Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 48 (2020) 2083–2095

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

Developing driving cycles using k-means clustering and determining their optimal duration

Ramya Madhuri Desineedi[a], Srinath Mahesh[a]*, Gitakrishnan Ramadurai[a]

[a]*Department of Civil Engineering, IIT Madras, Chennai, India, 600036*

Abstract

Driving cycles are used to understand the driving pattern of vehicles and in estimating their emissions. Although several studies exist on driving cycles worldwide, few studies have focused on developing driving cycles for intra-city buses in heterogeneous traffic conditions. In this study, driving cycles for intra-city buses were developed using real-world GPS data collected during peak and off-peak periods in Chennai city, India. The methodology for the construction of the candidate cycle was based on k-means clustering and one-step Markov modelling. For Markov chain modelling, a transition matrix is constructed which is a probability matrix based on one step succession. To understand the effect of duration of the driving cycle, the candidate cycles were developed for different durations ranging from 400 seconds to 2800 seconds. Further, the average error for each duration of the candidate cycles was determined. The duration which corresponds to the least average error was chosen for developing the final driving cycle. Three driving cycles - corresponding to morning peak hour, off-peak hour, and evening peak hour - were developed. Finally, the developed cycles were compared with the existing local and international cycles. The developed driving cycle was found to be significantly different from the existing cycles for buses.

Keywords: Driving cycle; k-means clustering; buses.

1. Introduction

A driving cycle is a plot of the speed of a vehicle with respect to time. They are used to characterize the driving conditions under which the vehicle is operated within a specified duration. Typically, the duration of the driving cycles varies from 10 minutes to 40 minutes and may be different for peak and off-peak periods. Moreover, for a particular city, several driving cycles may be developed for different road types (arterials, freeways, and local roads) and vehicle types (buses, trucks, cars, and motorcycles).

* Corresponding author. Tel.: +91-893-952-4548.
E-mail address: srinath.nda@gmail.com

10.1016/j.trpro.2020.08.268

The development of real-world driving cycles involves three stages: route selection, real-world driving data collection, and driving cycle construction. Route selection requires selection of the most representative routes to capture the driving behavior of all the vehicles. Generally, the routes which carry predominant traffic are chosen for data collection. The real-world driving data is collected every second using a GPS device mounted on the test vehicle. Finally, the data is used to develop driving cycles which represent the real-world driving conditions.

The developed driving cycles are used in emission testing and certification of vehicles in the laboratory. Accurate estimation of driving cycles would lead to better quantification of emissions from gasoline and diesel-powered motor vehicles. In addition, driving cycles of electric vehicles can be used to determine their range and power consumption which decides the characteristics of the battery used.

This study uses real-world second-by-second GPS data collected from intra-city buses to develop driving cycles in heterogeneous traffic conditions. The methodology for developing driving cycles involves clustering the microtrips using k-means clustering process and cluster sequencing using one step Markov modeling process. The developed driving cycles are then compared with the existing cycles.

This paper is organized into five sections. Section 1 provides an introduction to the paper. Section 2 presents the existing literature related to driving cycles. Section 3 explains the methodology adopted in this study. Section 4 presents the results and discussion of the findings. Finally, section 5 presents the concluding remarks.

2. Literature review

Literature review suggests several definitions of driving cycle such as “a representation of a speed-time sequenced profile developed for a specific area or city" (Hung et al., 2007) and "is a sequence of operating conditions (idle, acceleration, deceleration and cruise) developed to represent a typical driving pattern of a city" (Nesamani and Subramanian, 2011). Another definition of driving cycle being "a representative plot of driving behavior of a given city or a region and is characterized by speed and acceleration" (Kamble et al., 2009).

The driving cycles of a particular region are affected by following factors: type of roads, geography, method of data collection, and method of cycle construction. Driving cycle consists of smaller elements called microtrips (MT) which has different definitions, though the most widely used definition is "trip between two idling periods". The duration of driving cycles ranges between 10-40 minutes as this duration is long enough to capture the driving behaviour and is feasible in practice (Arun et al., 2017).

The development of driving cycles for various locations began in 1978 in Sydney (Kent et al., 1978). Subsequently, driving cycles were developed worldwide to capture local traffic conditions. Major driving cycles include Taipei (Tzeng and Chen, 1998), Delhi (Badusha and Ghosh, 1999), Hong Kong (Tong et al., 1999), Pune (Kamble et al., 2009), Chennai (Nesamani and Subramanian, 2011), Edinburgh (Saleh et al., 2012), Singapore (Ho et al., 2014), Toronto (Amirjamshidi and Roorda, 2015), and Khon Kaen (Seedam et al., 2015). Almost all the driving cycles being constructed in recent past use similar assessment parameters such as average speed, average acceleration, and percentage idle. In the driving cycle of Sydney, only three parameters were used i.e. average speed, rms acceleration, and percentage idle time, while in the modern driving cycles such as Toronto and Singapore used up to 10 assessment parameters. However, while developing a driving cycle, most of the studies adopted random selection of microtrips and the constructed candidate cycle is then compared with target parameters to find the most representative driving cycle.

