. This serves as a very useful tool for collecting various kind of data related to people's daily activities or behaviours. Despite the attractiveness of this data collection technique, it has rarely been used to collect speed-time data for the purpose of characterising vehicle driving patterns or developing driving cycles. The primary reason might be only very limited published results are available on the assessment of their navigation performances (Gikas and Perakis, 2016). However, as far as concerned for a specific type of GPS embedded smartphone (e.g. an iPhone), some studies assessing their accuracy in collecting vehicle tracking data can still be found. Previous assessment of different versions of iPhones indicated that the relative spatial accuracy of its internal GPS devices was up to 99% (Garnett and Stewart 2015; Menard, et al., 2011) and thus could be a reliable option comparable to (or even more accurate than) other more expensive vehicle tracking devices (Menard and Miller, 2010, 2011). Another iPhone assessment study also pointed out that the GPS sensor of iPhones performed well in providing a satisfactory navigation solution for different transport applications such as intelligent transportation systems and safety applications (Gikas and Perakis, 2016). These proved that the positioning capability of iPhones could provide very reliable and consistent speed-time profiles, and are very sensitive and suitable for collecting vehicle movement data. Thus, in this study, the collection of bus speed data has taken the advantage of the increasing popularity of smartphones in the general public as well as their capability in collecting users' daily activity data. Voluntary surveyors were invited to use their own smartphones (mainly an iPhone 6) installed with a free and simple tracking APP to collect bus speed data during their daily travelling activities on buses.

The interface for collecting bus data on the iPhone is a smartphone APP "MyTracks", which has been adopted in other transportation related studies before (Keertipati, et al., 2016; Williams, 2015). It is a simple APP for uses on smartphones to log the trajectory and positioning data of the user while they are moving. These data can then be converted into other useful information such as speed, distance and elevation for further analysis. The collected positioning data (latitude and longitude) can also be displayed real-time on a smartphone map for immediate visual evaluation by the user. In particular, Williams et al. (2015) recommended the use of the MyTracks APP to collect on-road vehicle activity data after a detailed analysis of its features and performances as well as a comparison with 7 other data collection APPs and tools. It was found that the MyTracks APP on smartphones provided similar accuracy with standard GPS units in collecting data related to the paratransit system. In particular, the MyTracks APP allowed for easier digital collection of meta-data (e.g. stop location). Based on these results, it is believed that the MyTracks APP can provide reliable bus speed data for the analysis of this study.

A total of 12 voluntary surveyors were agreed to collect speed time data using their own smartphones during their daily travels on buses from September to December 2017. The surveyors were advised to do their daily bus travel activities as usual with their own smartphones (installed with the MyTracks APP and set at 1 second data collection time interval) on-board throughout the bus journey. The surveyors were requested to start recording when they were on-board of the bus until they had completed their bus journey. Bus location and speed information would be logged on a per second basis via the smartphone GPS device. For every bus idling (which could be a bus dwelling or a stop due to congestions or traffic junctions), the surveyors were also required to record the time shown on the counter of the APP when the bus had come to a complete stop and when it had re-started after the idling. This could help further enhancing the accuracy of locating the idling period by cross-checking with the trajectory recorded on the road map. Apart from the data recorded through the smartphone APP, the surveyors also recorded the background information of the bus trip such as date, time, bus route number, origin and destination of the trip, etc. This information would be used later for classifying the trip data. Eventually, a total of 107 trips of bus journey speed-time data were collected which covered more than 30 bus routes across the whole territory of Hong Kong. Among these 107 trips, 16 were collected for a circular bus route where supercapacitor buses were deployed. For these 16 trips, separate analyses were conducted and documented in another paper (Tong, 2019) in which a driving cycle for this specific supercapacitor bus route was developed. This further proved that this approach of data collection is viable, reliable and accurate enough under the Hong Kong driving environment. The other 91 trips collected, 58% and 42% were on weekdays and weekends respectively, would serve as the basis for the analysis in this paper to characterise the driving patterns of the franchised bus network in Hong Kong as well as to develop the corresponding representative driving cycles.

[Table 3]

In short, this approach of bus speed data collection has the following advantages over other reviewed approaches in collecting vehicle speed-time data for the purpose of developing driving cycles: (1) cost effective with limited or even no equipment costs as long as the surveyors are agreed to use their own mobile devices; (2) capable of providing a good coverage containing various kinds of bus routes; and (3) competent in capturing a wide range of different activity patterns and driving characteristics (i.e. different time of a day, different day of a week, different districts/regions). While this approach possesses the above mentioned merits, it is important to note that the selection of surveyors is critical in assuring data quality and representativeness. First, it is generally not easy to recruit sufficient among of appropriate surveyors due to privacy concerns as the collected data would disclose the surveyors' travelling history. Secondly, the routes coverage is closely related to the surveyors' travelling and activity patterns. This data collection approach does not have direct control over the routes to be included. The routes to be included totally depend on the surveyors. This is also the reason why the selection of surveyors is important. As such, surveyors with daily travel patterns covering different districts should be invited so as to assure a wider route coverage and variety of activity patterns.

5. Data Analysis

Each trip of speed time data collected were first manually screened for any obvious irregularities that could be easily identifiable in the raw data. Afterwards, the data cleaning process basically followed the principles suggested by Duran and Earleywine (2012), and was conducted on the MS Excel platform. It included four major steps: (1) removal of duplicate time records and replacing the sudden extremely high-speed or low-speed (or even zero speed) by linear interpolation; (2) correcting short time gaps (within 3 seconds) due to street canyon effects or occasional signal loss; (3) replacing extreme accelerations and decelerations outside the range of +2.0 m/s^2 to –2.0 m/s^2 by linear interpolation; and (4) identifying the location of zero speed idling by cross-checking with the surveyor-recorded actual stop and start times (this possibly included replacing the periods with zero speed drift effects by zero speed values). Further details of the actual data cleaning procedures can be found in another paper (Tong, 2019).

6. Analysis of Bus Driving Patterns

To provide a quantitative basis for the analysis of bus driving patterns, a representative set of assessment parameters is necessary to first extract the driving characteristics from each set of bus speed data. The literature commonly agrees that trip average speed, idling proportion, acceleration parameters and speed/acceleration distributions are frequently used parameters, particularly for those vehicle emissions related studies (Galgamuwa, et al., 2015; Heurtas, et al., 2019; Quirama, et al., 2020; Tong and Hung, 2010a; 2010b). Some studies even determined their parameters by regression analyses of a very comprehensive set of variables (up to about 30 variables) against their target response variable such as energy economy (Brady and O'Mahony, 2016; Gong, et al., 2018). The resultant parameters of these regression analyses were also consistent with the list mentioned above. The assessment parameters eventually adopted in this study were mainly based on the recommendations by Tong and Hung (2010). These parameters have also been widely used by numerous driving cycle development studies worldwide and are summarised in Table 4:

[Table 4]

Values of the 13 assessment parameters were first calculated for each trip and then analysed according to three stratification criteria:

(1) Day of the week for which the trip was made (i.e. weekdays or weekends);
(2) Time period for which the trip was made (i.e. AM Peak, Off Peak (Day), PM Peak, and Off Peak (Night)). The definition of the time periods were: AM Peak – 07:00 to 10:00; Off Peak (Day) – 10:00 to 17:00; PM Peak – 17:00 to 21:00; Off Peak (Night) – 21:00 to 07:00; and
(3) District(s) of the route covered (i.e. HKI, Kowloon, NT and Island, or Inter-districts).

The calculation of the 13 assessment criteria and the corresponding mean values for each group were encoded in Delphi programming language for implementation. These stratification criteria were determined with reference to the latest territory wide transport model in Hong Kong (ARUP, 2014) and the analysis of the franchised bus route network structure discussed earlier. The models developed in the Travel Characteristics Survey 2011 (TCS) were the latest version referenced by most local transport planning studies in Hong Kong. The first two stratification criteria are consistent with the analysis scenarios adopted in the TCS 2011, which implies that these scenarios represent significantly different traffic conditions warrant separate analyses. In particular, criterion (2) is also consistent with the four peak and off-peak periods defined in the Franchised

Bus Service Topical Study, which has been set with reference to the passengers' travel patterns and expectation of bus service levels (LC Paper, 2015). For the third stratification criterion, it is based on the analysis of the franchised bus route network structure.

To provide a more direct and visual examination of the differences in driving patterns, scatter plots between two of the most commonly used parameters (i.e. idling proportions vs trip average speed) under each stratification criterion were also developed. These plots are helpful to further affirm any significant differences that could be observed and thus characterised the corresponding driving patterns. It is important to note that the driving pattern identification process was mainly based on the set of quantitative assessment parameters while the scatter plots mainly served as a direct and visual demonstration of the differences between different driving patterns. This approach of visualising the driving characteristics has also been adopted by other studies (Fotouhi and Montazeri-Gh, 2013).

The scatter plots of idling proportions versus trip average speeds are shown in Figures 2 to 4. The mean values of the 13 assessment parameters under each stratification criterion are also summarised in Tables 5 to 7 together with the overall mean values for the whole data set.

[Figure 2]

[Figure 3]

[Figure 4]

[Table 5]

[Table 6]

[Table 7]

The scatter plots show a reasonable inversely proportional pattern. Longer idling proportions generally slow down the trip average speed. Further investigation of the plots for each stratification criterion indicate that clear differences in driving patterns can be observed for different districts and different time periods of a day. However, the scatter plot for weekdays vs weekends did not show a very clear difference where trips recorded for both categories had a very similar span of idling proportions and trip average speeds (Figure 2). Weekend trips appeared to be slightly centralised at higher speed and lower idling proportion ranges while weekday trips tended to locate at lower speed and higher idling proportion ranges. A closer look at the mean values of other assessment parameters further confirmed the above observations (Table 5). While most of the acceleration related parameters were very similar for both categories, weekday trips generally experienced slower driving conditions with longer idle times. Another characteristic worthwhile to mention was that weekend trips exhibited a longer micro-trip length than weekday trips. This indicated that weekend driving generally experienced less stops due to traffic congestions than during weekdays. The difference in the average number of acceleration/deceleration changes within a driving period (i.e. M) was simply due to the fact that weekend trips had a longer micro-trip length (i.e. C) than weekday trips, and thus boosted up the value of M for weekend trips. It did not necessarily indicate that weekend driving was significantly more aggressive than weekday driving. Generally speaking, weekend driving was slightly faster than weekday driving with fewer stops and smaller idling proportions while the driving aggressiveness were similar to weekday driving. Given the above observations, it could be concluded that the dataset did not show a significant difference in bus driving patterns that warranted a separate driving cycle be developed for weekday and weekend trips.

When looking at the scatter plot for different districts, very clear grouping of trips could be observed (Figure 3). The scatter plot showed a very different pattern for trips recorded for inter-districts when they were compared with other trips. For inter-district trips, they were more centralised at the high speed and low idling proportion ranges. For other trips (i.e. Kln, HKI, and NT and Island), they were all within a low average speed range of below 30 km/h with a relatively higher proportion of idle. This reflected a very typical driving condition at the urban areas with different levels of congestion. In fact, the trips recorded for these three categories were travelling within individual urban areas of each district. For inter-district trips, the higher speed and lower idling proportions were mainly due to the fact that these trips normally ran through high speed roadways (i.e. highways, or roads with limited stops due to traffic congestions or bus stops). Those bus trips were usually connecting one urban area to another with very limited bus stops in between. Therefore, the speed-time profiles of many inter-district trips usually consisted of one portion containing a number of relatively short micro-trips (i.e. reflecting the typical driving pattern at the urban areas with frequent stop-and-go activities due to bus stops, congestions or traffic signal junctions) and another portion with one or two very long and relatively high speed driving periods (i.e. reflecting the driving on high speed roadways with limited stops). Further investigation of the summary statistics for different districts (Table 6) also showed clear differences in the driving characteristics for these two groups of trips. Inter-district trips exhibited much faster average speed (44 km/h) and lower idling proportion (12.4%) than trips travelling within a district (14-18 km/h average speed and 30-40% of idle). The mean length of a micro-trip also showed a significant difference between the two groups of trips (about 4.5 minutes for inter-district trips versus 1-2 minutes for trips within a district). These results indicated that it was necessary to develop two separate driving cycles for inter-district trips and within a district trips.

