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DEVELOPING A TAIPEI MOTORCYCLE DRIVING CYCLE FOR EMISSIONS AND FUEL ECONOMY

GWO-HSHIUNG TZENG and JUNE-JYE CHEN
Energy and Environmental Research Group and Institute of Traffic and Transportation, National Chiao Tung University,
4F, 114, Sec. 1, Chung Hsiao W. Rd., Taipei, 100, Taiwan

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Abstract—The purposes of this study are to develop a representative driving cycle for motorcycles in metropolitan Taipei and to ascertain the emissions and fuel economy of the cycle. We collected extensive driving cycle data and proposed a methodology to develop a Taipei motorcycle driving cycle (TMDC). The characteristics of TMDC are high average acceleration and deceleration, high acceleration–deceleration changes and low average travel speed. Forty-five motorcycles were tested in a laboratory by using the ECE-40 and TMDC test procedure. The emissions of motorcycles tested by TMDC are higher than ECE, whether they are two-stroke or four-stroke engines. Furthermore, the CO and HC emissions of two-stroke engine motorcycles are higher than four-stroke engine motorcycles, and the NOx emission of two-stroke engine motorcycles are lower than four-stroke engine motorcycles, whether they are tested by TMDC or ECE. The fuel economy of two-stroke engine motorcycles tested by TMDC is lower than ECE, but the fuel economy of four-stroke engine motorcycles tested by TMDC is higher than ECE. A linear regression of TMDC in terms of ECE emissions shows them to be highly correlated, as is fuel economy. © 1998 Elsevier Science Ltd. All rights reserved

1. INTRODUCTION

The motorcycle is one of the most important transportation modes in the tropical–subtropical countries. In metropolitan Taipei, the number of motorcycles had already reached 1.95 million in 1995. The ownership rate is 0.33 units per person. Though motorcycles are convenient, the emissions of motorcycles are quite serious. According to the information from the Environmental Protection Administration, the HC and CO emissions of motorcycles occupy the first and second places among all transportation modes. How to control motorcycle emissions is a major issue in improving air quality in metropolitan Taipei.

The European driving cycle (ECE-40) has been employed as the motorcycle emissions test procedure (CNS 11386) since 1987 in Taiwan. ECE is one kind of steady-type driving cycle. However, it seems not quite suitable for the crowded traffic of Taiwan so environmental protection authorities and research institutes are interested in how to develop a domestic motorcycle driving cycle and to discover the emissions and fuel economy of the domestic driving cycle. Therefore, the purposes of this study are to develop a representative motorcycle driving cycle in metropolitan Taipei and to ascertain the emissions and fuel economy of the cycle. We proposed a methodology, collected extensive motorcycle driving cycle data and developed a representative driving cycle. Then, we randomly sampled 45 motorcycles in use and tested the emissions of both the representative cycle and ECE. Carbon balance method was used to calculate the fuel economy. We find that the characteristics of the motorcycle driving cycle are high average acceleration and deceleration, high acceleration–deceleration changes, and low average travel speed. The emissions tested by the Taipei motorcycle driving cycle (TMDC) are higher than ECE. The fuel economy of two-stroke engine motorcycles tested by TMDC is lower than ECE, but the fuel economy of four-stroke engine motorcycles tested by TMDC is higher than ECE. A linear regression of TMDC in terms of ECE emissions shows them to be highly correlated, as is fuel economy.

We first introduce the purposes and contents of this study. In the second section, we propose a methodology to develop a representative driving cycle. How to collect the driving cycle data in the metropolitan Taipei is described in the third section. Then, the characteristics of driving cycles in metropolitan Taipei are analyzed in the fourth section, and a representative driving cycle is developed in the fifth section. In the sixth section, the emissions and fuel economy tested by the representative driving cycle and ECE are analyzed. Finally, conclusions and recommendations are made.

