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Developing Singapore Driving Cycle for passenger cars to estimate fuel consumption and vehicular emissions

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HIGHLIGHTS

- Lack of a realistic driving cycle to evaluate energy and emissions in road transport.
- Develop a representative driving cycle for passenger cars in Singapore.
- Methodology incorporate multi-levels of representativeness – distance, road type, peak, lull.
- Representativeness characteristics are determined from extensive surveys and data collection.

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ABSTRACT

Singapore has pledged to attain 7–11% Business-As-Usual carbon emissions reduction by 2020. Road transport sector is a significant source of carbon emissions, estimated to be the third largest sector in Singapore. A current gap in environmental evaluation for road transport activities in Singapore is the lack of a representative driving cycle for passenger cars (64% of the total population of 974,170 vehicles). This Singapore Driving Cycle (SDC) is hence developed for Singapore roads and traffic conditions. A chase-car (instrumented vehicle) was used to collect on-road data along 12 designed routes, and circulation driving on highly utilized arterial roads (including those in Central Business District (CBD) and both inner and outer ring roads fringing the CBD area). The SDC was thus hence constructed, with consideration of road type proportions, time periods and desired distance, duration and peak-lull proportion. In essence, the SDC is a 2400-s speed–time profile to represent the driving pattern for passenger car in Singapore. Microscopic estimation model (CMEM) shows that, as compared to SDC, the New European Driving Cycle (NEDC) underestimates most of the vehicular emissions (fuel, CO_2, HC and NO_x by 5%, 5%, 22% and 47%, respectively) and overestimates CO by 8%. The SDC is thus more suitable than the NEDC that is currently in use in Singapore; the SDC can be used to generate more accurate fuel consumption and emissions ratings for various uses (for example, inventory of vehicular emissions and fuel economy labelling).

1. Introduction

1.1. Overview

Ever since the Fifteenth session of the Conference of the Parties (COP-15 in 2009) session held by The United Nations Climate Change Conference till COP-18 (in 2012), Singapore had reiterated her commitment to achieve 7–11% below Business-As-Usual (BAU) carbon emissions by 2020 as unconditional pledge in the absence of a legally binding global agreement (Singapore's National Statement, 2011) and full commitment to a 16% below BAU pledge in presence of a legally binding agreement (Singapore's National Statement, 2012). In Singapore, the top three energy consumers are electricity generation, industry and road transport. However, it is difficult for electricity generation and industry to reduce significantly without affecting the economy. Therefore, road transport is a key area to work towards mitigating climate change. International Energy Agency (IEA) consolidated statistics shows that Singapore road transport sector produced 7.18 million tonnes of CO_2 in 2008 and 8.17 million tonnes of CO_2 in 2009, indicating a 78.3% (Year 2008) and 102.9% (Year 2009) increment from 1990 (International Energy Agency (IEA), 2010; International Energy Agency (IEA), 2011). Currently, Singapore has yet to establish her

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national inventory of greenhouse gases (GHGs) and associated air pollutants from anthropogenic activities such as road transport. In time to come, national inventory will be in place to facilitate downstream applications such as mitigation reduction targets and quantifications. This is also important in terms of air quality – air pollution management.

Passenger car population reached 392,961 in 2000 and increased to 617,570 in 2012, translating to a 57% growth within a 12-year span (Land Transport Authority (LTA), 2013). Passenger car population forms about 64% of the total vehicle population, with an average annual mileage of 19,000 km in 2011 (Land Transport Authority (LTA), 2012). Hence, the passenger car was chosen as the focus vehicle type for evaluating the impact of road transport on the environment. On the other hand, remaining 36% of the vehicles (buses, goods vehicles and motorcycles) are diverse in their classification and trip making patterns. These differences require incorporating minute details in constructing their driving cycles, which in turn, are of lesser urgency than the need of a single driving cycle for the passenger car.

1.2. Motivation: the need to develop Singapore Driving Cycle (SDC)

In Singapore, the driving cycle in use to date for testing in a laboratory setting is the New European Driving Cycle (NEDC). Being a synthesized cycle of artificially jointed mode of operations (cruising, accelerating, decelerating and idling), NEDC is not well representative of the driving conditions in a highly urbanized island-state like Singapore. The lack of a representative local driving cycle is a critical gap that warrants urgent action. It is also clear that driving cycle-related applications such as fuel consumption and vehicular emissions are dependent on the quality of applicable driving cycle. In essence, the use of ill-fitting driving cycles would not allow derivation of accurate estimations. Moreover, estimations should not be based solely on average speeds as in NEDC's case as the proportion of speed changes, accelerations and idling are critical as well. Alongside with vehicular emissions, harmful air pollutants are emitted. The emission inventory is then dependent on the accurate emission rates that are in turn to be derived from a representative driving cycle.

Besides NEDC's inability to characterize the speed changes, it is also not designed to match the modes of operation (percentages of idling, acceleration, deceleration and cruising) as well as maximum and average speeds. The proportions of expressway and arterial roads coverage in a trip will be indigenous to the road network; in Singapore, the road network is concentrated within a small nation of 710 square km, and peak period and lull period characteristics are also quite different. Hence, the NEDC is not well suited for use in Singapore.

In this paper, the authors formulated an unique driving cycle framework covering in-depth study of data collection methods, route selection, cycle construction and data analysis. The results are representative of Singapore's road network and drivers' trip making patterns (trip distance, expressway-to-arterial proportions, peak-to-lull proportions and trip duration). The finalized driving cycle, known as SDC, is presented. Comparisons are also made with the generic driving cycle, NEDC, whereby its unsuitability is highlighted. Estimations of fuel consumption and emissions are also computed via modelling the passenger car population in Singapore.

2. Literature review

2.1. Overview of driving cycle framework

In a broad sense, driving cycles are essentially driving patterns that are synthesized to indicate real-world driving in an average sense. Such synthesized driving cycles are structured as speed–time profiles that constitute snippets of different modes of operations joined up sequentially; these driving cycle constructs are also known as modal driving cycles. Synthesized cycles include the New European Driving Cycle (NEDC) of 69 modes, Japanese driving cycles (10-mode and 15-mode) and California seven-mode cycle (Montazeri-Gh and Naghizadeh, 2003; Kamble et al., 2009; Lee et al., 2010). Real-world driving cycles are derived from actual trip data on the roads. Various real-world driving cycles in use are ARTEMIS European driving cycles, Urban Emissions Drive Cycles (UEDC), Bangkok Driving Cycle, Hong Kong Driving Cycle, Kaohsiung Driving Cycle, Athens Driving Cycle, FTP-75 Driving Cycle, LA92 Driving Cycle, SC03 and US06 driving cycles (Brown et al., 1999; Tong et al., 1999; Montazeri-Gh and Naghizadeh, 2003; Tsai et al., 2005; Karavalakis et al., 2007).