When categorising the trips by different time of a day, some interesting patterns could also be observed. As expected, there was a significant difference between peak and off-peak travels. The scatter plot (Figure 4) showed that both AM and PM peak trips were centralised at low speed and high idling proportion ranges while off-peak trips spread across the whole range of average speed and idling proportion. The mean values of summary statistics also showed that peak driving was much slower (around 15 km/h) and experienced more idle time (32-35% of idle) than driving at off-peak periods. Acceleration parameters also exhibited clear differences between the two groups that peak hour driving was more aggressive due to the more congested traffic conditions than during the off-peak periods. For peak driving, PM appeared to be a bit more congested than AM. For off-peak driving, it was expected that there should be significant differences between daytime and night time (including the mid-night periods). Table 6 showed that night time off peak travel was much faster (38 km/h versus 27 km/h) and experienced much less idle time (17.5% versus 27.5% of idle) than daytime. Based on the above analysis, it was desirable to develop three separate driving cycles for peak (i.e. combining AM and PM peaks), off-peak (daytime) and off-peak (night time). As mentioned earlier, this result was also consistent with the definition adopted by the government (LC Paper, 2015).

To summarise, the above analysis has identified five different bus driving patterns that warrant a separate driving cycle. These patterns are summarised in Table 8. It is important to note that statistical classification techniques such as Principal Component Analysis (PCA) or Cluster Analysis were adopted in the literature in classifying trip data. However, these techniques were not employed in this paper because it was managed to collect detailed information on the predetermined stratification criteria along with the speed time data collection process. Trip data could then be directly classified according to the stratification criteria to examine if any significant differences in driving patterns could be identified.

[Table 8]

7. Constructing Bus Driving Cycles for Hong Kong

For each of the five identified bus driving patterns, separate driving cycles would be developed using the following method. Constructing driving cycles based on actual vehicle speed data have been well researched and reviewed in earlier sections. In this study, the random selection and matching approach was employed. It is important to emphasize that this approach has been widely used and accepted. Details of the method can be found in the literature (Tong, et al., 1999; Hung, et al., 2007; Tong and Hung, 2010b; Tong, 2019) and is outlined below and in Figure 1.

First, mean values of the 13 assessment parameters were derived for all the filtered trip datasets classified under each identified driving pattern and set as target statistics. Candidate cycles were constructed by first identifying the micro-trips for each dataset. In this study, micro-trips were defined as speed profiles bounded by two consecutive idling periods. A designated number of micro-trips were then randomly selected to constitute a candidate cycle with the idling period preceding each subject micro-trip also included. The number of micro-trips constituting the candidate cycle depended on different driving patterns identified above. After the candidate cycle was established, the assessment parameters were compared against the corresponding target statistics. Cycles with all the 13 assessment parameters within 5% of the target statistics would be an acceptable cycle. If not, another candidate cycle would be generated and matched in the same way. As a result, 10 acceptable cycles were generated and ranked according to an aggregated assessment indicator – the average absolute percentage error (AAPE), for the determination of the best cycle. Speed acceleration probability distributions (SAPD) and vehicle specific power (VSP) distributions between the acceptable cycles and those derived from the whole dataset under each driving pattern would also be compared. The whole cycle synthesis process was automated in the same self-written Delphi program package as described before for easy and rapid implementation. The formula for calculating VSP for buses was as follows (Chen, et al., 2019).

$$\mathrm{VSP} = v\ (\ 1.1 \times a + 0.132\ ) + 0.0000745\ v^3$$

where v is the speed (in m/s) and a is the acceleration (m/s^2)

For Patterns I(a), I(b) and II(a), the above cycle development method, which was consistent with other micro-trip random selection methods adopted elsewhere, was directly applied to the dataset under these three categories. A total of 20 micro-trips were selected to constitute a candidate driving cycle for Patterns I(b) and II(a) which was consistent with the other driving cycles developed under the Hong Kong driving environment (Tong, et al., 1999; Hung, et al., 2007; Tong, 2019). This would result in a cycle of about 20 to 30 minutes. As for Pattern I(a), the mean length of micro-trips was much longer than that of other patterns, only 10 micro-trips would be selected so as to avoid having too lengthy cycles. This would result in a cycle of about 45 to 55 minutes which was consistent with the characteristics of inter-district trips having relatively longer durations than within a district trips.

For Patterns II(b) and II(c) (i.e. Off-Peak (Day) and Off-Peak (Night)), the average micro-trip lengths were much longer than that of Pattern II(a) (i.e. Peak). Therefore, the driving cycles for Patterns II(b) and II(c) should reflect, to certain extent, the characteristics of inter-district travels as identified in Table 8. Therefore, the resultant driving cycles for these two patterns should contain one long micro-trip with high speed. To ensure this, the micro-trips categorised under these two patterns were first separated into two groups to develop two sub-cycles and then appended together to become the final cycles. Therefore, micro-trips longer than 5 minutes were sorted out first. The cycle construction method described earlier was then applied to the rest of the micro-trips under each category to develop a Sub-cycle 1 using 20 randomly selected micro-trips. For the micro-trips with length longer than 5 minutes, the single micro-trip with summary statistics closest to the mean values would be selected as Sub-cycle 2 under each of these two categories. Again, the cycle synthesis process was done with the self-written Delphi program package. The two sub-cycles under each category were then concatenated together to form the final cycles for Patterns II(b) and II(c).

The resultant driving cycles for each pattern are shown in Figures 5 and 6 and the comparison of summary statistics between the synthesized cycle and the target statistics are also summarised in Tables 9 and 10. Patterns I(a) and I(b) cycles are characterised by cycle durations of 3218 and

1956 seconds and average speeds of 45 km/h and 15 km/h respectively. This is consistent with the characteristics of these two patterns that inter-district cycle is much faster and having a longer trip length due to the smooth driving on high speed roads. The inter-district cycle (Figure 4(a)) shows two long and high speed micro-trips reflecting the high speed road driving conditions without bus stops or traffic junctions. Figure 4(b) shows a series of relatively short micro-trips reflecting the congested driving conditions within a district with frequent bus stops and/or traffic junctions.

[Figure 5]

[Figure 6]

[Table 9]

[Table 10]

The SAPD and VSP distributions (with resolutions of 5 km/h for speed and 0.5 m/s/s for acceleration) assessments for the synthesized cycles for each driving patterns are shown in Figures 7 to 10. Both comparisons also showed fairly good agreements between the synthesized cycles and the targets. The differences appeared to be slightly bigger for Patterns II(b) and II(c) as the 5% tolerance limit was not imposed on the generation of Sub-cycles 2. For Sub-cycle 1, the SAPD and VSP matched very well. For demonstration purposes, comparisons of VSP distributions of synthesized Sub-cycle 1 and Sub-cycle 2 for Pattern II(b) and II(c) were shown in Figures 11 to 12. It could be observed that all the sub-cycles matched quite well with the corresponding targets. Similar results were also obtained for SAPD.

[Figure 7]

[Figure 8]

[Figure 9]

[Figure 10]

[Figure 11]

[Figure 12]

8. Comparison with other Bus Driving Cycles

The major driving parameters of the synthesized driving cycles together with other bus driving cycles elsewhere are summarised in Table 11. Regarding the most important parameters (i.e. average speed and idling proportion), the comparisons between the synthesized cycles and international cycles of the same pattern are generally consistent. Pattern I(a) cycle (i.e. Inter-district) generally agrees with other cycles involving highways while Pattern I(b) cycle can be matched with cycles developed for urban areas. However, when comparing the acceleration parameters, bus driving in Hong Kong is remarkably different from bus driving cycles for other cities around the world. Bus driving cycles in Hong Kong exhibit much higher acceleration and deceleration rates, longer idling periods as well as much shorter cruising periods. These results further confirm the very unique bus driving characteristics in Hong Kong (Tong, 2019).

[Table 11]

As a result of the above comparisons, some important typical bus driving characteristics in Hong Kong could be highlighted as follows. First, bus transport in Hong Kong normally contains significantly longer idling proportions. This is possibly because of the heavy reliance of franchised bus transport in Hong Kong, which results in many closely spaced bus stops at the urban and residential areas, as well as long dwell times due to the high patronage at individual bus stops. These directly contribute to the unique long idling bus driving pattern in Hong Kong. Secondly, bus drivers in Hong Kong also appeared to be more aggressive than bus drivers elsewhere because of the tight bus schedules, short bus stops spacing as well as frequent stop-and-start operations due to the congested driving conditions in Hong Kong. On one hand, the above mentioned route characteristics and on-road driving environments might be contributors of the drivers' aggressiveness. On the other hand, numerous research studies also indicated that psychosocial work factors such as fatigue, stress and driving styles of the bus drivers are also important factors for aggressive driving behaviours. In particular, poor psychosocial work environment in job demand, job content, work-individual interface as well as having a car accident history were found to be associated with poor level of health and well-being and more stress symptoms (Aminian, et al., 2015). Another study also found that over 95% of urban bus drivers working for more than 10 hours per day would present fatigue factors related to perceptions of demands at work and exposure to environmental stressors. Theoretically, these would eventually associate with higher rates of risk behaviours and driving accidents (Useche, et al., 2018). Moreover, shift patterns may also lead to bus drivers' sleepiness and fatigue as a result of cognitive overload (Anund, et al., 2018; Miller, et al., 2020). In Hong Kong, known causes of bus driver fatigue include long hours behind the wheel, chronic sleep debt, and weakened bio-rhythm (Tang, 2018). According to the current guidelines on working hours, rest time and meal breaks in Hong Kong, franchised bus drivers are restricted to a maximum of 12 duty-hours with a cap of 10 driving hours per day. A minimum of 40 minutes break is required after six hours of driving. The break times between two successive shifts should not be less than 10 hours. Similar guidelines can also be found in nearby cities such as Singapore, Taiwan and South Korea. Therefore, even though there are related guidelines to manage the potentially long working hours, rest times and shift schedules, these might still be valid reasons for the observed aggressive bus driving patterns. Although it is not the major focus of this study, the observed aggressive bus driving characteristics may require further investigations in the future as they may eventually lead to aberrant driving behaviours and create road traffic safety concerns. Previous research indicated that aberrant driving behaviours were related to factors like public self-consciousness and social anxiety (Huang, et al., 2018), job strain, effort-reward imbalance and social support at work (Useche, et al., 2017). In particular, altruism was found to be negatively correlated with aggressive violations for bus drivers (Mallia, et al., 2015; Shi and Zhang, 2017). Therefore, specialised traffic safety education reflecting individual driving behaviours was recommended along with periodic traffic safety education to prevent repetitive abnormal driving behaviours (Kim et al., 2016). Bus driver's crashes could also be reduced by less driving time and mistakes which is dependent on mileage they drove (Varmazyar, et al., 2013).

9. Conclusions

In this paper, a set of bus driving cycles representative of different bus driving conditions in Hong Kong have been developed. Actual speed-time data records were collected using a cost effective approach utilising the GPS capability of smartphones. This approach is particularly useful for developing economies where there are tight resources constraints because of its cost effectiveness and capability in capturing a wide range of bus routes, driving characteristics and activity patterns. However, it is important to note that the selection of surveyors is critical in assuring data quality and representativeness. Surveyors with daily travelling patterns covering different districts should be invited so as to assure a wide route coverage and variety of activity patterns.