Research on driving cycles in India has been growing over the past few decades due to an increase in the number of vehicles and the need to estimate their emissions. The Indian driving cycles neglected higher speed and assumed similar behavior irrespective of heterogeneity in traffic. In the case study by Kamble et al. (2009), important parameters describing time-space profile namely percentage time spent in acceleration, deceleration, idle, cruise and creep modes are used. Microtrips were shortlisted for candidate cycle construction by comparing parameters of each microtrip. In another study, a driving cycle was developed for Intra city buses of Chennai (Nesamani and Subramanian, 2011). The study used 14 assessment parameters to construct a distance based driving cycle. Microtrips were selected randomly to construct candidate cycle until it reached target distance and then compared against the target values. The bus driving cycle on state highway, Maharashtra is another driving cycle for buses in highway driving. In this study, assessment parameters were calculated for each microtrip and compared with assessment parameters of the population (target statistics). If difference was greater than 5%, then those microtrips were rejected and the rest are used for constructing the candidate cycle.

3. Methodology

3.1. Data collection

The second-by-second data was collected from intra-city buses in Chennai city using hand-held GPS units. Buses plying on several different routes were selected for data collection. The data were collected on different days (including weekdays and weekends) and included peak and off-peak periods. The collected data involved multiple to and fro trips from the same bus depot for an entire day.

3.2. Data processing

The collected data were checked for accuracy, continuity, smoothened to remove noise (data when the bus is idle in the depot), and then used to derive other parameters such as acceleration, deceleration, etc., which are used in assessing the candidate cycle. The speed data related to an individual trip from the origin to the destination was separated for further analysis.

3.3. Driving cycle construction

The flow chart of the methodology adopted for driving cycle construction is shown in Fig. 1. The four main steps were: generation of microtrips, categorization of microtrips using k-means clustering, determination of assessment parameters, and construction of the candidate cycle. From the second-by-second speed data, microtrips were generated assuming a microtrip to start when speed increases from zero and end at the next start from speed zero. Thus, every microtrip has an idling period in the end. Microtrips are then categorized into different classes using k-means clustering. The optimal number of clusters were found from elbow plot. In order to assess how closely candidate cycle represents whole data, a set of assessment parameters are used as shown in Table 1. The candidate cycles are selected by comparing 'test statistics' (assessment parameters of the candidate cycle) with population parameters also known as 'target statistics'.

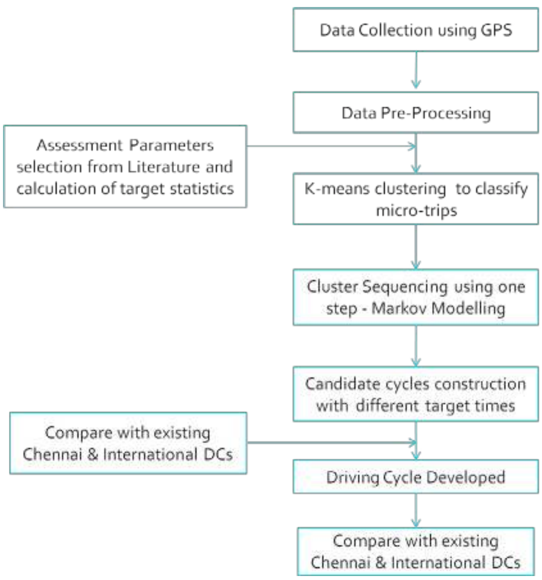

Fig. 1. Flow chart of methodology.

Table 1. Selected assessment parameters.

S. No.	Assessment parameter	Units
1	Average speed (V) for entire trip	km h^{-1}
2	Average running speed (V_r)	km h^{-1}
3	Average acceleration (a) of all acceleration phases	m s^{-2}
4	Average deceleration (d) of all deceleration phases	m s^{-2}
5	Percentage of time spent in idle mode (P_i) (speed=0)	%
6	Percentage of time spent in acceleration mode (P_a) (acceleration >= 0.1 m/s^2)	%
7	Percentage of time spent in deceleration mode (P_d) (acceleration <= -0.1 m/s^2)	%
8	Percentage of time spent in creeping mode (P_{cr}) (-0.1m/s^2 < acceleration < 0.1 m/s^2, speed < 5 kmph)	%
9	Percentage of time spent in cruise mode (P_c) (-0.1 m/s^2 < acceleration < 0.1 m/s^2, speed > 5 kmph)	%
10	Average no. of acceleration – deceleration phases (vice versa) in one driving period (P_{ad})	%
11	Root mean square acceleration (a_{rms}) $a_{rms} = \sqrt{\Sigma acceleration^2}$	m s^{-2}
12	Positive acceleration kinetic energy (PKE)	m s^{-2}

The construction of the candidate cycle involves the following steps. (1) Initial microtrip of the whole data is used to start every candidate cycle. Second microtrip is then selected based on one-chain Markov modeling and the process continues. (2) For Markov chain modeling, the transition matrix is constructed which is a probability matrix based on one step succession. Here, the probability of succession of a specific cluster by another cluster is calculated. Table 2 provides a sample of a transition matrix. (3) After construction of transition matrix, it is cumulated along the row as shown in Table 3. A random number between 0 and 1 is selected and based on where it falls i.e., between which columns for a particular row, succeeding cluster is decided. (4) This process is repeated till the required time for candidate cycle is achieved.

In this study, the duration of the candidate cycle is taken from 400 seconds to 2800 seconds with bins of 200 seconds. For every duration fixed to construct driving cycle, best candidate cycle with least total mean error is selected as the driving cycle.