2. METHODOLOGY

How to develop a representative driving cycle is an important issue. There is much literature on this issue. Kent *et al.* (1978), Kuhler and Karstens (1978), Yoshizumi *et al.* (1980), Watson *et al.* (1982), Lansell *et al.* (1983), Lyons *et al.* (1986), Crauser *et al.* (1989) and Andre *et al.* (1995) developed transient-type driving cycles. Perkins (1982), Gandhi *et al.* (1983) and Wang *et al.* (1985) developed steady-type driving cycles. We have tried to develop a transient-type driving cycle by using a new methodology in this study.

The idea for developing a representative driving cycle in this study was to select, from all the driving data, a driving cycle whose characteristics are most similar to those of all the driving data. An important feature of the representative driving cycle is that it really occurs on the road. The methodology to develop a representative driving cycle is described as follows.

2.1. Step 1: Define some of the assessment criteria to describe the characteristics of driving cycles

There is much literature setting forth some assessment criteria to describe and compare the characteristics of driving cycles (e.g. Kuhler and Karstens, 1978; Watson *et al*., 1982; Lyons *et al*., 1986). We mainly adopt the 10 criteria used by Kuhler and Karstens. One criterion, the average travel speed, is broken into total travel distance and total travel time so as to avoid the long total travel time. It can avoid the difficulties of long testing times in the laboratory. The definitions of the 11 criteria are shown in Table 1.

2.2. Step 2: Calculate the values of the 11 criteria for each driving cycle

We calculate the values of the 11 criteria, according to the definitions made in Step 1, for each driving cycle. For example, if we collect 442 driving cycles, it is necessary to calculate the values of the 11 criteria of these 442 driving cycles.

2.3. Step 3: Calculate the mean values of the 11 criteria for all the driving data

We calculate the mean values of the 11 criteria for all the driving data and treat them as data for a single driving cycle (a fictitious cycle). The values of these 11 criteria represent the characteristics of the population.

2.4. Step 4: Derive factor scores by using factor analysis method in statistics

Due to the fact that the criteria depend on each other (for example, the time percentages of four modes depend on each other) and are highly correlated, we use factor analysis method in statistics to derive the factor scores of driving cycles. If we directly compare the driving cycle by using these 11 criteria, which depend on each other, the results may be biased. In this step, if we collect 442 driving cycles, we must calculate the factor score of 443 driving cycles (including the cycle derived in Step 3).

Factor analysis is a kind of statistic method developed by Spearman *et al.* (Thurstone, 1947; Anderson, 1958). Its purpose is to find out the independent factors to explain the variance of criteria. The factor scores derived in factor analysis are independent. The theory of factor analysis is rather complicated but details can be found in Johnson and Wichern (1988).

Table 1. Assessment criteria for developing representative driving cycle

Criteria	Abbreviation	Unit
Travel time	**T**	s
Travel distance	**D**	m
Average running speed (idle excluded)	$\overline{V}_2$	$km\,h^{-1}$
Average acceleration of all acceleration phases (**a** > $0.1\,m\,s^{-2}$)	**a**	$m\,s^{-2}$
Average deceleration of all deceleration phases (**d** > $0.1\,m\,s^{-2}$)	**d**	$m\,s^{-2}$
Mean length of a driving period (from start to idling)	τ	s
Average numbers of acceleration–deceleration changes (and vice versa) within one driving period	**M**	
Percentage of idling time ($v < 3\,km\,h^{-1}$, $\mathbf{a} \leqq 0.1\,m\,s^{-2}$, $\mathbf{d} \leqq 0.1\,m\,s^{-2}$)	**S**	%
Percentage of acceleration time (**a** > $0.1\,m\,s^{-2}$)	**B**	%
Time percentage at constant speeds ($\mathbf{a} \leqq 0.1\,m\,s^{-2}$, $\mathbf{d} \leqq 0.1\,m\,s^{-2}$)	**K**	%
Percentage of deceleration time (**d** > $0.1\,m\,s^{-2}$)	**V**	%