Analysis of the speed data considered the structure of the franchised bus route network as well as the traffic characteristics of the territory wide transport planning model. Eventually, 5 bus driving patterns with significantly different characteristics were identified. Pattern descriptors were defined to specifying the characteristics of each pattern. Separate driving cycles were then synthesized by using the micro-trips random selection approach to match the target statistics and incorporating the special features of individual pattern identified (e.g. inclusion of a longer micro-trip in the resultant driving cycle). SAPD and VSP distributions were also derived to further confirm the representativeness of the developed cycles. The developed bus driving cycles reflected very unique bus driving patterns in Hong Kong as compared to other bus driving cycles elsewhere. In particular, buses driving in Hong Kong exhibited much longer idling as well as more aggressive accelerations and decelerations. Even though the data collected in this study did not have a complete coverage of all the franchised bus routes, however, the sampled dataset did represent a significant improvement over pervious similar studies concerning buses in terms of the number of bus routes included. The validity and generalisation of results from this paper for sure can be further improved with a larger dataset. It is believed that this study, in the current form, should still be able to highlight some important bus route driving characteristics in Hong Kong. First, the developed data collection method is useful in collecting representative speed data for studies with tighter resources constraints. Secondly, the five identified bus driving patterns could be of references for other studies in interpreting the driving patterns of fixed-route transport modes. The developed driving cycles can be served as a representative platform for bus emissions and/or energy consumption estimations. Local authorities (i.e. the Transport Department and/or the Environmental Protection Department) as well as the bus operators can choose appropriate driving cycles representing specific route structure or driving pattern for annual bus emissions testing or type-approval testing.

10. Discussions of the Study Methodology and Limitations

This study employed 12 surveyors, carefully selected according to the districts they lived in, to conduct on-board bus speed data collection during their daily travelling activities. Second-by-second speed data were collected using the GPS function of the surveyors' smartphone with the "MyTracks" APP. Detailed trip information and bus stop-and-go timing were also collected for every trip data collected. Data quality and validity were assured because (1) the mobile device and the APP used were consistent with those adopted in relevant literature and proven to be reliable; (2) a set of well-established and commonly used data cleaning procedures was employed to process the collected data before further analyses; (3) the bus drivers were completely unaware of the data collection process and thus data reflecting their real driving behaviours would be guaranteed. While data quality was assured, the method itself still had some shortcomings. The major limitation of this data collection method was that the activity patterns of the surveyors employed (which were out of the control of the researchers) would directly affect the representativeness of the data collected. Therefore, prior knowledge on the approximate daily activity patterns of the surveyors was obtained. Appropriate surveyors were then carefully selected to cover different districts and route patterns. The results showed that the collected data did cover a reasonable distribution of route patterns (Table 3). Secondly, the data collection process also experienced the common issues of GPS speed data collection methods mentioned in the literature (e.g. occasional signal loss, zero-speed drifting, etc.). To address this, a set of well-known data cleaning procedures (as described in Section 5) was utilised to process the collected data so as to make sure that the data for further analysis were in the best quality possible. Also, the detailed trip information collected by the surveyors (such as the actual stopping and starting time for each idling) could further enhance the data quality and validity. Eventually, 91 bus trip datasets were collected. While it might be difficult to judge if this sample size was sufficient when compared to the comprehensive and highly utilised franchised bus route network, the collected data (in terms of the number of bus routes covered) already represented a significant improvement over other similar bus driving cycle studies. It is believed that the collected data should be reliable to highlight some important findings as discussed before.

To identify specific bus route driving patterns, 13 commonly used representative assessment parameters were employed and the trip data were analysed based on the (1) day of a week; (2) time of a day (which were according to the in-use transport model); and (3) district of travel. Five distinct bus driving patterns were eventually identified and then interpreted based on the knowledge on the bus route network. Pattern descriptors were then developed according to the characteristics exhibited in the 13 assessment parameters. First, most of the studies in the literature had clear stratification criteria at the beginning stage. The whole process of data collection, analysis as well as cycle synthesis would then deliberately follow the same set of stratification criteria. However, this study did not incorporate any stratification criteria for data collection. It implied that the collected data would contain mixed driving characteristics. The driving patterns might not be easily separable and thus composite driving cycles would commonly be developed. To overcome this difficulty, this study adopted both quantitative statistics (i.e. the 13 assessment parameters) and qualitative assessments (i.e. the traditional classification factors such as peak vs non-peak, and the structure of the bus route network). This approach is not only consistent with the traditional driving data classification principles with the support of quantitative statistics, but also has incorporated the qualitative assessment of the unique characteristics of the bus network.

On the basis of a very comprehensive literature review on cycle development methodologies, the micro-trip based approach (which was the most commonly used and proven to be valid for the unique environment in Hong Kong) was adopted to develop the driving cycles for each of the five patterns identified. While each approach has its own pros and cons, the micro-trip based approach is still the most commonly used and well recognised to be valid and suitable for uses under the Hong Kong environment. To further enhance the representativeness, differences in three more metrics (i.e. VSP distributions, SAPD, and the AAPE of the 13 assessment parameters) between the target statistics and the candidate driving cycles were compared to determine the most representative synthesized driving cycles for each pattern.

Declaration of interests

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.

Acknowledgement

The work described in this paper was fully supported by a grant from the College of Professional and Continuing Education, an affiliate of The Hong Kong Polytechnic University.

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Figure 13 Comparison of Worldwide Bus Driving Cycles

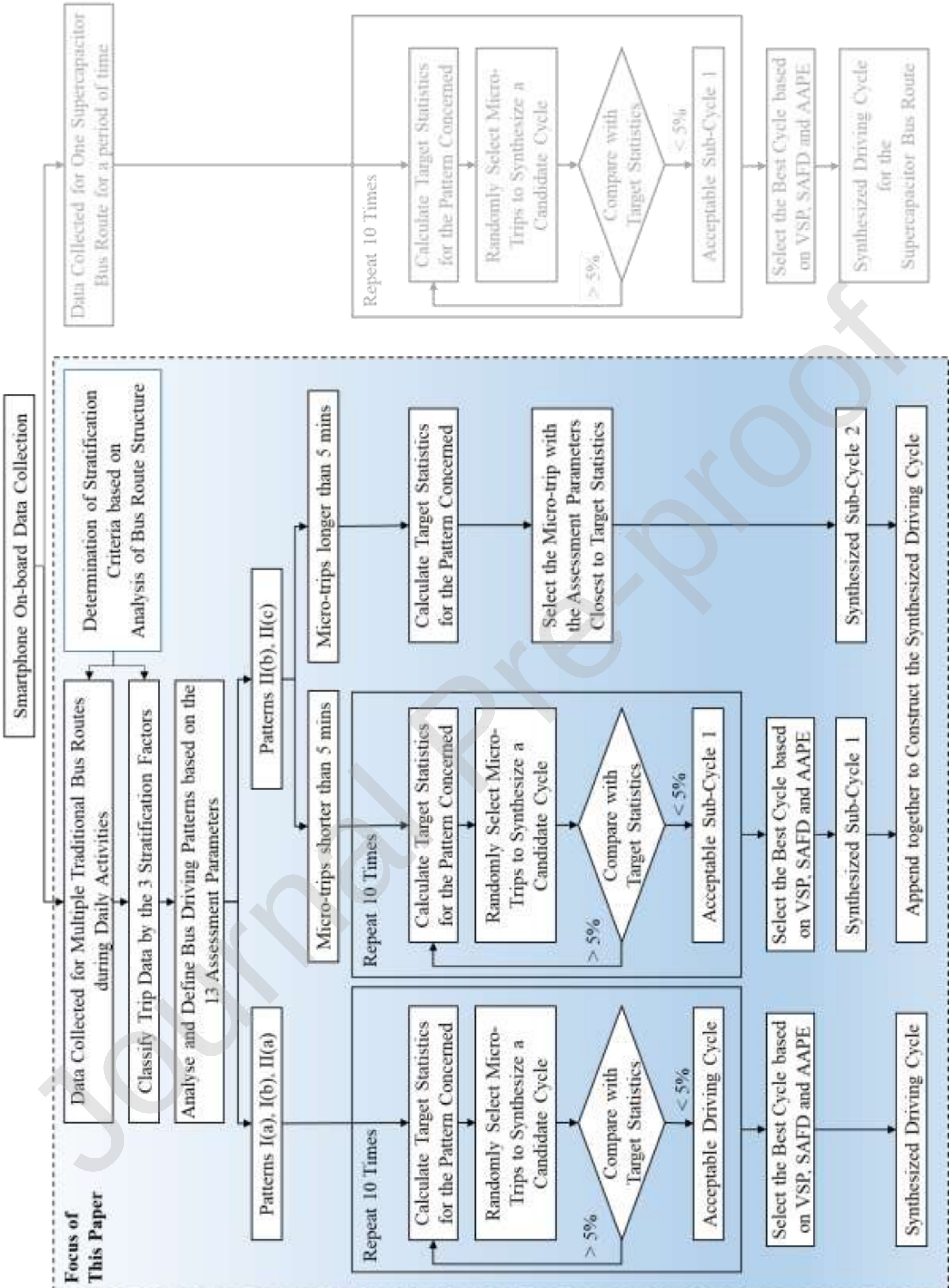


Figure 1 Flowchart of the Study Methodology

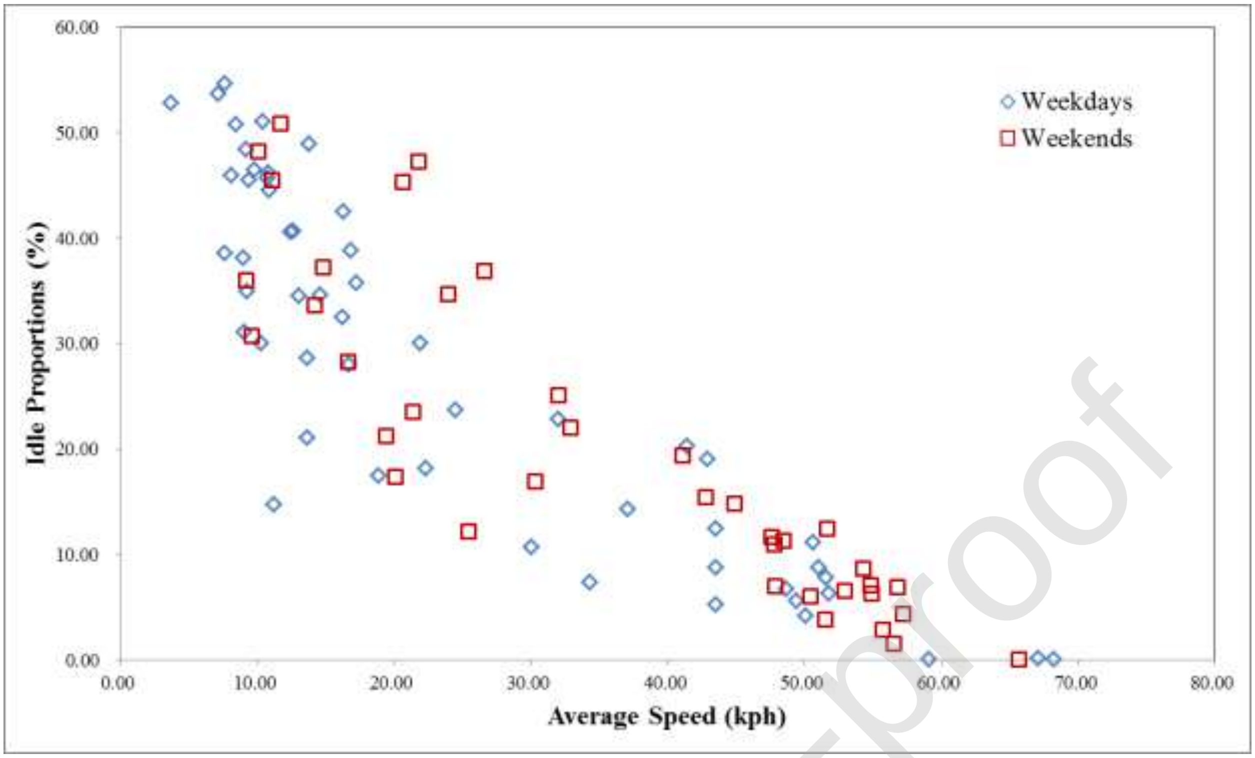


Figure 2 Trip Idling Proportions versus Trip Average Speed (by Day of a Week)