2.2. Data collection

From literature survey, data collection can be categorized into three methods, namely (1) chase-car method (instrumented car to collect data as it follows randomly selected vehicles); (2) on-board measurement methods (instruments installed in subject vehicles to collect their trip activities); and (3) combined method of chase-car, on-board measurement and circulation driving (instrumented car driven during the lull and peak periods on pre-selected routes) (Niemeier et al., 1999; Tong and Hung, 2010; Zhang et al., 2012).

The chase-car method involves a random selection of a target vehicle in the traffic stream and the chase-car follows this target vehicle and keeps a constant distance during cruise conditions and allowing a time lag for both acceleration and deceleration phases (Kent et al., 1977). Real-world driving cycles derived directly from the chase-car method includes Bangkok Driving Cycle (BDC), Hong Kong Driving Cycle (HKDC), Edinburgh Driving Cycle (EDC), Sydney Driving Cycle and Pune Driving Cycle. The Bangkok Driving Cycle was constructed using data collected during peak periods via a chase-car equipped with data logger capturing speed–time profiles, similarly for the case of the Hong Kong Driving Cycle which also included instrumented vehicles' records (Tong et al., 1999; Hung et al., 2007; Tamsanya et al., 2009). In the United States, chase-car data have been widely used to derive driving cycles (Morey et al., 2000; Lin and Niemeier, 2003b). Unified Cycle (LA92 Driving Cycle) was developed using chase-car data comprising 102 runs with second-by-second speed data (Lin and Niemeier, 2002). In Europe, several studies have used the chase-car technique as well (Esteves-Booth et al., 2001).

On-board measurement technique is considered as instrumented vehicle. The instrumented technique is often coupled with chase-car method, as seen in driving cycles developed in South Korea, Delhi and Malaysia. The South Korean driving cycle in a military area was developed using both methods to enable capturing hard accelerations and decelerations as military routes involved unpaved surfaces. Global Positioning System (GPS) data were the basis of the vehicle speed (Dong et al., 2012). On the other hand, Dublin driving cycle was developed from data collected via on-board diagnostic reader (OBD II) that extracts vehicle data including OBD speed, engine speed, coolant temperature and engine load during the recorded runs conducted over a period of 3 days whereas Delhi instrumented vehicles made four runs per day for six days a week (Achour et al., 2011; Chugh et al., 2012). The ARTEMIS European driving cycles were developed with a fleet of 58 instrumented vehicles with 73,000 km covered in a total of 1400 days (André, 2004). The Australian urban emissions drive cycles (UEDC) were developed using the on-board measurement for diesel-powered vehicles (Brown et al., 1999).

2.3. Route selection

Many studies adopted the practice of selecting 5–12 routes for specific vehicle type (Kent et al., 1977; Tong et al., 2011). In a Vietnam case study, 10 routes were used for developing a motorcycle's drive cycle. Other case studies had employed the use of traffic flow models with traffic data obtained from transport authorities to select the suitable routes, for example 7 routes were chosen in the Bangkok Driving Cycle study (Tamsanya et al., 2009). Some driving cycles were developed from routes chosen to provide adequate coverage on land uses, road type and driving conditions as seen in Sydney, Perth, Melbourne and Hong Kong (Kent et al., 1977; Watson et al., 1982; Kenworthy et al., 1983; Hung et al., 2007). South Korea military driving cycle was based on eight representative military routes and 11 h of data were collected for both lull and peak periods (Dong et al., 2012).

Many driving cycles utilized routes taken for home-to-work and work-to-home trips as these form a substantial portion of daily trips. Such driving cycles included Dublin Driving Cycle (conducted during morning and evening peak periods and a night time lull period on two main routes on two major roads), Edinburgh Driving Cycle (6 pre-defined routes were used for data collection for 3 peak periods and a lull period at night time to simulate congested traffic conditions and free flow traffic conditions), and Delhi Driving Cycle (with consideration of traffic density and land use pattern) (Esteves-Booth et al., 2001; Tong and Hung, 2010; Achour et al., 2011; Chugh et al., 2012). Using the traffic flow model, traffic speed determined the route selection in the case of Bangkok driving cycle which achieved realistic on-road traffic conditions (Tamsanya and Chungpaibulpatana, 2009).

2.4. Stratification of driving cycles

The driving cycle is developed according to specific vehicle type determined the usage of different road types in the infrastructure network is determined subsequently. Driving cycles developed for passenger car includes the Dublin Driving Cycle, ARTEMIS European driving cycles and Delhi Driving Cycle (André, 2004; Achour et al., 2011; Chugh et al., 2012). Driving cycles for motorcycle and bus include the Vietnam Driving Cycle and Seoul City Bus Driving Cycle (Tong et al., 2011; Wi et al., 2009). Many Chinese cities also utilized the chase-car method for data collection with road classifications of three types, namely freeways, arterial and residential roads for both lull and peak periods (Wang et al., 2008). Driving cycles for motorcycle in urban and rural areas were also developed with the motorcycle-to-motorcycle chase method (Chen et al., 2003). Sydney Driving Cycle was developed with data collection during the morning peak periods whereas Pune Driving Cycle was developed from the database collected during peak and off-peak periods (Kent et al., 1977; Kamble et al., 2009).

2.5. Cycle construction and data analysis

Two major approaches – matching and simulation, are used by most studies. Matching approach can be applied to driving data (microtrips or driving segments) with the target statistics using random selection while simulation approach can be applied to produce a speed–time profile (Tong and Hung, 2010). Many driving cycles are developed using the random method of combining a number of periods or microtrips and an iterative process is then conducted to determine the most representative cycle (Kent et al., 1977; Tsai et al., 2005; Hung et al., 2007; Kamble et al., 2009; Tamsanya et al., 2009; Khumla et al., 2010; Tong et al., 2011). Microtrip is defined as the speed–time profile between two consecutive idling periods, whereby the start and end are at zero speeds. One widely used method is combining a series of microtrips (or a random selection) that best represents the total data set of raw trip records. The resultant driving cycle is established based on a set of pre-defined assessment measures (Hung et al., 2007; Zhang et al., 2012). Another approach is minimization of the original pool of microtrips via clustering technique to gather the representative microtrips which are then randomly selected to form the driving cycle as evaluated by the assessment measures (Chugh et al., 2012).