Error of candidate cycle is calculated by the formula given below:

$$S_i = \left(\frac{|\,p_i - P_i\,|}{P_i} \right) \tag{1}$$

P_i = Target parameter i of entire collected data

p_i = Target parameter i of the candidate cycle

The mean error is calculated using the following equation:

$$ME = \sum_{j=1}^{n} S_i / (n) \tag{2}$$

n = No. of assessment parameters
S_i = Relative error of ith parameter
Through this method, dynamic driving cycles are constructed which helps when there is a time constraint in the duration of driving cycle.

Table 2. Transition matrix of clusters used for Markov chain modeling.

Succeeding cluster / Starting cluster	1	2	3	4	5	6
1	0.593	0.034	0.212	0.076	0.034	0.051
2	0.226	0.129	0.129	0.161	0.194	0.161
3	0.189	0.038	0.575	0.066	0.085	0.047
4	0.157	0.118	0.157	0.137	0.255	0.176
5	0.057	0.091	0.091	0.091	0.295	0.375
6	0.055	0.039	0.000	0.118	0.236	0.551

Table 3. Transition matrix of clusters cumulated row-wise for selecting succeeding cluster Markov chain modeling.

Succeeding cluster / Starting cluster	1	2	3	4	5	6
1	0.593	0.034	0.212	0.076	0.034	0.051
2	0.226	0.129	0.129	0.161	0.194	0.161
3	0.189	0.038	0.575	0.066	0.085	0.047
4	0.157	0.118	0.157	0.137	0.255	0.176
5	0.057	0.091	0.091	0.091	0.295	0.375
6	0.055	0.039	0.000	0.118	0.236	0.551

4. Results and discussion

4.1 Driving cycle for morning peak hour

The developed driving cycle for the morning peak hour is shown in Figure 2. This cycle was chosen from the candidate cycles of different durations based on the least error. The variation in the errors with duration of the candidate driving cycles is shown in Figure 3. The error is about 20% for a driving cycle of duration 400 seconds and decreases drastically with increase in duration up to 1200 seconds. The least average error of the candidate cycles is observed for a duration of 1200 seconds. Subsequently, there seems to be a saturation in the error values to about 10%.

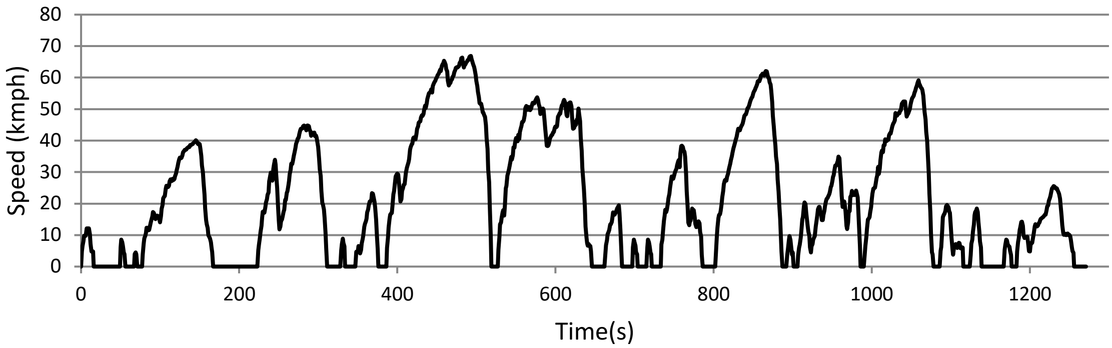

Figure 2 Driving cycle for morning peak hour

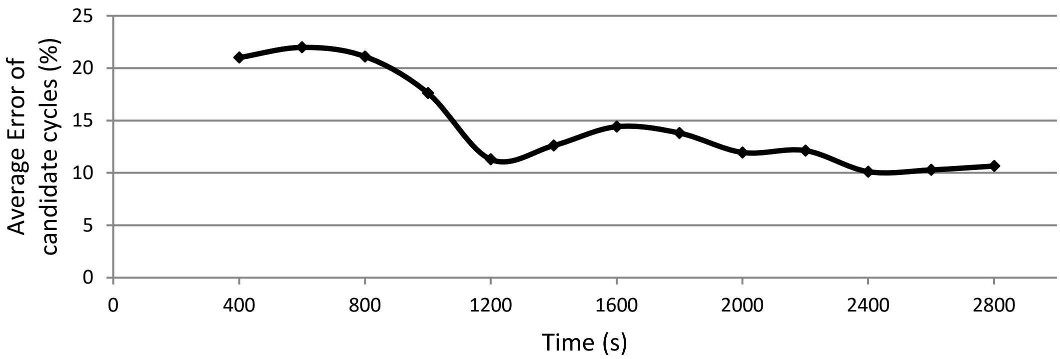

Figure 3 Average total error of candidate cycle versus approximate time period of cycle

The assessment parameters used for determining the candidate cycles and the microtrips comprising the developed cycle (Figure 2) are shown in Table 4 and Table 5, respectively. As seen from Table 4, the total duration of the driving cycle is 1271 seconds with an average speed of 23 kmph and average running speed of 30.82 kmph. The other parameters of the developed driving cycle were very similar to the target statistics. In total, there are 21 microtrips comprising the developed driving cycle for morning peak hour.

Table 4 Assessment parameters for morning peak hours.