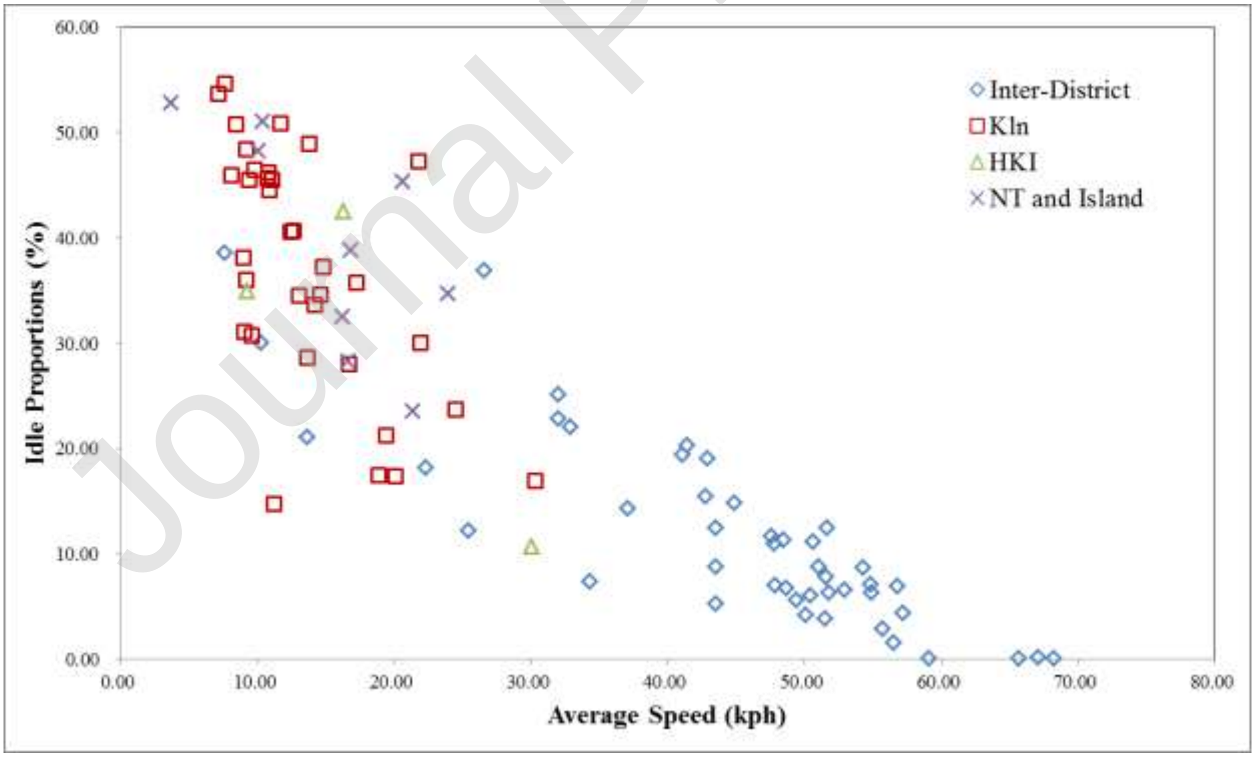


Figure 3 Trip Idling Proportions versus Trip Average Speed (by Districts)

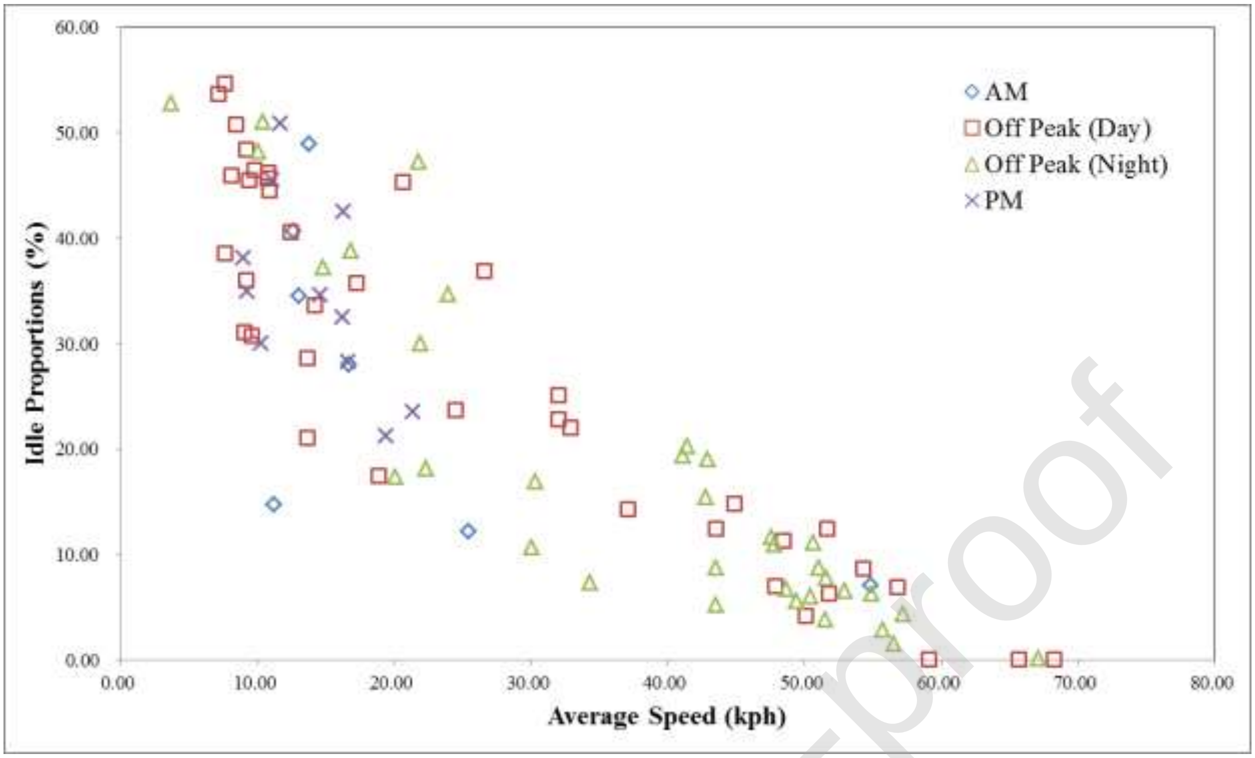


Figure 4 Trip Idling Proportions versus Trip Average Speed (by Time of a Day)

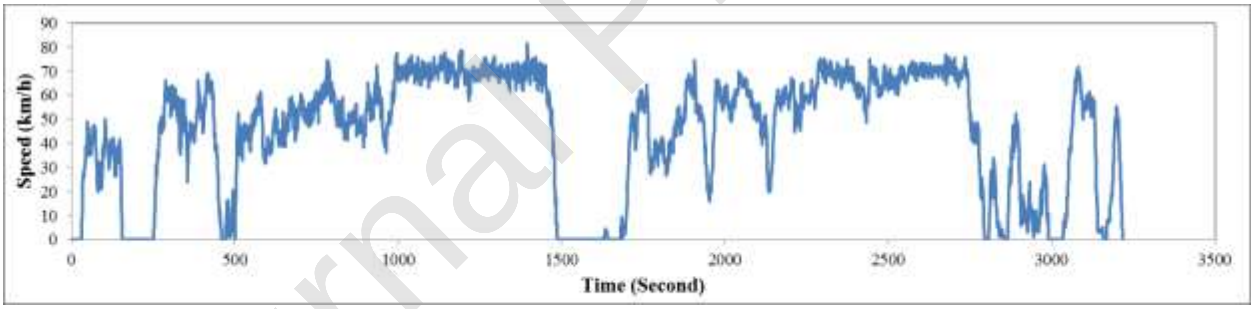


Figure 5a Synthesized Bus Driving Cycle for Pattern I(a) (Inter-District)

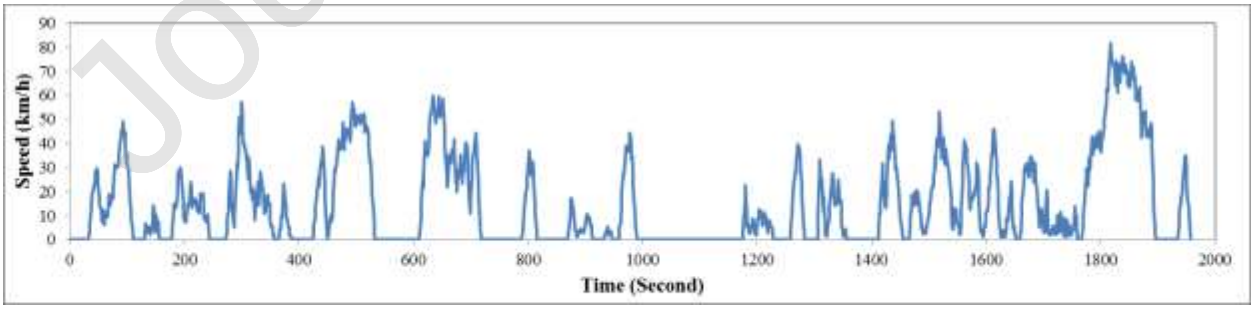


Figure 5b Synthesized Bus Driving Cycle for Pattern I(b) (Within a District)

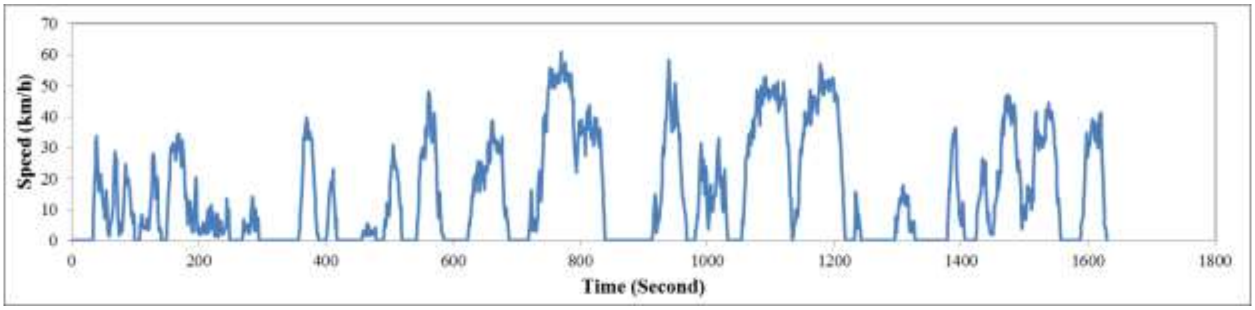


Figure 6a Synthesized Bus Driving Cycle for Pattern II(a) (Peak)