Driving cycles in Hong Kong and Chinese cities were constructed via the random approach combined with a 20-min duration and absolute differences of each target assessment measure to be within 5% (for Hong Kong); and with 900–1200 s duration and absolute difference of each assessment measure being within 5% (for China) (Hung et al., 2007; Wang et al., 2008). Driving cycles in Delhi and Pune used data reduction technique to derive representative microtrips for constructing the driving cycles (Kamble et al., 2009; Chugh et al., 2012).

Apart from microtrip construction, other construction techniques include kinematic sequences (similar to microtrips), segment-based according to road types or level of service and mode-based. The Unified Cycle (LA92 Driving Cycle) was developed using the 'quasi-random' selection of microtrips coupled with an improvement to match the sample Speed Acceleration Frequency Distribution (SAFD) as opposed to the LA01 Driving Cycle, which was constructed via stochastic approach (Monte Carlo simulation and Markov process theory) (Lin and Niemeier, 2002). Dai et al. (2008) processed the driving data into mode sequences and subsequently generated the arterial cycles (according to speed bands) via the Markov Chain process. This method was also used by Lin and Niemeier (2003a) via Markov process theory and maximum likelihood estimation (MLE) partitioning algorithm to separate into different operating mode sequence (e.g. idling, acceleration, deceleration and cruising). Markov Chain model and the use of transition probability matrix are used to generate driving cycles (Gong et al., 2011; Bishop et al., 2012).

Data analysis includes assessment measures (distance, speed, acceleration, time and proportion based) for cycle selection alongside speed–acceleration frequency matrix (SAM) or speed–acceleration frequency distribution (SAFD). In some studies, cluster analyse are adopted to categorize microtrips into different road types (Dembski et al., 2002; Tong and Hung, 2010; Chugh et al., 2012).

The majority of construction techniques and methodologies used the random approach, with further iterations to obtain the desired driving cycle. The random approach often entails incorporation of a pre-determined number of microtrips (for example, 10 microtrips) or a pre-determined duration of more than 1000 s without rational scientific justification which is a shortcoming in the methodology. The random approach can be performed with or without data reduction of the total data set. The resultant driving cycle is a combination of randomly selected microtrips separated by idling periods.

3. The proposed methodology

3.1. Data collection

The choice of data collection methods (chase-car, instrumented vehicle with on-board measurement and hybrid method of the chase-car, instrumented vehicle and circulation driving) is based on suitability and appropriateness for the driving environment. Key considerations are data types and quality. In terms of data quality, on-board diagnostics (OBD II) derived data are of greater accuracy, hence, superior as compared to GPS derived speed data. In most

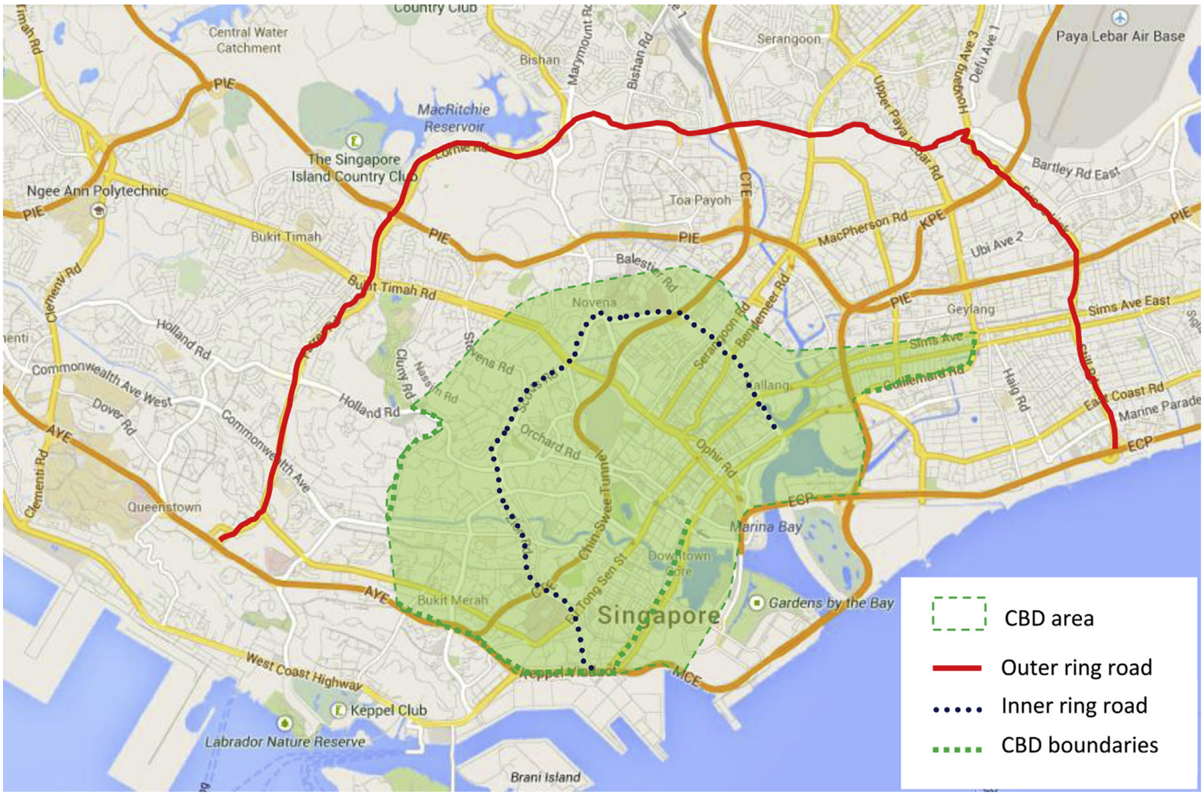

Fig. 1. Inner ring and outer ring road (red outline) systems in Singapore for circulation driving runs (base map adapted from google map). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cases, GPS data have been obtained for speed–time profiles. However, there are many problems with GPS derived speed data which include loss of signal, stuck speeds and false zero speeds, and correction or filtering are required to process the GPS data. In this study, a combined approach was used – the chase-car method and instrumented vehicle employed in circulation driving. The data logger is attached via the OBD II port and data (second-by-second resolution) are downloaded via Bluetooth signal using an android handphone. The use of GPS data in this study was limited to identification of road types during data analysis.