Type	Time (s)	V (kmph)	V_r (kmph)	a (m/s2)	d (m/s2)	P_a (%)	P_d (%)	P_i (%)	P_c (%)	P_{cr} (%)	P_{ad} (%)	a_{rms} (m/s^2)	PKE (m/s^2)
Target statistics		21.28	28.02	0.37	0.64	36.45	24.14	14.89	24.06	0.46	17.19	0.51	0.33
Driving cycle	1271	23.03	30.82	0.36	0.66	36.64	23.48	14.19	25.28	0.34	13.15	0.51	0.32

Table 5 Microtrips comprising driving cycle of morning peak hour.

Microtrip	Time (s)	V (kmph)	V_r (kmph)	a (m/s^2)	d (m/s^2)	P_a (%)	P_d (%)	P_i (%)	P_c (%)	P_{cr} (%)	P_{ad} (%)	a_{rms} (m/s^2)	PKE (m/s^2)
1	49	2.64	8.62	0.51	0.84	12.14	0.64	1.32	8.16	8.16	69.39	10.2	4.08
148	18	2.08	6.23	0.67	0.48	8.59	0.67	1.1	5.56	27.78	66.67	0	0
96	10	1.24	4.14	0.14	0.63	4.51	0.14	1.09	10	20	70	0	0
25	146	15.09	24.76	0.31	0.5	40.07	0.95	1.26	24.66	17.12	39.04	19.18	0
235	105	24.15	29.14	0.4	0.71	44.78	1.04	1.66	43.81	26.67	17.14	12.38	0
91	19	1.84	7.01	0.52	0.82	8.89	0.55	1.78	10.53	15.79	73.68	0	0
278	39	9.56	13.31	0.4	0.79	23.32	0.74	1.49	35.9	23.08	28.21	7.69	5.13
171	141	44.88	47.94	0.33	0.68	66.88	1.04	2.71	47.52	25.53	6.38	20.57	0
209	135	34.56	39.54	0.4	0.65	53.74	1.6	1.68	42.96	28.15	12.59	16.3	0
36	35	8.19	13.65	0.33	1.11	19.5	0.75	1.96	37.14	14.29	40	8.57	0
35	18	2.08	6.23	0.67	0.48	8.59	0.67	1.1	5.56	27.78	66.67	0	0
256	18	2.08	6.23	0.67	0.48	8.59	0.67	1.1	5.56	27.78	66.67	0	0
244	69	16.55	21.96	0.45	0.65	38.39	1.18	1.61	37.68	30.43	24.64	7.25	0
291	90	38.79	41.56	0.32	0.82	62.1	1.04	1.45	54.44	23.33	6.67	15.56	0
12	14	3.6	6.3	0.46	0.73	9.66	0.8	1.26	28.57	28.57	42.86	0	0
223	84	17.6	18.71	0.43	0.7	34.9	1.25	1.85	51.19	33.33	5.95	9.52	0
195	96	35.71	39.41	0.37	0.81	59.13	0.83	1.9	48.96	23.96	9.38	17.71	0
102	38	8.14	10.67	0.52	0.66	19.51	1.48	1.66	26.32	26.32	23.68	23.68	0
75	43	3.97	12.18	0.51	0.85	18.46	0.98	1.69	18.6	13.95	67.44	0	0
5	16	3.6	6.4	0.46	0.55	8.6	0.49	1.01	12.5	25	43.75	18.75	0
247	88	11.45	14	0.34	0.42	25.55	0.83	1.21	27.27	27.27	18.18	25	1.14

4.2 Driving cycle for evening peak hour

The driving cycle for evening peak hour is shown in Figure 4. This cycle was chosen from the candidate cycles by adopting a similar procedure as for the morning peak hour driving cycle. The variation in average error of the candidate cycles for different time periods is shown in Figure 5. The average error is about 30% for driving cycles of duration 600 seconds and decreases continuously with increase in the duration of the cycle. The lowest error was about 13% corresponding to a duration of 2000 seconds. The developed driving cycle has a duration of 2055 seconds.