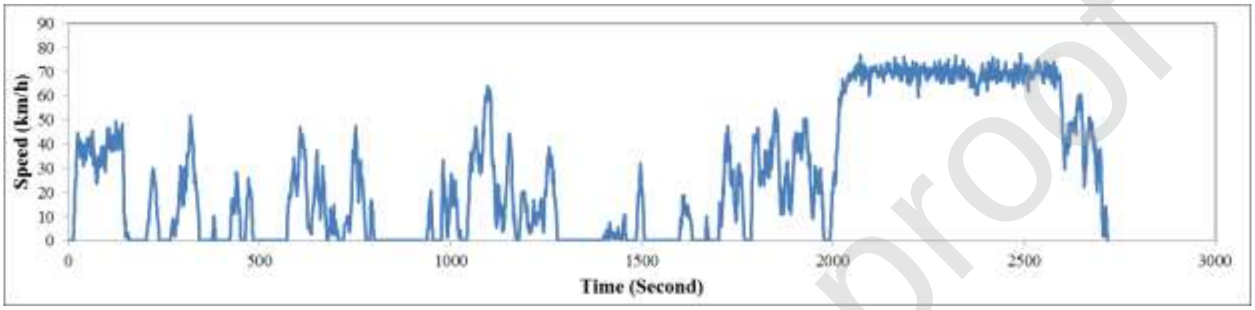


Figure 6b Synthesized Bus Driving Cycle for Pattern II(b) (Off Peak (Day))

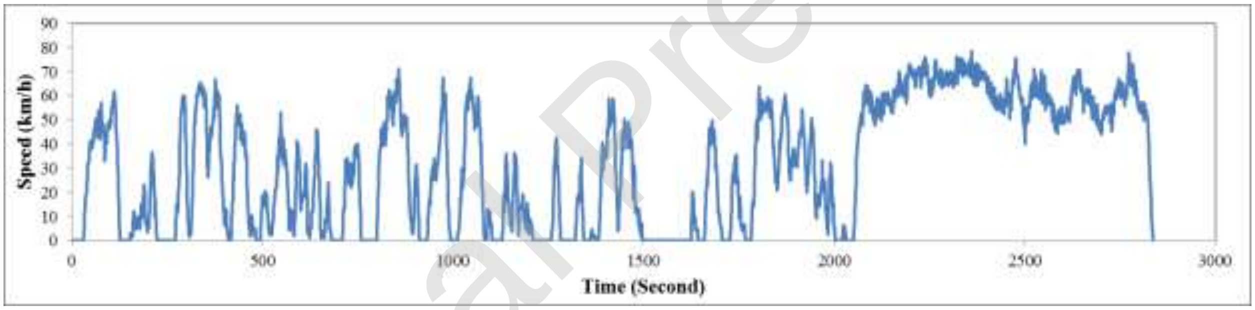
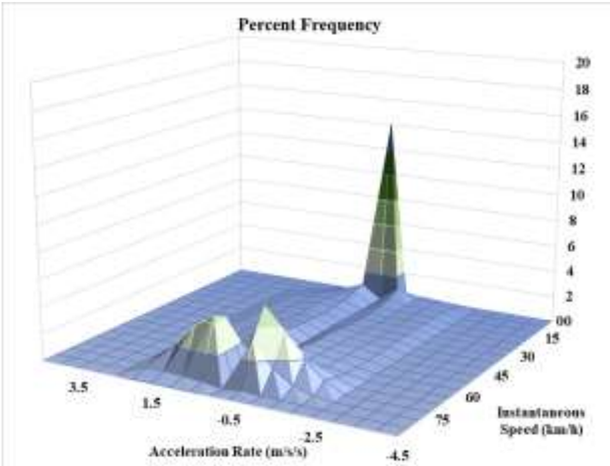
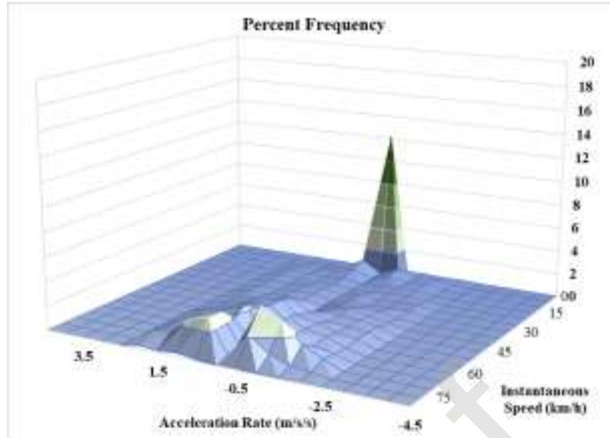
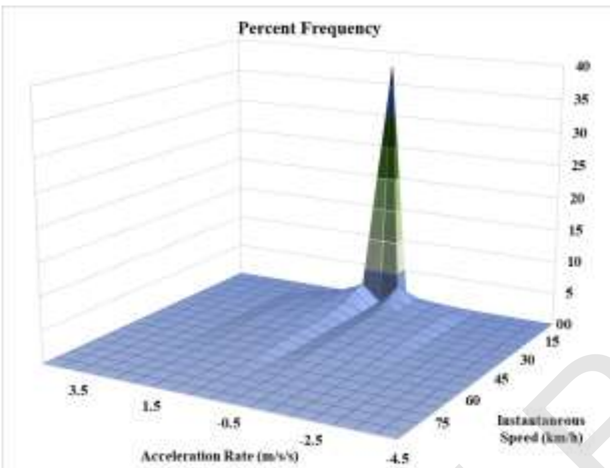


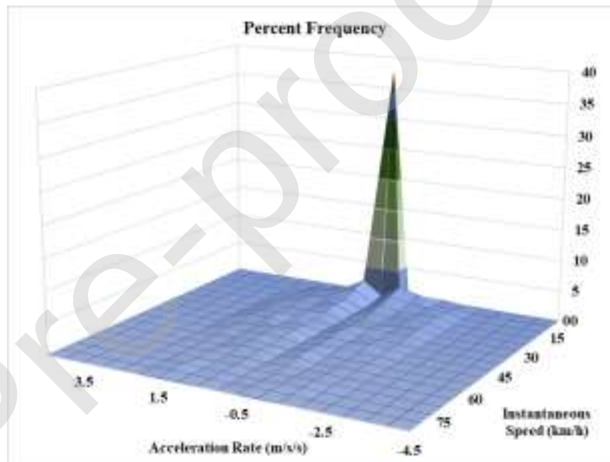
Figure 6c Synthesized Bus Driving Cycle for Pattern II(c) (Off Peak (Night))





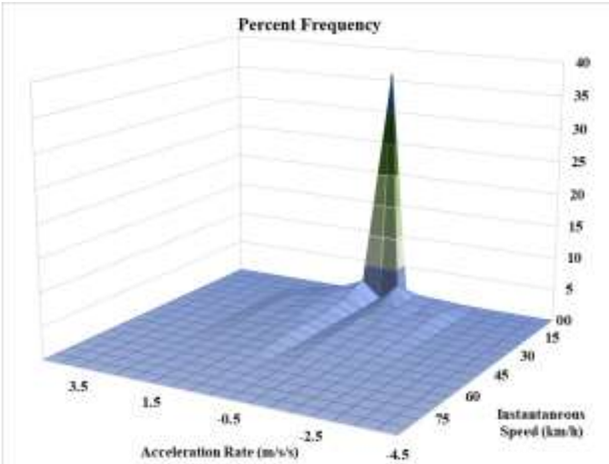
(a) All Data (Inter-Districts) **(b) Synthesized (Inter-Districts)**



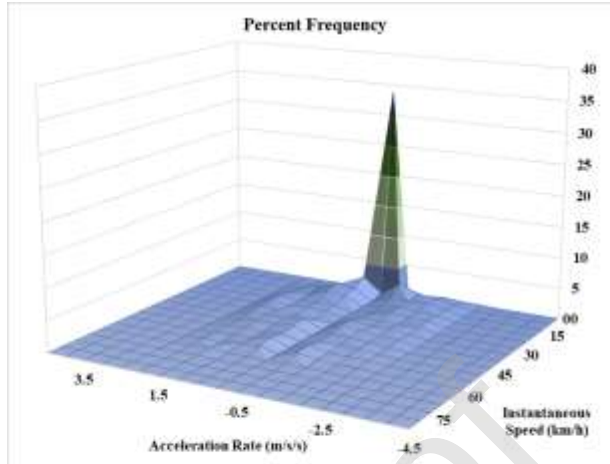


(a) All Data (Within a District) **(b) Synthesized (Within a District)**

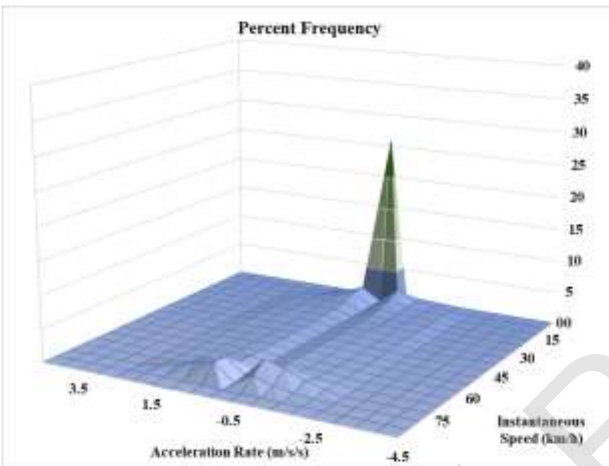
Figure 7 Comparisons of SAPDs for the Synthesized Cycles I and the Whole Dataset



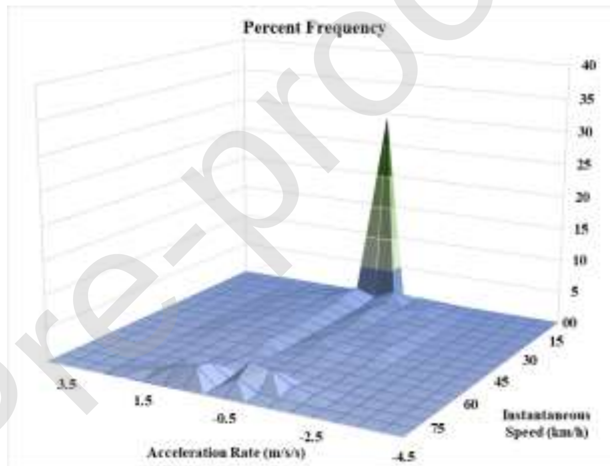
(a) All Data (Peaks)



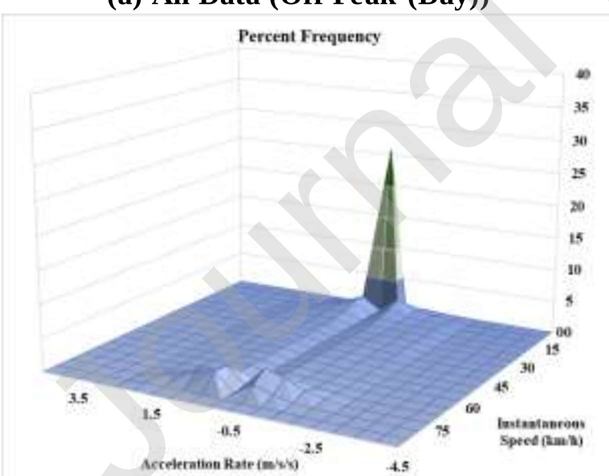
(b) Synthesized (Peaks)



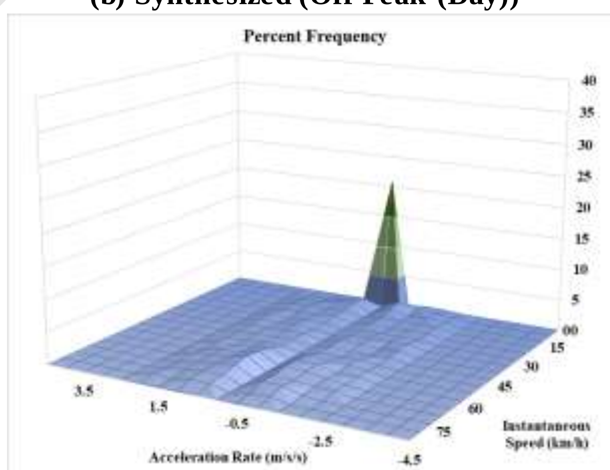
(a) All Data (Off Peak (Day))