3.2. Route selection

Route selections are more relevant for chase-car and instrumented car (coupled with circulation driving) but inappropriate for instrumented vehicles alone as the latter vehicles travel along routes dictated by vehicle owners. A key issue is to ensure routes of high utilization are included. Other factors such as traffic density and land use pattern were considered in route selection. Traffic density was assessed through the online website to monitor the traffic speeds along major expressways during both lull and peak periods. Real-time traffic data are interpreted via online website as illustrated with traffic traces of colour-coded speed bands for the road network. These speed data are provided by the Land Transport Authority via the Traffic Smart application. Highly utilized pathways can be observed and routings based on shortest distances and durations were deliberated via routing enquiries on the Google map. Land use pattern was assessed through a good interpretation of the Singapore map available from the Google map, Singapore Land Authority (SLA) and Urban Redevelopment Authority (URA) sources. Surveys were also conducted via interviews and mail-back envelopes. Fieldwork was conducted at certain stretches on the expressway to verify and validate routes of high utilization. From surveys, it is found that over 60% of the trip purposes were based on home-to-work and vice versa. It is important to ensure data are collected on routes that are representative of network-wide conditions instead of any few particular routes or a single road type or time period. However, it is an infeasible task to collect on-road driving data on all road networks; hence, route selection involves identification of highly utilized routes. The practical solution is to select a number of routes that are most representative of the traffic conditions in the city. Drive routes were pre-determined with consideration of both traffic activity (origin-destination travel patterns) and traffic characteristics in terms of speed profiles and travel times.

Both morning and evening peak periods during weekdays are the periods with highest traffic flows being experienced on most expressways and major roads. Morning peak periods (typically 0730H till 0930H, as observed on live traffic feeds via the online websites – Onemotoring and Google map) and evening peak periods (typically 1700H/1730H till 2000H, as observed via online monitoring and fieldwork sites monitoring) are used for data collection. Data were also collected for lull periods (outside of the peak periods on weekdays and the whole of weekends) so as to include a more complete picture in the driving cycle development.

Twelve key routes were designed, with four starting from the centroids of the eastern, western, northern and southern Central Business District (CBD) areas to end at the centroids of the eastern, western, northern and southern regions respectively. Major arterial roads were also included in the data collection activities. As discussed with a local land transport expert, arterial roads in the Central Business District (CBD) are roads of interest in terms of transport management. The inner ring and outer ring road systems are also taken into consideration, as shown in Fig. 1. The outer ring road is a network of major roads forming a partial ring along the city's exteriors; it is a complementary route for motorists to travel between the east and west and vice versa without going into the city. Collecting data on these major roads is important as considerable traffic flows take place on these roads on a daily basis. Instrumented vehicle was used to perform circulation driving on the ring roads and CBD roads.

The island was partitioned into four sectors, namely Eastern sector, Western sector, Northern sector and the Southern sector. The chosen routes were derived from the origin-destination pairs among these four sectors. Primary route was detailed in solid line, with alternative routes in dash and dotted lines, as shown in Fig. 2. Due to the compact size of the island and its high population density, there are various routes via different expressways for the same origin-destination pair. As observed, the network of 9 expressways is well inter-connected to allow transits across each other. In essence, the same stretch on any expressway can be utilized for numerous origin-destination pairs.

3.3. Stratification (road type and time period)

The driving cycle was set to be developed for the passenger car in an urban city, as the passenger car represents 64% of the total vehicle population. The road types involved in the route selection include all road types under the two main categories of expressway and arterial roads. Unlike other vehicle types such as public bus (restricted to bus routes such as purely arterial roads in trunk service) or heavy goods vehicle (restricted use of expressway travelling), the passenger car utilizes all road types during travelling. In addition, passenger car (private vehicle) is used extensively in both peak period (weekday morning and evening hours) and lull period (weekday periods excluding peak and weekends). In order to develop a representative driving cycle, the data collection has to entail stratifications of road types and time periods that depict closely the driving activities of the passenger car.

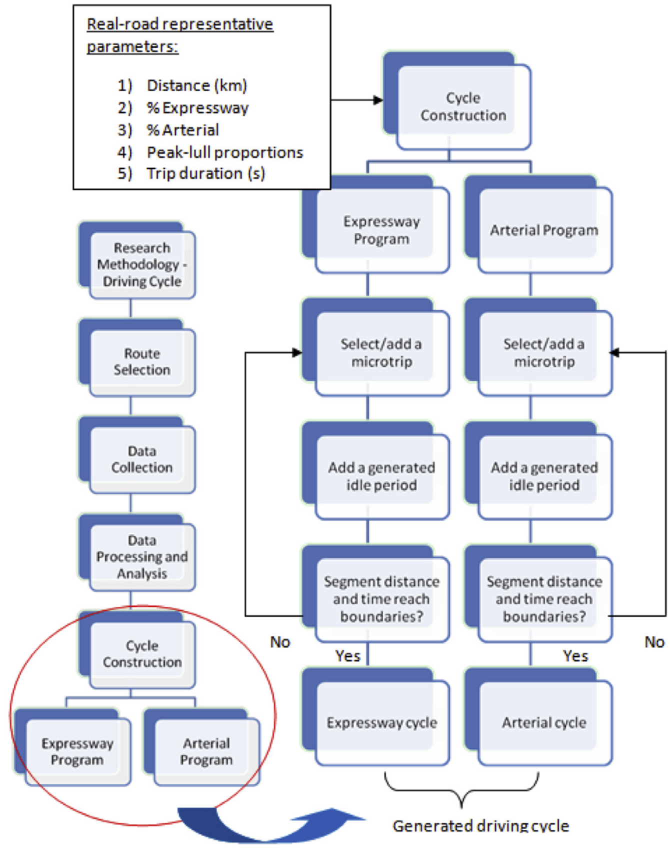

Fig. 3. Overall process flow of driving cycle development and detailed cycle construction flow.