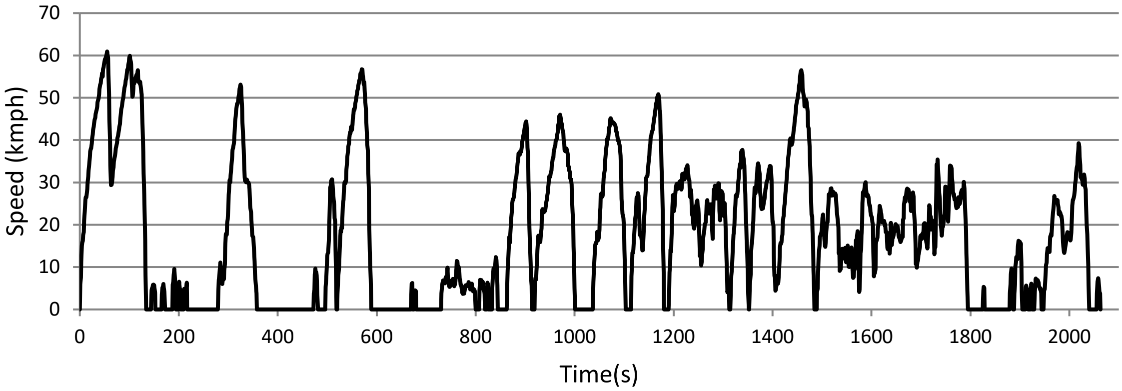

Figure 4 Driving cycle for evening peak hour

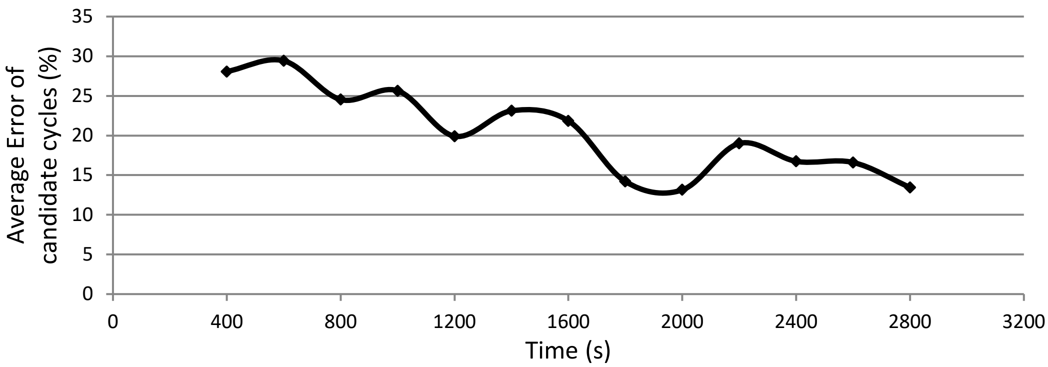

Figure 5 Average total error of driving cycle versus approximate time period of cycle

The assessment parameters and the observed values of the parameters for the developed evening peak hour driving cycle are given in Table 6. The average speed of the cycle is about 17 kmph which is significantly lower than the morning peak hour cycle. The assessment parameters values for the developed cycle match well with the target statistics. The assessment parameter values for the microtrips comprising the evening peak hour driving cycle is given in Table 7. The number of microtrips is comparatively higher with many of them of short durations. The assessment parameters also vary considerably among the microtrips.

Table 6 Assessment parameters for evening peak hour.

Type	Time (s)	V (kmph)	V_r (kmph)	a (m/s^2)	d (m/s^2)	P_a (%)	P_d (%)	P_i (%)	P_c (%)	P_{cr} (%)	P_{ad} (%)	a_{rms} (m/s^2)	PKE (m/s^2)
Target statistics		18.45	25.27	0.39	0.57	32.58	25.61	14.20	27.01	0.60	19.03	0.49	0.34
Driving cycle	2055	17.43	24.90	0.40	0.64	33.14	24.42	11.72	29.99	0.73	16.70	0.53	0.37

Table 7 Microtrips comprising driving cycle of evening peak hour.

Microtrip	Time (s)	V (kmph)	V_r (kmph)	a (m/s^2)	d (m/s^2)	P_a (%)	P_d (%)	P_i (%)	P_c (%)	P_{cr} (%)	P_{ad} (%)	a_{rms} (m/s^2)	PKE (m/s^2)
1	144	40.52	43.87	0.29	0.92	60.93	1.06	2.29	61.11	20.83	7.64	10.42	0
399	21	1.95	5.11	0.16	0.53	5.86	0.18	1.09	9.52	14.29	61.9	9.52	4.76
510	22	1.33	4.88	0.34	0.56	6.03	0.44	1.15	9.09	13.64	72.73	4.55	0
443	12	3.48	6.96	0.34	0.88	9.55	0.42	1.23	25	25	50	0	0
195	5	4.2	5.25	0.26	0.61	6.57	0.26	1.04	20	60	20	0	0
134	6	1.44	4.32	0.12	1.26	4.54	0.12	1.26	16.67	16.67	66.67	0	0
419	69	0.41	4.74	0.27	0.72	6.3	0.49	1.75	4.35	4.35	91.3	0	0
262	193	11.08	27.41	0.43	0.53	53.1	1.09	1.06	18.13	16.06	59.59	6.22	0
408	24	2.31	6.94	0.54	0.67	9.67	1.03	1.22	12.5	16.67	66.67	4.17	0
205	24	18.37	20.04	0.59	0.95	30.77	1.59	2.19	50	37.5	8.33	4.17	0
2	149	17.1	37.46	0.38	0.82	56.73	1.14	2.08	27.52	13.42	54.36	4.7	0
216	6	2.68	5.37	0.62	1.73	6.22	0.62	1.73	16.67	16.67	50	16.67	0
326	55	0.31	4.27	0.16	1.21	4.54	0.16	1.21	1.82	1.82	92.73	0	3.64
281	77	5.6	6.25	0.3	0.29	11.44	0.7	1.05	22.08	28.57	10.39	28.57	10.39
356	15	4.23	5.77	0.3	0.49	7.02	0.69	1.01	26.67	33.33	26.67	13.33	0
115	7	2.18	5.09	0.73	0.88	6.34	0.73	1.45	14.29	28.57	57.14	0	0
477	4	2.15	4.3	0.16	1.27	4.58	0.16	1.27	25	25	50	0	0
200	30	3.42	9.32	0.53	0.71	12.36	0.81	1.59	13.33	16.67	63.33	6.67	0
258	56	26	29.12	0.36	0.98	44.41	0.92	1.66	53.57	23.21	10.71	12.5	0
264	118	20.38	29.68	0.33	0.49	45.99	0.91	1.54	30.51	22.88	31.36	15.25	0
27	77	26.18	31.01	0.45	0.58	45.17	0.96	2.5	32.47	28.57	15.58	23.38	0
55	76	26.46	30.47	0.39	1	50.86	1.05	2.26	52.63	23.68	13.16	10.53	0
226	125	22.85	23.41	0.51	0.58	34.07	1.65	1.76	40	37.6	2.4	20	0
70	38	23.22	24.51	0.51	0.72	37.66	1.03	1.55	47.37	39.47	5.26	7.89	0
297	136	29.34	30.46	0.38	0.65	56.5	1.43	1.91	51.47	32.35	3.68	11.76	0.74
208	336	18.24	20.09	0.46	0.56	35.4	2.66	1.87	40.18	33.93	9.23	16.67	0
456	54	0.27	4.94	0.25	1.41	5.32	0.25	1.41	1.85	1.85	94.44	1.85	0
524	9	4.53	6.8	0.54	0.89	9.64	0.64	1.34	33.33	33.33	33.33	0	0
225	23	8.06	11.59	0.63	0.98	16.2	1.19	1.85	34.78	26.09	30.43	8.7	0
286	10	2.4	4.81	0.2	0.62	5.67	0.28	1.31	20	30	50	0	0
304	8	1.99	5.3	0.49	0.85	6.11	0.49	1.52	12.5	25	62.5	0	0
146	19	4.18	5.67	0.28	0.37	7.33	0.55	1.06	21.05	31.58	26.32	15.79	5.26
107	107	18.72	22.01	0.39	0.51	39.26	1.06	1.58	36.45	29.91	14.95	17.76	0.93
165	9	4.19	5.39	0.5	0.5	7.41	0.76	1.06	22.22	44.44	22.22	0	11.11