(b) Synthesized (Off Peak (Day))

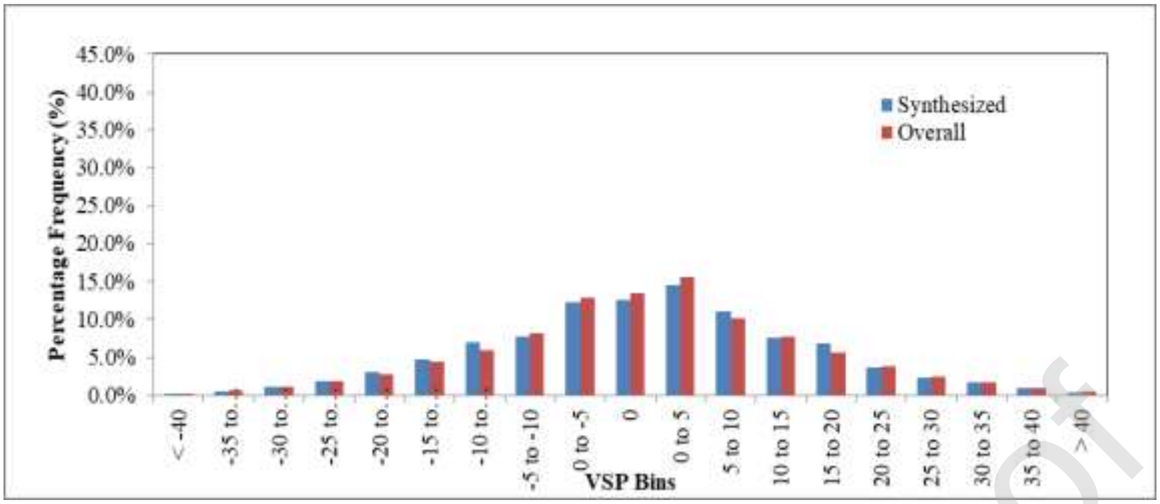


(a) All Data (Off Peak (Night))

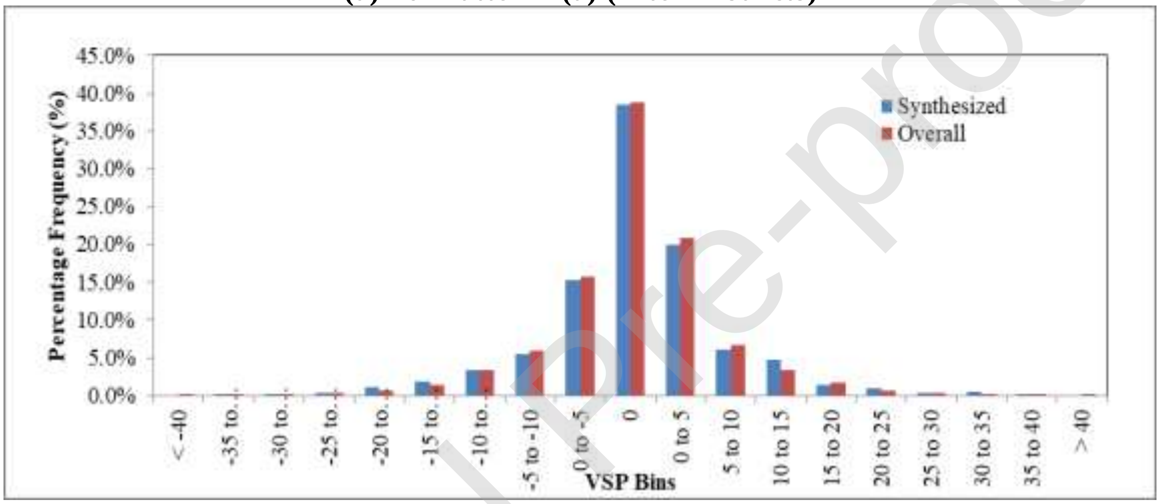


(b) Synthesized (Off Peak (Night))

Figure 8 Comparisons of SAPDs for the Synthesized Cycles II and the Whole Dataset

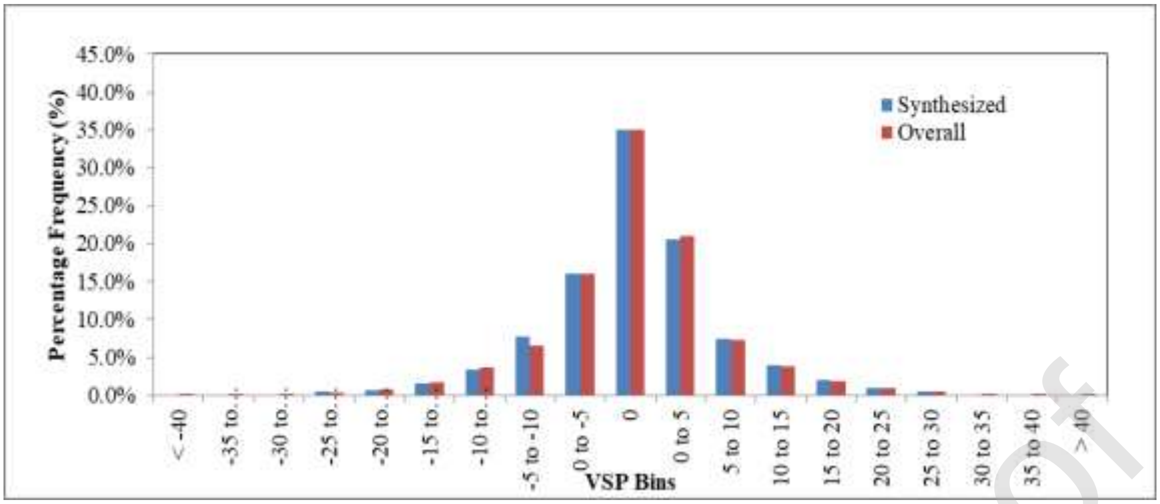


(a) For Pattern I(a) (Inter-Districts)

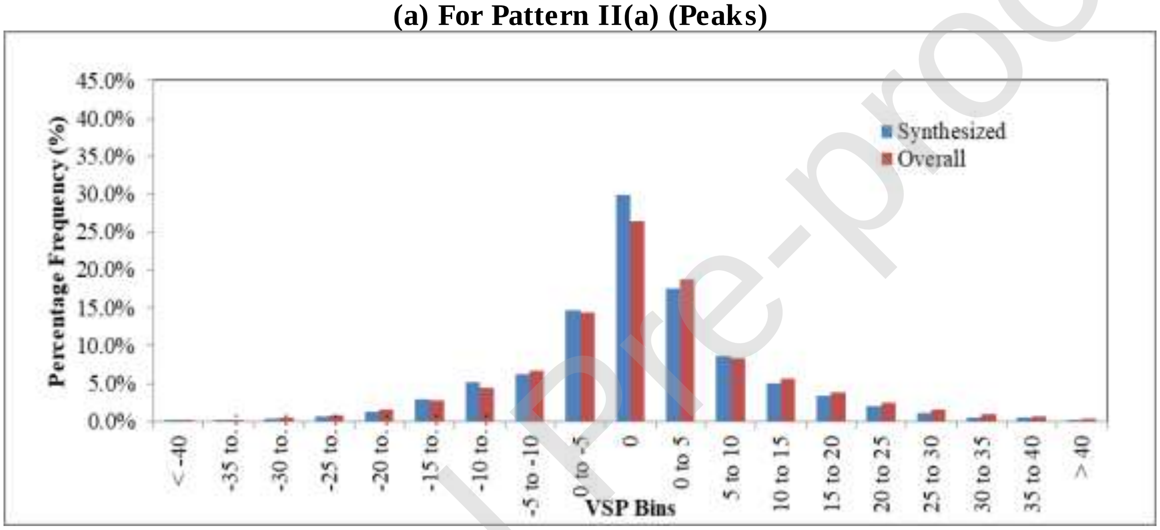


(b) For Pattern I(b) (Within a District)

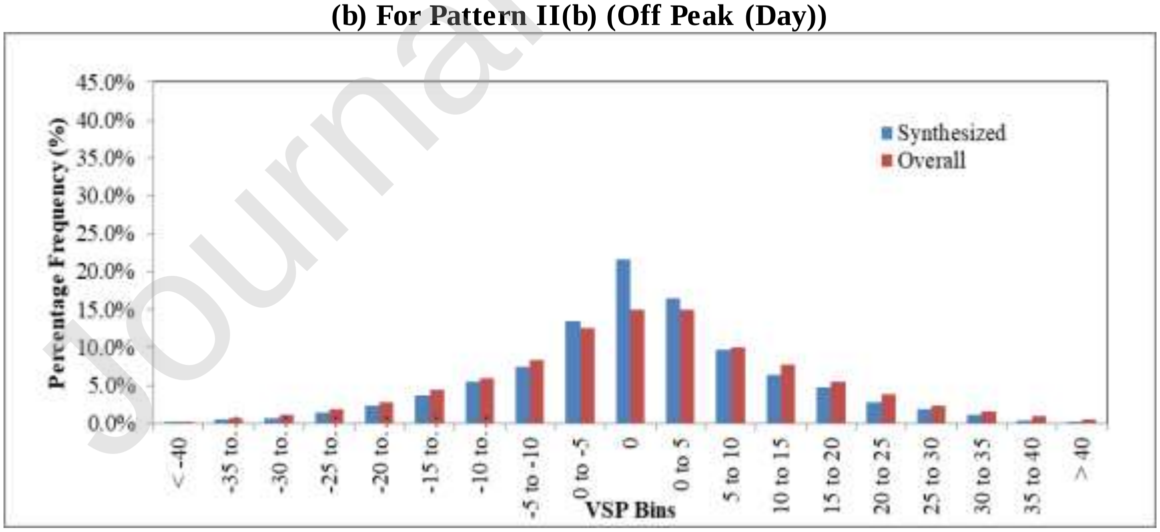
Figure 9 Comparisons of VSP Distributions for the Synthesized Cycles I and the Whole Dataset



(a) For Pattern II(a) (Peaks)

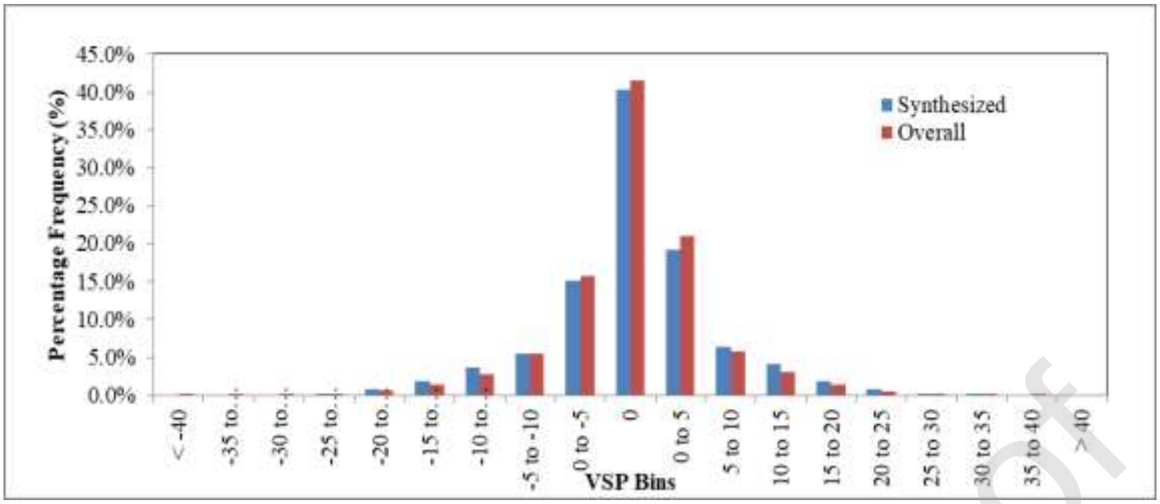


(b) For Pattern II(b) (Off Peak (Day))