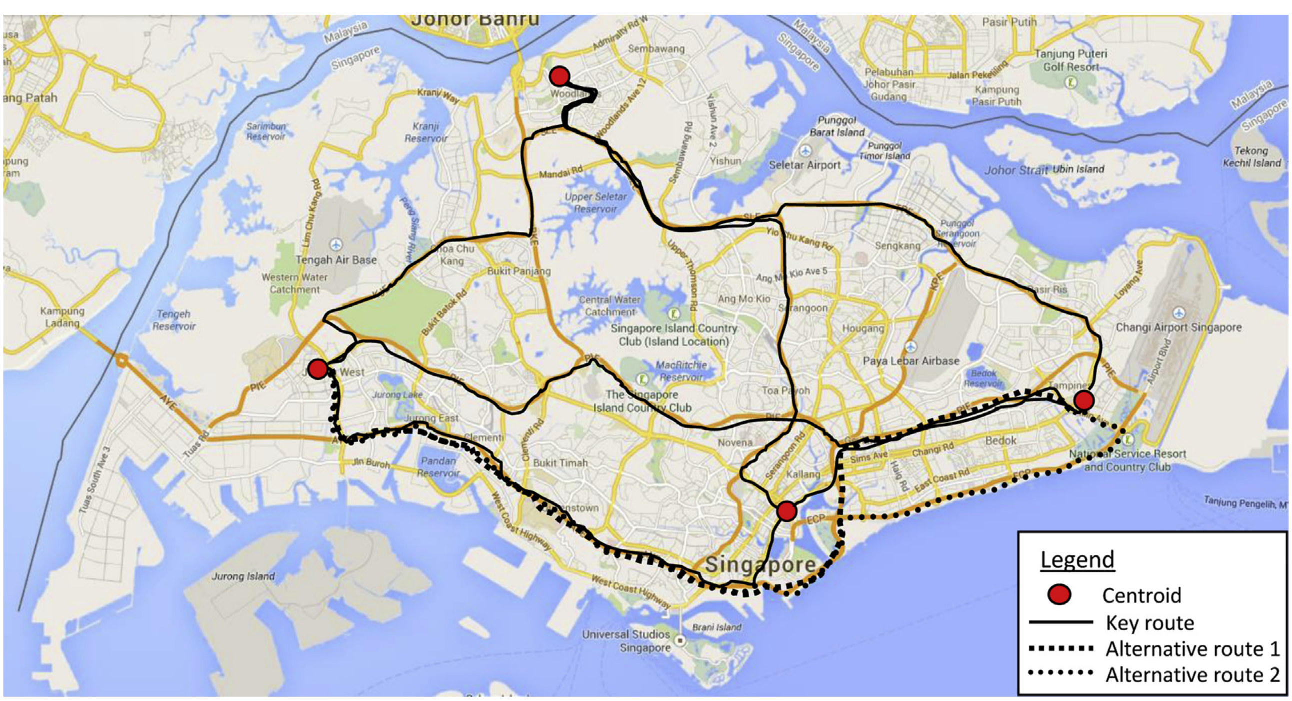

Fig. 2. Chosen routes for chase-car (12 key routes of West-East, West-North, West-South/CBD, North-East, North-South, East-South and vice versa and alternative routes of West-East in dashed and dotted lines); (base map adapted from google map).

3.4. Cycle construction and data analysis

The cycle construction method proposed in this study is different from existing ones in the following ways. First of all, road types and time periods are clearly identified for every microtrip without the need of estimation via cluster analysis as seen in other studies. This is done by matching the global positioning system (GPS) coordinates with the timestamps of collected data on map during the post processing to segregate the data according to different road types and peak/lull period. Next, a new/unique framework is established to construct a representative driving cycle for Singapore. It involves evaluation of the typical trip's (1) Distance, (2) Proportion of expressway driving, (3) Proportion of arterial roads driving, (4) Peak and lull proportions, and (5) Trip duration to tailor the construction process (see Section 4.2). These five factors set the constraints/boundaries for the driving cycle to maximise the representativeness of local driving (instead of being representative of total data set). A semi-random approach is taken on selecting the microtrips from the road type and timings by classified categories. The idle period is derived as an average duration according to the road types and time periods. Iterations are performed till convergence of within 10% is achieved for the assessment criteria. The resultant driving cycle is then selected from the pool of candidate driving cycles. The overall construction process flow and the detailed cycle construction flow are shown in Fig. 3. The resultant driving cycle comprises clearly defined arterial segments (peak and lull) and expressway (peak and lull).

The selection of assessment criteria are shortlisted from the following driving parameters (Tong et al., 1999; Kamble et al., 2009; Tong and Hung, 2010; Zhang et al., 2012):

1. Average speed of the entire trip
2. Average running speed
3. Average acceleration of all acceleration phases
4. Average deceleration of all deceleration phases
5. Average micro-trip duration
6. Mean duration of a driving trip
7. Percentage of driving mode = Idling
8. Percentage of driving mode = Cruising
9. Percentage of driving mode = Acceleration
10. Percentage of driving mode = Deceleration
11. Percentage of driving mode = Creeping
12. Average number of stops per kilometre
13. Average number of acceleration–deceleration changes
14. Average root square acceleration
15. Positive acceleration kinetic energy
16. Maximum speed
17. Maximum acceleration
18. Minimum acceleration
19. Maximum deceleration
20. Minimum deceleration

3.5. Modelling for fuel consumption and emissions

Comprehensive Modal Emission Model (CMEM), a microscopic emission model, is developed with funding support from USEPA and National Cooperative Highway Research Program (NCHRP). CMEM estimates emissions for passenger cars, light duty vehicles and heavy duty vehicles and is used in this study. It utilises the power-demand method to derive the fuel consumption and emissions prediction. Tailpipe emissions estimation is obtained second-by-second.

Road transport fuel consumption and emissions are significant in building up accurate inventory of greenhouse gases (GHGs) and air pollutants. Using a top-down approach of inventory-building, emission factors are fundamental and the degree of accuracy is important. Accurate emission factors can only be derived from representative driving cycle, hence, the importance of establishing the real-world driving cycle for downstream applications should be greatly emphasised.