4.3 Driving cycle for off-peak hours

The driving cycle for off-peak hours is shown in Figure 6. Clearly, the number of microtrips are lower relative to the peak hour cycles and higher speeds are observed. The duration of the microtrips comprising the driving cycle is also higher. The driving cycle duration is dominated by four microtrips of duration above 200 seconds each. Overall, there are 12 microtrips in the developed driving cycle with a total duration of 1649 seconds. The variation in the average error of candidate cycles with time is shown in Figure 7. In this case, the error ranges from 2% for a duration of 400 seconds to 0.5% for a duration of 2800 seconds.

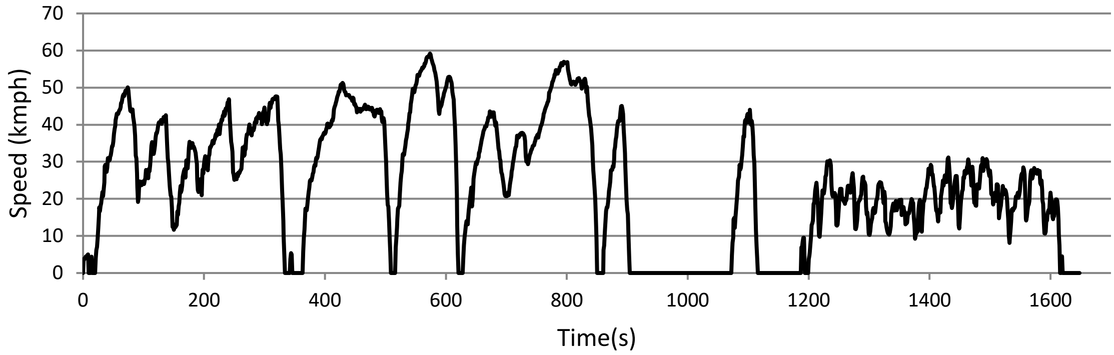

Figure 6 Driving cycle for off-peak hour.

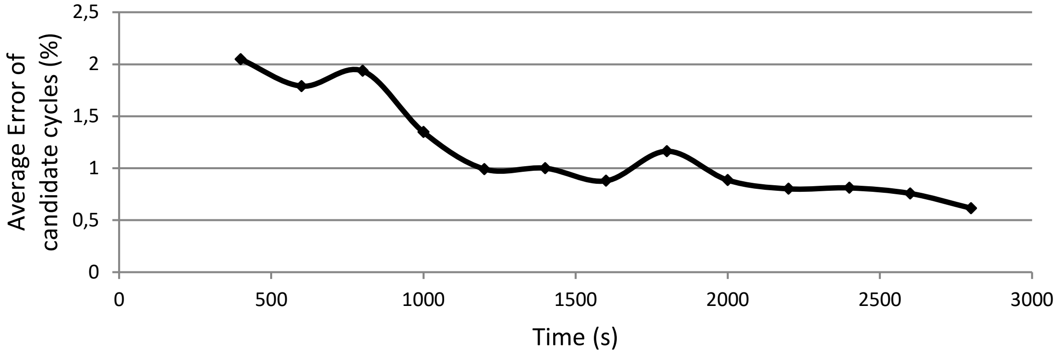

Figure 7 Average total error of driving cycle versus approximate time period of cycle.

The assessment parameters for the development of the off-peak hour driving cycle is given in Table 8. The parameter values of the developed driving cycle match well with the target statistics for off-peak hour. The parameters of the 12 microtrips comprising the off-peak hour driving cycle is given in Table 9. Although the duration of the microtrips vary widely, four microtrips of more than 200 seconds duration almost cover the entire cycle. Also, the average speed of the off-peak hour driving cycle is higher relative to the peak hour cycles.

Table 8 Assessment parameters for off-peak hours.