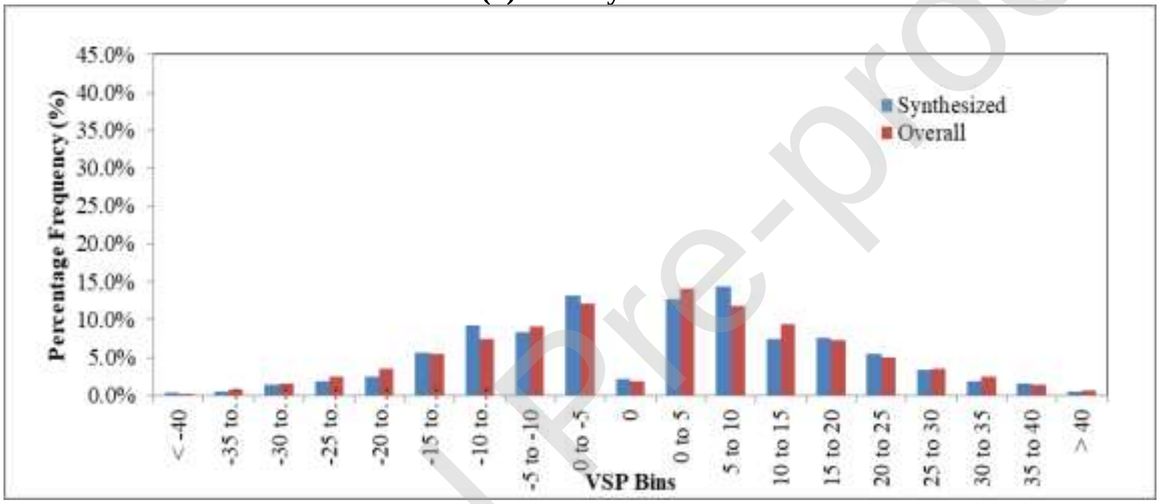


(c) For Pattern II(c) (Off Peak (Night))

Figure 10 Comparisons of VSP Distributions for the Synthesized Cycles II and the Whole Dataset

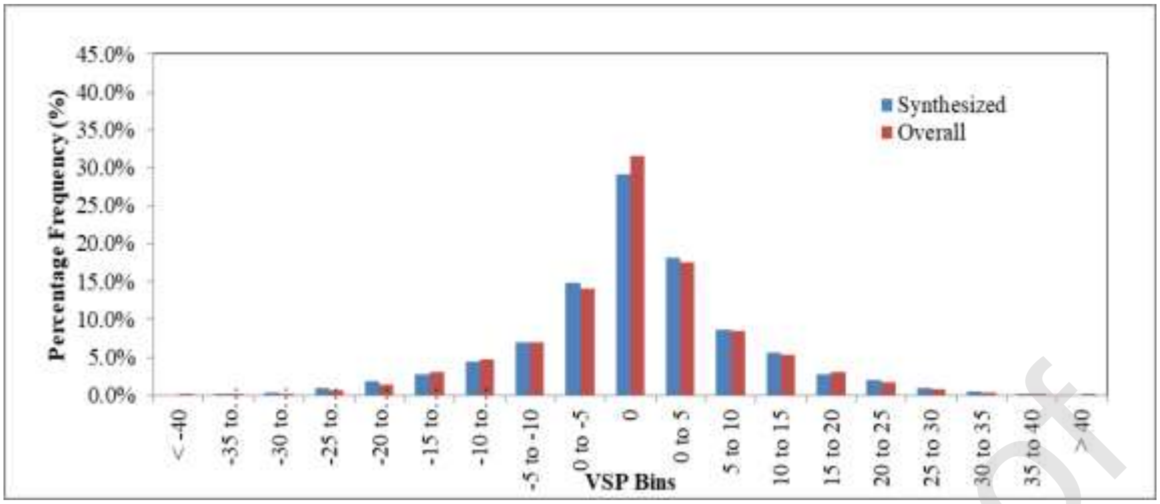


(a) Sub-Cycle 1

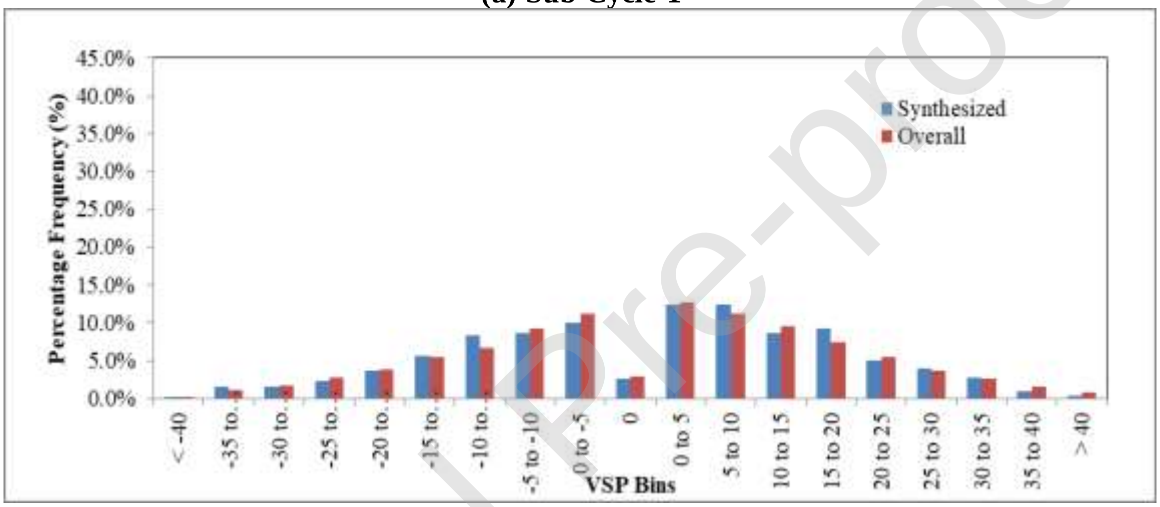


(b) Sub-Cycle 2

Figure 11 Comparisons of VSP Distributions for the SubCycles II(b) and the Whole Dataset



(a) Sub-Cycle 1



(b) Sub-Cycle 2

Figure 12 Comparisons of VSP Distributions for the SubCycles II(c) and the Whole Dataset

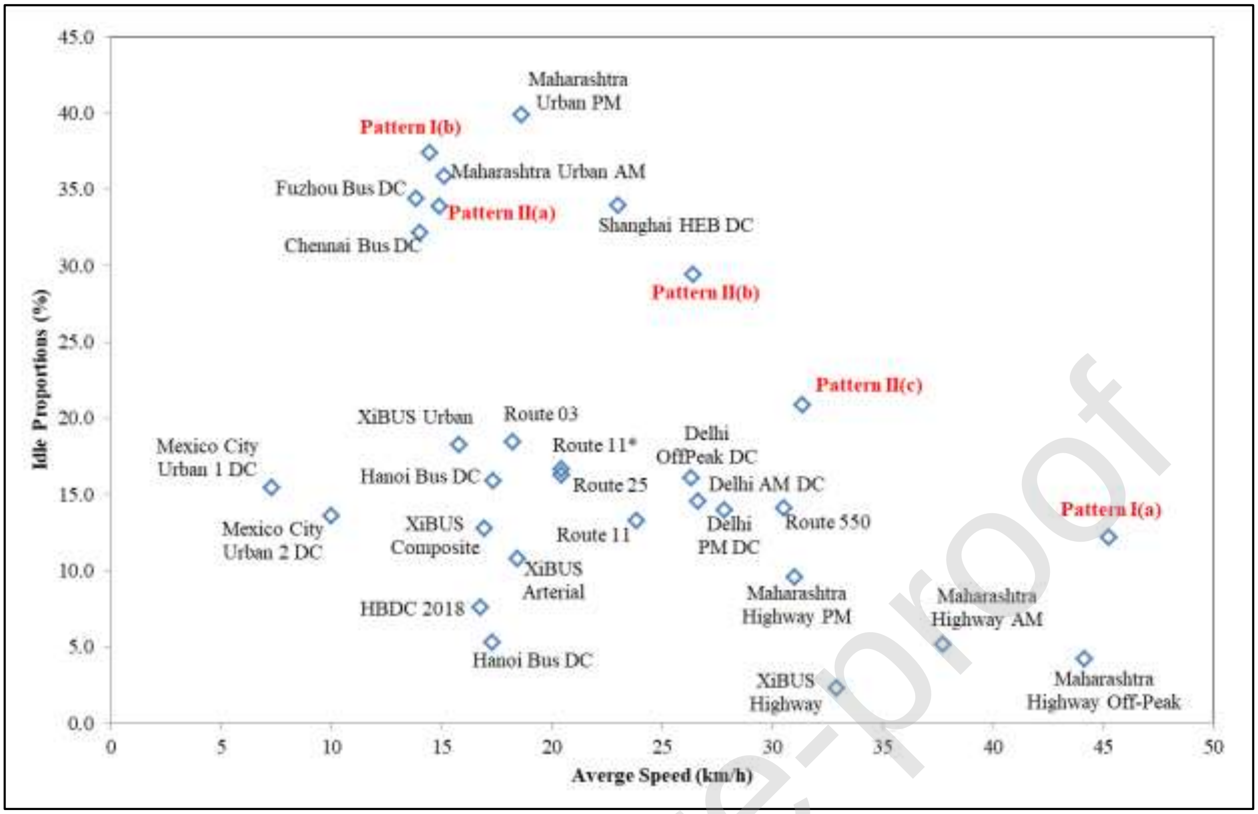


Figure 13 Comparisons of Worldwide Bus Driving Cycles

Table Captions

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
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
Hanoi, Vietnam	Emission estimation	Urban	GPS Onboard	1 existing bus Route	Markov chain with Transition Probability Matrix and SAFD	Regular	Nguyen, et al., 2016
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
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
Espoo, Finland	Energy consumption evaluation	Suburban	GPS Onboard	1 existing suburban bus route	Segment Based (between bus stops)	Electric	Kivekas, et al., 2018a; 2018b
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
Mexico City, Mexico	Emission and Fuel Consumption	Urban	GPS Onboard	15 existing routes	Micro-trip selection	Regular	Quirama, et al., 2020