4. Results and discussions

4.1. Overview

Singapore Driving Cycle comprises both expressway and arterial segments. The expressway microtrips are collected from 9 expressways spanning across the city. As for the arterial microtrips, they are sub-classified into 4 groups, namely (1) urban, (2) CBD, (3) Outer ring road, and (4) Inner ring road. Majority of the arterial segments are the urban microtrips as these microtrips predominantly occurred at the start and end of a trip. CBD sub-category is necessary as high traffic volumes are experienced in the city centre. This outer ring road serves as a 'semi-expressway' to provide routing alternatives, hence, is considered as part of the arterial roads system. Lastly, the inner ring road serves to divert traffic away from the city centre to the respective expressways for different regions on the island. Table 1 summarises the descriptive statistics for the total data set. The equations used in data analysis and generation of the driving cycle comprise the following:

1. $$S\left(\frac{\text{km}}{\text{h}}\right) = \text{Dm}(\text{km}) \div t\left(\text{h}\right) \tag{1}$$

2. $$\text{FE}(\text{km/liter}) = \text{Dm}(\text{km}) \div \text{F}(\text{liter}) \tag{2}$$

3. $$\text{FC}(\text{liter/100 km}) = 100\ \text{km} \div \text{FE}(\text{km/l}) \tag{3}$$

4. $$\text{AS}\left(\frac{\text{km}}{\text{h}}\right) = \sum_{i=1}^{n}(S_i \cdot t_i) \div \sum_{i=1}^{n}(t_i) \tag{4}$$

where S is the average speed of a microtrip, Dm is the distance travelled in a microtrip, t is the microtrip duration (whilst moving), FE is fuel economy, F is fuel used in a microtrip, FC is fuel consumption, AS is average speed (weighted average based on time) in accordance to road types and time periods, S_i = Speed and t_i = Microtrip i duration (whilst moving).

4.2. Real-road representative parameters and assessment measures

Real-world representative parameters are evaluated via a series of surveys conducted over a period of more than 2 years by the team. The team also leveraged on the database of an external online survey on expressway-arterial proportions ($n = 904$). Trip distance parameter was set at 21.5 km after a vigorous evaluation of trip distance via surveys carried out through face-to-face interviews, mail-back replies and routes simulation ($n = 653$ without simulated routes; and $n^* = 1498$ with simulated routes; simulated

Table 1
Descriptive statistics of data collected.

Road types (microtrips)		Total duration (hours)	Total distance (km)
Expressway		26.7	1646.6
Arterial	Urban	9.1	308.8
	CBD	2.6	96.8
	Outer ring	2.2	120.3
	Inner ring	1.9	64.8

routes in the designed survey are trips generated from home-to-work and work-to-home using the land use plan for origin–destination pairs based on residential–industrial/commercial estates). Expressway and arterial proportions parameters were investigated and found to be 54% and 46% via surveys carried out through face-to-face interviews, mail-back replies, online platform and route simulation (n = 1232 without simulated routes; and n^* = 2077 with simulated routes). Peak-lull proportion parameters were estimated to be approximately 60%–40% based on survey data from a sample of 2519 households. Trip duration parameter was found to be 2400 s or 40 min based on a sample size of 296 respondents; this parameter was not used within the construction flow as it was a verification step to check that the selected candidate cycle conformed with the overall real-road representativeness of local driving patterns.

Candidate cycles (acceptable cycles) comprising 4 segments were constructed – expressway peak, expressway-lull, arterial peak and arterial lull, as per the intention to provide a high degree of representativeness in a more reliable manner. Assessment measures selected for cycle selection among candidate cycles (acceptable cycles) as suitable for analysis with microtrips partitioning (according to road types and time periods) are as follows:

1. Average running speed, V
2. Average acceleration of all acceleration phases, A
3. Average deceleration of all deceleration phases, D
4. Percentage of driving mode = Cruising, Pc
5. Percentage of driving mode = Acceleration, Pa
6. Percentage of driving mode = Deceleration, Pd

The equations of the assessment measures (per road type and corresponding time period sub-category) are as defined:

1. $$V(\mathrm{km/h}) = \text{Trip Distance}(\mathrm{km}) \div \text{Microtrips duration}(\mathrm{s}) \times 3600\left(\frac{\mathrm{s}}{\mathrm{h}}\right) \tag{5}$$

2. $$A\left(\mathrm{m}/\mathrm{s}^2\right) = \frac{1}{n}\sum_{i=1}^{n} A_i \tag{6}$$

3. $$D\left(\mathrm{m}/\mathrm{s}^2\right) = \frac{1}{n}\sum_{i=1}^{n} D_i \tag{7}$$

4. $$T_{i,c} = T_i - T_{i,a} - T_{i,d} = \sum_{k=1}^{n}\begin{cases} t_{k+1} - t_k, -0.28\,\mathrm{m/s/s} \le A_k, \text{acceleration} \le 0.28\,\mathrm{m/s/s} \\ 0, \text{otherwise} \end{cases} \tag{8}$$

5. $$T_{i,a} = T_i - T_{i,c} - T_{i,d} = \sum_{k=1}^{n}\begin{cases} t_{k+1} - t_k, A_k, \text{acceleration} > 0.28\ \mathrm{m/s/s} \\ 0,\ \text{otherwise} \end{cases} \tag{9}$$

6. $$T_{i,d} = T_i - T_{i,a} - T_{i,c} = \sum_{k=1}^{n}\begin{cases} t_{k+1} - t_k, A_k, \text{acceleration} < -0.28\ \mathrm{m/s/s} \\ 0,\ \text{otherwise} \end{cases} \tag{10}$$

7. $$P_{i,c} = \frac{T_{i,c}}{T_i} \tag{11}$$

8. $$P_{i,a} = \frac{T_{i,a}}{T_i} \tag{12}$$

9. $$P_{i,d} = \frac{T_{i,d}}{T_i} \tag{13}$$

10. $$\text{Average microtrip duration} = \frac{1}{n}\sum_{i=1}^{n} T_i \tag{14}$$

where A_i = positive acceleration = $(v_t - v_{t-1})/1$ and $A_i > 0\ \mathrm{m/s^2}$; D_i = negative acceleration = $(v_t - v_{t-1})/1$ and $D_i < 0\ \mathrm{m/s^2}$ for all i = 1, 2, 3, …, n and v_t = instantaneous speed at time t; i represents individual microtrip and i = 1, 2, 3, …, n; T_i = trip time (whilst moving) for individual microtrip i and i = 1, 2, 3, …, n; and t_{k+1} and t_k are time increments in a microtrip.

4.3. Singapore Driving Cycle (SDC)

Selection of the candidate cycles (4 segments) are based on two levels of qualification. The first level of qualification is dependent on the three percentage measures (Pc, Pa and Pd) which have to meet the criterion of absolute difference within 10% from the target values. The second level of qualification is dependent on the three average measures (V, A and D). Target values were computed for total data set as per road type and time period, as shown in Table 2. The remaining measures which were omitted are evaluated and found to be impractical in this driving cycle construction methodology, for example, averages of maximum speed/acceleration/deceleration. The average idle periods are found to be 10 and 8 s on expressway (peak and lull, respectively), and 30 and 27 s on arterial roads (peak and lull, respectively).