Type	Time (s)	V (kmph)	V_r (kmph)	a (m/s^2)	d (m/s^2)	P_a (%)	P_d (%)	P_i (%)	P_c (%)	P_{cr} (%)	P_{ad} (%)	a_{rms} (m/s^2)	PKE (m/s^2)
Target statistics		21.67	27.29	0.39	0.59	35.5	26.45	16.98	20.6	0.47	22.02	0.52	0.33
Driving cycle	1649	24.31	30.70	0.38	0.58	35.72	25.05	18.13	20.80	0.30	21.24	0.48	0.31

Table 9 Microtrips comprising driving cycle of off-peak hour.

Microtrip	Time (s)	V (kmph)	V_r (kmph)	a (m/s²)	d (m/s²)	P_a (%)	P_d (%)	P_i (%)	P_c (%)	P_{cr} (%)	P_{ad} (%)	a_{rms} (m/s²)	PKE (m/s²)
1	12	2.85	4.28	0.15	1.39	5.00	0.17	1.39	16.67	8.33	33.33	0.00	41.67
335	8	1.04	4.15	0.15	1.23	4.42	0.15	1.23	12.50	12.50	75.00	0.00	0.00
388	322	32.41	33.34	0.38	0.54	50.05	1.57	1.55	44.41	32.61	2.80	20.19	0.00
15	21	0.67	4.71	0.42	0.74	5.33	0.42	1.38	4.76	9.52	85.71	0.00	0.00
470	153	36.60	38.61	0.28	0.51	51.29	1.07	1.54	35.29	21.57	5.23	37.91	0.00
191	112	41.40	44.58	0.36	0.67	59.19	0.96	2.30	41.96	25.89	7.14	25.00	0.00
355	232	36.42	38.23	0.27	0.46	56.94	0.96	2.58	44.83	27.59	4.74	22.84	0.00
426	212	5.67	27.94	0.47	0.96	45.02	0.99	1.66	10.85	6.13	79.72	3.30	0.00
378	115	10.49	28.06	0.57	0.85	44.04	1.37	1.97	20.00	14.78	62.61	2.61	0.00
251	12	3.96	7.91	0.37	1.32	9.53	0.45	1.70	16.67	16.67	50.00	16.67	0.00
478	418	20.22	20.32	0.45	0.58	31.18	1.46	2.06	44.98	34.69	0.48	19.86	0.00
424	32	0.26	4.22	0.16	1.25	4.51	0.16	1.25	3.13	3.13	93.75	0.00	0.00

4.4 Comparison with existing driving cycles

In order to understand the differences between the developed driving cycles of buses in Chennai with the existing driving cycles, a comparison between the different cycles was conducted (Table 10). The average speed and average running speed of the developed cycle was lower than the Hong Kong and the FTP driving cycles. The average acceleration was also lower than all the existing driving cycles. This indicates the effect of congested traffic conditions prevalent on the arterial roads of Chennai city. Other assessment parameters such as root mean square acceleration and PKE also show significant difference with respect to the existing driving cycles. Since these cycles were developed primarily for passenger cars, a comparison with the existing driving cycles for buses is required.

Table 10 Comparison of the overall driving cycle with international cycles.

Parameter	Chennai	HK	FTP 72	FTP 75	LA 92	ECE 15	10 Mode	10 - 15 Mode
Average speed (kmph)	22.29	25	31.5	34.1	39.6	18.4	17.6	22.7
Average running speed (kmph)	29.00	30.4	38.3	41.6	46.7	26.5	24.1	33.1
Average acceleration (m/s²)	0.35	0.595	0.597	0.607	0.673	0.642	0.673	0.569
Average deceleration (m/s²)	0.57	0.593	0.695	0.7	0.754	0.748	0.654	0.647
Percent acceleration (m/s²)	34.65	34.5	32.8	32.4	38.2	21.5	24.3	25.2
Percent deceleration (m/s²)	24.60	34.2	28.3	28.2	34.1	18.5	25	22.1
Percent idle (%)	17.06	17.8	17.6	17.9	15.2	30.8	27.2	31.4
Percent cruise (%)	23.15	12	20.9	21.2	12.2	29.2	23.5	21.4
Percent creep (%)	0.53	1.5	0.4	0.3	0.3	-	-	-
RMS acceleration (m/s²)	0.48	0.73	0.74	0.76	0.846	0.661	0.692	0.612
PKE (m/s²)	0.30	0.39	0.38	0.384	0.409	0.565	0.577	0.427

Table 11 compares the developed driving cycles with the existing bus driving cycles in India as well as abroad. The Central Business District Cycle (CBDC) and Dutch Urban Bus Driving Cycle (DUBDC) are given in Pelkmans et al. (2001) and Delhi Bus Driving Cycle (DBDC) is given by ARAI (2007). Further, the driving cycles for buses in highways (SHM driving cycle) is given by Maurya and Bokare (2012). The average speed and average running speed are similar for all the urban driving cycles. However, it is higher for the SHM cycles, as they are developed for highways with less traffic and high speeds. The DBDC has the lowest average speed in contrast to the SHM cycles. Idling periods are higher in the CBDC and DUBDC cycles whereas cruising time is highest in the Pune driving cycle.

Table 11 Comparison of the developed driving cycle with existing bus driving cycles and Pune driving cycle.