Table 1 Comparison of Reviewed Bus Driving Cycles

Types of Cycle Construction Methods Adopted		Studies in Developing Countries*	Studies in Developed Countries*
	Markov Chain Based	• Galgamuwa et al, 2016a in Sri Lanka • Gong et al, 2018 in China • Huang et al, 2017 in China • Li et al, 2017 in China • Ma et al, 2019 in China • Nguyen et al, 2016 in Vietnam • Nguyen et al, 2018 in Vietnam • Peng et al, 2019b in China • Mayakuntla and Verma, 2018 in India • Shi et al, 2011 in China	• Ashitari et al, 2014 in Canada • Bishop et al, 2012 in England • Brady and O'Mahony, 2016 in Ireland • Nyberg et al, 2014 in Sewden
	Micro-Trip Based	• Abas et al, 2018 in Malaysia • Anida et al, 2017 in Malaysia • Arun et al, 2017 in India • Adak et al, 2016 in India • Atiq et al, 2017 in Malaysia • Feroldi et al, 2016 in Argentina • Gamalath et al, 2012 in Sri Lanka • Jing et al, 2017 in China • Kancharla et al, 2018 in India • Koossalapeerom et al, 2019 in Thailand • Lai et al, 2013 in China • Li et al, 2016 in China • Le et al, 2012 in Vietnam • Maurya and Bokare, 2012 in India • Mongkonlerdmanee and Koetniyom, 2019 in Thailand • Nesamania and Subramanian, 2011 in India • Outapa et al, 2018 in Thailand • Peng et al, 2019a in China • Pouresmaeili et al, 2018 in Iran • Quirama, et al, 2020 in Mexico • Seedam et al, 2015 in Thailand • Tharvin et al, 2018 in Malaysia • Tong et al, 2011 in Vietnam • Yang et al, 2019 in China • Zhang et al, 2017 in China	• Amirjamshidi and Roorda, 2015 in Canada • Chiang et al, 2014 in Taiwan • Gunther et al, 2017 in Germany • Han et al, 2012 in Korea • Ho et al, 2014 in Singapore • Kivekas et al, 2018a in Finland • Kivekas et al, 2018b in Finland • Lipar et al, 2016 in Slovenia • Liu et al, 2016 in US • Pfriem and Gauterin, 2016 in Germany, France • Seers et al, 2014 in Canada
	Other Methods	• Abu Mallouh et al, 2014 in Jordan • Fotouhi and Montazeri, 2013 in Iran • Galgamuwa et al, 2016b in Sri Lanka • Kumar et al, 2013 in India • Mansour et al, 2018 in Lebanon • Shen et al, 2018 in China • Zhao et al, 2018 in China	• Achour and Olabi, 2016 in Ireland • Bender and Sawodney, 2015 in Germany • Berzi et al, 2016 in Italy • Knez et al, 2014 in Slovenia • Zamboni et al, 2015 in Italy

*Classification of developing and developed economies are based on the International Monetary Fund's World Economic Outlook (IMF, 2018)

Table 2 Summary of Reviewed Driving Cycle Studies

	HKI	Kln	Island/NT
HKI	6.3%	-	-
Kln	7.2%	21.6%	-
Island/NT	1.0%	18.3%	45.7%

(a) Number of Trips (%)

	HKI	Kln	Island/NT
HKI	1637	-	-
Kln	2996	32297	-
Island/NT	2731	41899	20121

(b) Trip Duration (s)

	HKI	Kln	Island/NT
HKI	8.4	-	-
Kln	8.7	126.5	-
Island/NT	32.5	545.3	182.8

(c) Trip Distance (km)

Table 3 Distribution of Bus Journeys Collected

Abbr.	Name	Unit	Definitions of the Variable
v_1	Average speed of the entire driving cycle	*km/h*	$\frac{\sum v_i}{N} \forall v_i$
v_2	Average running speed	*km/h*	$\frac{\sum v_i}{N_r} \forall v_i > 0$
a	Average acceleration of all acceleration phases	m/s^2	$\frac{\sum a_i}{n_a}$
d	Average deceleration of all deceleration phases	m/s^2	$\frac{\sum d_i}{n_d}$
RMS	Root mean square acceleration	m/s^2	$\sqrt{\frac{\sum a_i^2}{n_a}}$
PKE	Positive acceleration kinetic energy	m/s^2	$\frac{1}{2}\left(\frac{\sum\left(u_f^2 - u_i^2\right)}{\text{Distance Travelled}}\right)$
c	Mean length of a micro-trip	*sec*	$\frac{\sum l_i}{N_l}$
P_{idle}	Time proportions of idling modes	%	Percentage of zero speed
P_{acce}	Time proportions of acceleration modes	%	Percentage of positive speed changes ≥ 0.1 m/s^2
P_{cruise}	Time proportions of cruising modes	%	Percentage of speed changes within ± 0.1 m/s^2, and speed > 5 m/s
P_{dece}	Time proportions of deceleration modes	%	Percentage of negative speed changes ≤ -0.1 m/s^2
P_{creep}	Time proportions of creeping modes	%	Percentage of speed changes within ± 0.1 m/s^2, and speed < 5 m/s
M	Average number of acceleration/deceleration changes (and vice versa) within one micro-trip	*Number of times*	Simply counting the number of acceleration/deceleration changes within a micro-trip

where n_a, n_d = number of acceleration and deceleration; u_i, u_f = starting and ending speed of an acceleration period (m/s)
a_i, d_i = ith acceleration and deceleration rate (m/s/s); v_i = ith speed data (m/s);

N = total number of speed data; N_l = number of micro-trip; N_r = number of positive speed data; l_i = length of the ith micro-trip (s).

Table 4 **Definition of the 13 Assessment Parameters Adopted for Analysis**

	P_{idle} (%)	P_{acce} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	RMS (m/s²)	PKE (m/s²)	a (m/s²)	d (m/s²)	v_1 (km/h)	v_2 (km/h)	C (s)	M ($time$)
Weekdays	27.77	33.39	5.24	32.36	1.24	0.983	0.589	0.838	0.868	24.79	31.19	142.3	70.3
Weekends	20.61	36.60	6.05	35.86	0.88	0.980	0.559	0.841	0.856	35.48	42.30	200.4	103.7
Overall	24.57	34.81	5.62	33.93	1.08	0.980	0.580	0.840	0.860	29.40	35.95	169.0	85.6

Table 5 **Summary Statistics by Day of a Week**

	P_{idle} (%)	P_{acce} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	RMS (m/s²)	PKE (m/s²)	a (m/s²)	d (m/s²)	v_1 (km/h)	v_2 (km/h)	C (s)	M ($time$)
Inter-Districts	12.40	40.08	7.33	39.45	0.75	0.944	0.502	0.802	0.815	44.11	49.17	274.7	147.4
Kln	35.88	28.65	3.69	27.57	1.34	0.975	0.615	0.836	0.870	14.10	21.67	58.2	22.6
HKI	29.44	33.42	4.68	31.60	0.86	1.104	0.706	0.960	1.010	18.49	25.37	112.3	38.9
NT and Island	39.50	27.98	3.89	27.09	1.54	1.043	0.677	0.898	0.920	15.51	25.05	54.6	20.1
Overall	24.57	34.81	5.62	33.93	1.08	0.980	0.580	0.840	0.860	29.40	35.95	169.0	85.6

Table 6 **Summary Statistics by Districts**

	P_{idle} (%)	P_{acce} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	RMS (m/s²)	PKE (m/s²)	a (m/s²)	d (m/s²)	v_1 (km/h)	v_2 (km/h)	C (s)	M ($time$)
AM	31.80	31.84	1.62	30.70	1.14	1.068	0.661	0.931	0.960	15.32	22.40	58.9	21.6
Off Peak (Day)	27.48	33.20	5.59	32.50	1.22	0.966	0.567	0.822	0.842	27.29	34.07	188.6	98.0
Off Peak (Night)	17.50	38.17	6.38	37.25	0.70	0.978	0.554	0.835	0.857	38.47	44.50	190.0	96.6
PM	34.77	30.58	3.86	29.20	1.57	1.014	0.639	0.875	0.911	14.14	21.61	54.4	20.3

Overall	24.57	34.81	5.62	33.93	1.08	0.980	0.580	0.840	0.860	29.40	35.95	169.0	85.6

Table 7 Summary Statistics by Time of a Day

Pattern	Description	Driving Conditions	Characteristics
I(a)	Inter-District	Relatively smoother driving composed of regular urban driving conditions and highway driving conditions.	Average speed: relatively faster Acceleration: less aggressive Idle time: shorter
I(b)	Within a District	Frequent stop-and-go aggressive driving due to congestions and frequent bus stops at urban areas.	Average speed: relative slower Acceleration: more aggressive Idle time: longer
II(a)	Peak	Frequent stop-and-go aggressive driving due to congestions during peak periods.	Average speed: relatively slower Acceleration: more aggressive Idle time: longer
II(b)	Off Peak (Day)	Relatively smoother driving with some stop-and-go situations due to congestions and bus stops.	Average speed: relatively faster Acceleration: less aggressive Idle time: relatively shorter
II(c)	Off Peak (Night)	Much smoother driving with fewer stop-and-go situations due to congestions and bus stops.	Average speed: relatively faster Acceleration: less aggressive Idle time: shorter

Table 8 Identified Bus Driving Patterns in Hong Kong

	P_{idle} (%)	P_{acce} (%)	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*)
Pattern I(a) – Inter-District Driving Cycle													
Synthesized	12.19	40.12	7.43	39.53	0.72	0.953	0.505	0.807	0.818	45.20	51.48	282.3	147.6
Target	12.40	40.08	7.33	39.45	0.74	0.944	0.502	0.802	0.815	44.11	49.17	274.7	147.3
Pattern I(b) – Within a District Driving Cycle													
Synthesized	37.44	29.1	3.73	28.34	1.38	1.025	0.644	0.877	0.897	14.45	23.10	61.15	23.05
Target	37.20	29.31	3.87	28.19	1.43	1.020	0.650	0.876	0.909	14.28	22.38	60.49	22.38

Table 9 Summary Statistics of Driving Cycles for Patterns I(a) and I(b)

	P_{idle} (%)	P_{acce} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	RMS (m/s²)	PKE (m/s²)	a (m/s²)	d (m/s²)	v_1 (km/h)	v_2 (km/h)	C (s)	M ($time$)
Pattern II(a) – Peak Driving Cycle													
Synthesized	33.91	30.54	4.06	30.17	1.42	1.054	0.628	0.909	0.909	14.91	22.53	53.75	21.20
Target	33.73	31.03	4.07	29.76	1.42	1.033	0.647	0.895	0.928	14.56	21.89	55.99	20.75
Pattern II(b) – Off Peak (Day) Driving Cycle													
Synthesized	29.44	32.45	5.11	32.16	1.14	0.964	0.500	0.809	0.817	26.40	37.26	91.71	40.81
Target	27.48	33.20	5.59	32.50	1.22	0.966	0.567	0.822	0.842	27.29	34.07	188.6	98.00
Pattern II(c) – Off Peak (Night) Driving Cycle													
Synthesized	20.87	37.50	5.18	35.71	0.74	1.006	0.556	0.856	0.898	31.32	39.58	106.9	45.67
Target	17.50	38.17	6.38	37.25	0.70	0.978	0.554	0.835	0.857	38.47	44.50	190.0	96.60

Table 10 Summary Statistics of Driving Cycles for Patterns II(a), II(b) and II(c)

International Driving Cycle	v_1 (km/h)	a (m/s^2)	d (m/s^2)	P_{idle} (%)	P_{aece} (%)	P_{cruise} (%)	P_{dece} (%)	P_{creep} (%)	Source
Pattern I(a)	45.2	0.807	0.818	12.2	40.1	7.4	39.5	0.72	This Study
Pattern I(b)	14.45	0.877	0.897	37.4	29.1	3.7	28.3	1.38	This Study
Pattern II(a)	14.91	0.909	0.909	33.9	30.5	4.1	30.2	1.42	This Study
Pattern II(b)	26.4	0.809	0.817	29.4	32.5	5.1	32.2	1.14	This Study
Pattern II(c)	31.32	0.856	0.898	20.9	37.5	5.2	35.7	0.74	This Study
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
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
Kanchanaburi DC	-	-	-	-	52.1	1.8	46.2	-	Mongkonlerdmanee and Koetniyom, 2019
Hanoi Bus DC	17.3	0.480	0.510	5.3	34.5	-	32.4	-	Nguyen, et al., 2016
HBDC 2018	16.8	0.500	0.520	7.6	34.2	14.1	32.7	11.4	Nguyen, et al., 2018
Chennai Bus DC	14.0	0.650	0.710	32.2	29.8	3.5	29.6	4.9	Nesamania and and Subramanian,, 2011
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
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
Shanghai HEB DC	23.0	0.710	0.830	34.0	33.0	5.0	28.0	-	Shen, et al., 2018
Fuzhou Bus DC	13.8	0.740	-	34.4	27.0	15.5	23.1	-	Peng, et al., 2019a
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

Table 11 Comparison of International Bus Driving Cycle Characteristics