The resultant cycle duration is 2344 s (approximately 39.1 min). In comparison to the desired trip duration of 2400 s, the resultant duration differs by 2.3% from the overall target. The candidate cycles are constructed from real-road representative parameters of trip distance, expressway-to-arterial proportions and peak-to-lull proportions. The trip duration parameter serves as a terminating step to ensure conformity in overall representativeness. Hence, the resultant cycle is accepted as the Singapore Driving Cycle (SDC), as

Table 2
Assessment measures of resultant segments for cycle selection.

	V (km/h)	A (m/s^2)	D (m/s^2)	Pc	Pa	Pd
Exp Peak Seg	50	0.58	−0.62	36%	34%	30%
Target	45	0.56	−0.60	36%	34%	31%
Abs Diff	9%	4%	4%	0%	2%	2%
Exp Lull Seg	50	0.52	−0.54	33%	35%	33%
Target	50	0.54	−0.59	36%	33%	30%
Abs Diff	0%	3%	8%	10%~	4%	8%
Art Peak Seg	32	0.90	−0.93	28%	38%	35%
Target	33	0.83	−0.87	29%	37%	34%
Abs Diff	1%	8%	6%	2%	1%	4%
Art Lull Seg	36	0.77	−0.83	28%	39%	33%
Target	38	0.73	−0.81	31%	37%	33%
Abs Diff	5%	6%	3%	8%	5%	2%

Notes: ~ refers to slight relaxation of 10% criteria to 10.2% (despite generation of more than 100 segments for selection) as this is largely due to the elimination of bias in microtrips selection with the use of microtrip shortening; Exp – Expressway; Seg – Segment; and Abs Diff – Absolute Difference.

shown in Fig. 3. It is found that creeping occurred for the expressway during peak period. In SDC, Pc of microtrips are in the range of 33–76% (expressway) and 18–50% (arterial); Pa of microtrips are in the range of 18–35% (expressway) and 17–45% (arterial); and Pd of microtips are in the range of 6–33% (expressway) and 26–41% (arterial).

4.4. Comparisons with NEDC

NEDC is the driving cycle in use at the present time for vehicle certification purposes in Singapore. However, the NEDC is not designed for estimations of downstream applications such as fuel consumption and emissions. This can lead to unreliable results in building up a national inventory for greenhouse gases and other air pollutants. The SDC gives a more realistic portrayal of real-world driving conditions. Tables 3 and 4 show summarized findings of the comparison of SDC and NEDC in terms of speed, mode proportions, distance, time and stops. NEDC is presented in Fig. 4. Incompatible features of NEDC for application in Singapore are as follows:

1. Maximum speed of 120 km/h (above speed limit of 90 km/h) on most expressways
2. Proportion of mode – idling and acceleration deviated by ±5.5%
3. Proportion of mode – deceleration and cruise deviated by ±10.9%
4. Distance of 10.93 km – an underestimate in per trip distance for local drivers by 50%
5. Approximately 10% difference for both arterial and expressway proportions between NEDC and SDC (for example, expressway proportion is higher in NEDC)
6. No peak and lull proportions being integrated
7. Short duration of 1180 s, half of the typical travel time for local drivers
8. Number of intermediate stops = 12, significantly fewer than observed locally

4.5. Cycle verification with SAFDs

Verification of the selected cycle is an essential step to assess the suitability and representativeness of the developed driving cycle. The majority of driving cycles were developed using 5%–10% as acceptable range of differences when compared to the total data set assessment measures.

In this study, cycle verification is partially established via the assessment measures embedded in the driving cycle construction flow. In addition, these measures are sub-categorised as road types and time periods to generate the candidate cycles consisting 4 segments. A key point of this study is the inclusion of very long-distance microtrips. The important step (for this development methodology) that is not mentioned in almost all the methodologies is the treatment of long-distance microtrips that can occur during lull periods on expressways. These long-distance microtrips are often characterised by smooth and higher speeds, which can be intentionally left out during the construction process due to the algorithm of setting the desired duration. This inherently leads to bias that omits lull periods totally, especially for the expressway environment. For the peak segment (expressway), roughly 40% of the microtrips exceed the target distance of 7.0 km. For the lull segment (expressway), approximately two thirds of the microtrips exceed the target distance of 4.6 km. In order to remove the bias,

Table 4
Comparison table of SDC with NEDC – distance, time and stops.

Driving cycle	Length (km)	Arterial/urban distance (km)	Highway/ expressway distance (km)	Duration (s)	No. of intermediate stops
SDC	21.50	9.89 (46.0%*)	11.61 (54.0%*)	2344	20
NEDC	10.93	3.98 (36.8%*)	6.95 (63.2%*)	1180	12

Notes: * refers to the proportioning of the driving cycle's distance according to arterial and expressway.

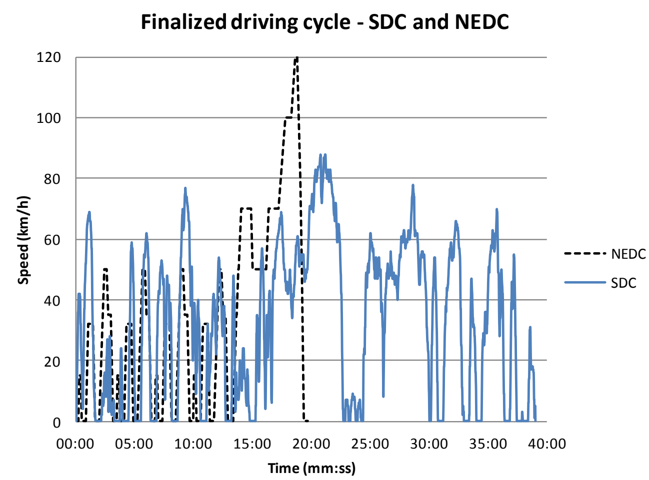

Fig. 4. Finalised driving cycle – Singapore Driving Cycle (SDC) and NEDC.

Table 3
Comparison table of SDC with NEDC – speeds and mode proportions.