Parameter	Morning peak	Evening peak	Off-peak	CBDC	DUBDC	DBDC	Pune	SHM Morning Peak	SHM Off-Peak	SHM Evening Peak
Average speed (kmph)	23.03	22.29	24.31	20.23	20.96	18	19.55	38.45	44.6	31.1
Average running speed (kmph)	30.82	29.00	30.7	27	28.29	23	-	40.5	46.84	34.31
Average acceleration (m/s^2)	0.36	0.35	0.38	0.89	0.57	0.4	3.72	0.28	0.32	0.29
Average deceleration (m/s^2)	0.66	0.57	0.58	1.22	0.69	0.49	4.57	0.37	0.32	0.58
Percent acceleration (%)	36.64	34.65	35.72	30.61	40	38.78	14.18	25.98	28.31	36.66
Percent deceleration (%)	23.48	24.60	25.05	14.29	33.1	32.65	11.48	21.54	15.46	15.53
Percent idle (%)	14.19	17.06	18.13	22.45	22.57	20.41	18.09	5.18	4.22	9.41
Percent cruise (%)	25.28	23.15	20.8	32.65	4.33	8.16	56.25	46.62	50.42	37.06
Percent creep (%)	0.34	0.53	0.3	-	-	-	-	-	-	-
PKE (m/s^2)	0.32	0.30	0.31	0.2	0.53	-	-	0.45	0.66	0.56

5. Conclusions

This study developed driving cycles for intra-city buses of Chennai in peak hours (morning and evening) and off-peak hours using k-means clustering and one-step Markov chain modelling method. The candidate cycles were developed based on twelve assessment parameters with eleven parameters as used in existing studies. Percentage time in changing from acceleration to deceleration modes is added to the list adopted from literature. The candidate cycles were developed by dividing the real-world speed-time data into microtrips and classifying them using k-means clustering. Then, one-step Markov chain modeling is used to sequence them into candidate cycle of a particular duration. This study also attempted to understand the effect of duration of the driving cycle on its representativeness of the real-world conditions. Thus, candidate driving cycles of time periods ranging from 400 seconds to 2800 seconds at an interval of 200 seconds were developed. The developed driving cycles were compared with the existing international and Indian driving cycles such as the Hong Kong, US, European, Japanese, Pune, and Delhi cycles.

Acknowledgements

The authors are thankful for the financial support from the Center of Excellence in Urban Transport (CoEUT), Ministry of Urban Development, Government of India.

References

Amirjamshidi, G., Roorda, M.J., 2015. Development of simulated driving cycles for light, medium, and heavy duty trucks: Case of the Toronto Waterfront Area. Transp. Res. Part D Transp. Environ. 34, 255–266. doi:10.1016/j.trd.2014.11.010

ARAI, 2007. Emission factor development for Indian vehicles, Air quality monitoring project - Indian Clean Air Program (ICAP).

Arun, N.H., Mahesh, S., Ramadurai, G., Shiva Nagendra, S.M., 2017. Development of driving cycles for passenger cars and motorcycles in Chennai, India. Sustain. Cities Soc. 32, 508–512. doi:10.1016/j.scs.2017.05.001

Badusha, A.A., Ghosh, B., 1999. Driving cycle for buses in Delhi city.

Ho, S.-H., Wong, Y.-D., Chang, V.W.-C., 2014. Developing Singapore Driving Cycle for passenger cars to estimate fuel consumption and vehicular emissions. Atmos. Environ. 97, 353–362. doi:https://doi.org/10.1016/j.atmosenv.2014.08.042

Hung, W.T., Tong, H.Y., Lee, C.P., Ha, K., Pao, L.Y., 2007. Development of a practical driving cycle construction methodology: A case study in Hong Kong. Transp. Res. Part D Transp. Environ. 12, 115–128. doi:10.1016/j.trd.2007.01.002

Kamble, S.H., Mathew, T. V., Sharma, G.K., 2009. Development of real-world driving cycle: Case study of Pune, India. Transp. Res. Part D Transp. Environ. 14, 132–140. doi:10.1016/j.trd.2008.11.008

Kent, J.H., Allen, G.H., Rule, G., 1978. A driving cycle for Sydney. Transp. Res. 12, 147–152. doi:10.1016/0041-1647(78)90117-X

Maurya, A.K., Bokare, P.S., 2012. Bus driving cycle on state highway in Maharashtra, India - a case study.

Nesamani, K.S., Subramanian, K.P., 2011. Development of a driving cycle for intra-city buses in Chennai, India. Atmos. Environ. 45, 5469–5476. doi:10.1016/j.atmosenv.2011.06.067

Pelkmans, L., De Keukeleere, D., Bruneel, H., Lenaers, G., 2001. Influence of vehicle test cycle characteristics on fuel consumption and emissions of city buses. Soc. Automot. Eng.

Saleh, W., Kumar, R., Kirby, H., Kumar, P., 2012. Real world driving cycle for motorcycles in Edinburgh. Transp. Res. Part D 14, 326–333. doi:10.1016/j.trd.2009.03.003

Seedam, A., Satiennam, T., Radpukdee, T., Satiennam, W., 2015. Development of an onboard system to measure the on-road driving pattern for developing motorcycle driving cycle in Khon Kaen city, Thailand. IATSS Res. 39, 79–85. doi:10.1016/j.iatssr.2015.05.003

Tong, H.Y., Hung, W.T., Cheung, C.S., 1999. Development of a driving cycle for Hong Kong. Atmos. Environ. 33, 2323–2335. doi:10.1016/S1352-2310(99)00074-6

Tzeng, G.-H., Chen, J.-J., 1998. Developing A Taipei motorcycle driving cycle for emissions and fuel economy. Transp. Res. Part D Transp. Environ. 3, 19–27. doi:10.1016/S1361-9209(97)00008-4