Driving cycle	Maximum speed (km/h)	Average speed (km/h)	Pi, % of driving mode = idling	Pa, % of driving mode = acceleration	Pd, % of driving mode = deceleration	Pc, % of driving mode = cruising
SDC	88.0	32.8 (33.2*)	20.6	28.5 (36.3~)	25.3 (32.9~)	25.7 (30.8~)
SDC[1]	88.0	49.7	NA	(34.4~)	(31.2~)	(34.5~)
SDC[2]	77.0	33.7	NA	(38.0~)	(34.3~)	(27.7~)
NEDC	120.0	33.4 (33.4*)	24.8	23.0 (30.6~)	15.8 (21.0~)	36.4 (48.5~)
NEDC[3]	120.0	69.4 (62.6~)	NA	(31.9~)	(26.8~)	(41.3~)
NEDC[4]	50.0	27.2 (18.8~)	NA	(28.7~)	(11.7~)	(51.6~)

Notes: 1/2 refer to SDC peak and lull segments on the expressway and arterial road, respectively; 3/4 refer to NEDC segments on the expressway (extra urban cycle) and arterial road (ECE urban cycle), respectively; * refer to obtaining speed value based on Total Distance/Total Time; ~ refers to proportion between 3 modes – accelerating, decelerating and cruising (exclude idling).

Table 5
CMEM pollutant emissions for SDC and NEDC.

Vehicle type	SDC					NEDC				
	Fuel (g)	CO_2 (g)	CO (g)	HC (g)	NO_x (g)	Fuel (g)	CO_2 (g)	CO (g)	HC (g)	NO_x (g)
Vehicle 1	1383.280	4287.099	58.453	2.729	15.487	693.289	2135.846	37.778	1.222	6.227
Vehicle 2	1502.962	4747.204	12.083	0.570	2.306	734.532	2321.019	5.412	0.223	0.619
Vehicle 3	1444.332	4564.705	9.984	0.431	3.839	700.440	2215.734	3.639	0.169	0.900
Vehicle 4	1551.174	4895.056	15.199	0.536	2.085	743.152	2346.772	6.439	0.182	0.507
Overall average	**1470.437**	**4623.516**	**23.930**	**1.067**	**5.929**	**717.853**	**2254.843**	**13.317**	**0.449**	**2.063**

further data processing is required for the expressway microtrips prior to generation of candidate cycles. Hence, data shortening is performed to reduce the long microtrips. This was done by removing some distance from the middle portion of long microtrips.

A designed drive (catering to 7.0 km and 4.6 km microtrip distance) on all 9 expressways is planned and executed for the purpose of data verification for the 'shortened' microtrips. Using the chase-car method, the drive involved exiting the expressways at suitable intervals to meet the target distances used in the driving cycle construction flow. The results shows absolute differences between Pc, Pa and Pd of the expressway-lull (with shortened microtrips) and designed drive are within 3%, 3% and 6%, respectively. Hence, use of microtrips shortening is a feasible tool to avoid bias in microtrip addition in cycle construction.

The finalised driving cycle is also verified by comparing the SAFD of the derived driving cycle with the observed SAFD. The SDC's SAFDs and the observed SAFDs are normalized for comparison. It is found that absolute differences between the SAFDs are small. The statistics for the expressway segment are: maximum difference = 5.99%, minimum difference = 0.00%, averaged difference = 0.16%, 15-percentile = 0.00%, 50-percentile = 0.01%, 85-percentile = 0.20%, 90-percentile = 0.34% and 95-percentile = 0.84%. The statistics for the arterial segment are: maximum difference = 1.09%, minimum difference = 0.00%, averaged difference = 0.07%, 15-percentile = 0.00%, 50-percentile = 0.01%, 85-percentile = 0.17%, 90-percentile = 0.22% and 95-percentile = 0.39%. Large deviations are not detected.

4.6. Estimation of passenger cars' fuel consumption and emissions

Estimation of the passenger car population was carried out using CMEM (microscopic model. SDC and NEDC were used as the speed profiles for comparison for 4 vehicle types (applicable level of technology in Singapore passenger cars). The pollutant emissions and the corresponding emission factors are presented in Table 5. Using the overall average emission factors to represent the passenger cars in Singapore, it is found that relative to SDC, NEDC underestimates fuel, CO_2, HC and NO_x by 5%, 5%, 22% and 47% respectively and overestimates CO by 8%.

5. Conclusions

This study developed a representative driving cycle for passenger car in Singapore, hence, bridging the gap of the lack of representativeness of the current driving cycle in use for testing. This Singapore Driving Cycle (SDC) will allow downstream applications (energy and emissions quantification; national inventories of greenhouse gases and air pollutants) to be established in a more realistic manner. A direct application will be the fuel consumption and emissions values shown on fuel economy label for new cars in the showroom.

The driving cycle construction framework contributes gainfully towards development of a highly representative driving cycle for passenger cars in Singapore, a feature that is not observed in other studies. It utilizes the 5 levels of representativeness in (1) Distance (21.5 km, $n = 653$), (2) % expressway (54%, $n = 1232$), (3) % arterial (46%, $n = 1232$), (4) Peak-lull proportions (60%–40%, $n = 54{,}267$), and (5) Trip duration (2400 s, $n = 296$). Selection among the candidate cycles were based on primarily 6 assessment measures, split into 2 levels, where level 1 is represented by the time related measures (Pc, Pa and Pd) and level 2 is represented by the speed and acceleration related measures (V, A and D). The finalized driving cycle – Singapore Driving Cycle (2344 s) shows conformity with the trip duration parameter of 2400 s. A high level of representativeness is achieved in the development methodology and framework which will give rise to greater realism in downstream applications of inventory-building concerning carbon emissions and air pollutants from road transport.

It is found that both the average speeds of SDC and NEDC (New European Driving Cycle currently in use) are approximately the same, while the characteristics such as maximum speeds, idling periods and speed changes are quite different. It is inferred that average speeds are not a good proxy to the fuel consumption and emissions on the roads, hence, models using average speeds as the key determinant for estimation of fuel and emissions will be subjected to a greater degree of error. The proportion of acceleration in a driving cycle must be sufficiently large (i.e. >30%) and greater than the proportion of deceleration to reach a maximum speed of 70 km/h and overall average speed >30 km/h. This is inferred from the comparison of various actual driving cycles, applicable for the arterial segment.

With the use of estimation model (CMEM), NEDC underestimates emission factors of fuel, CO_2, HC and NO_x by 5%, 5%, 22% and 47% respectively and overestimates CO by 8% as compared to SDC.

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