2.5. Step 5: Calculate the Euclidean distance between the cycle derived in Step 3 and each driving cycle by using the factor scores derived from Step 4

Euclidean distance is a dissimilarity method in statistics. It is often used to find out the dissimilarity of the samples. Therefore, we use this method to calculate the Euclidean distance between the cycle derived in Step 3 and each driving cycle by using the factor scores derived in Step 4. The formula to calculate the Euclidean distance is shown as eqn (1).

$$D_{ij} = (\sum_{k=1}^{m}(f_{ik} - f_{jk})^2)^{0.5} \tag{1}$$

where D_{ij} is the Euclidean distance between i and j driving cycle, f_{ik} is the kth factor score of i driving cycle and m is the number of factor score.

If we collect 442 driving cycles, the Euclidean distance between the cycle derived in Step 3 and each of the 442 driving cycles should be calculated.

2.6. Step 6: Find out the smallest Euclidean distance between the cycle derived in Step 3 and each driving cycle derived from Step 5

The driving cycle with the smallest Euclidean distance between the cycle derived in Step 3 is most similar to all the driving data. Thus, we select that driving cycle as a representative driving cycle.

3. DATA COLLECTION

One purpose of this study is to develop a representative motorcycle driving cycle in metropolitan Taipei, so we must collect some driving cycle data. This was done by chasing vehicle technique. Since the driving cycle reflects the condition of traffic flow and the driving behavior of the driver, and is also influenced by trip distribution and route choices, we adopted the notion of aggregate sequential demand model in transportation. We divided metropolitan Taipei into 14 large traffic zones and 172 small traffic zones based on the ‘Household Trip Survey of Metropolitan Taipei’ (Institute of Transportation, 1992). The chasing vehicles were installed with magnetic speedometers to record the speeds of the vehicles. We assigned the first investigation by chasing vehicle to each small traffic zone and randomly selected one vehicle for chasing. The proportion of first investigation in traffic zone was equal to the proportion of the trip produced in traffic zone. The chasing vehicle must finish the investigation from the origin to the destination. After the first investigation, the chasing vehicles began the second investigation at the destination of previous trip. Then, the chasing procedure was repeated until sufficient data were collected. The characteristics of all the driving data (442 cycles), collected in the process, will reflect the characteristics of the general population if we do it carefully.

The domain of the investigation included Taipei City, Taipei County and Kweishan. The chasing vehicles included 125, 90 and 50 c.c. motorcycles, which are frequently used in metropolitan Taipei. The investigation was undertaken in November and December 1995. We collected the driving cycle data from 7:00 a.m. to 9:00 p.m. The investigator also recorded the starting time, the origin and the destination of the trip.

We collected 442 motorcycle driving cycles comprising 4667 segments (the process from previous start to next start is defined as a segment). Total travel time was 109 h, while total travel distance was 2138 km. The Kolmogorov–Smirnov test (Ebdon, 1977) was used to test the starting time, the proportion of origin and destination of the samples. The results indicate that there are no significant differences between the sample and the population.

4. THE CHARACTERISTICS OF ALL THE DRIVING DATA

The values of 11 criteria and the average travel speed of all the driving data are shown in the second column of Table 2. For the convenience of comparison, the values of criteria of four well-known driving cycles are also shown in Table 2. The average travel time of all the driving data is 890 s, approximately 15 min, while the average travel distance is 4836 m. Both the average travel time and the average travel distance of all the driving data are higher than ECE, 10 Mode and 11 Mode (Japanese driving cycles), but lower than FTP75 (American federal test procedure).

Table 2. Values of criteria

Criteria	Mean of all driving data	TMDC	FTP75	ECE	10 Mode	11 Mode
T (s)	890	950	1877	195	135	120
$\underline{D}$ (m)	4836	5109	17 788	1014	663	1020
$\overline{V}_1$ (kph)	19.6	19.4	34.1	18.7	17.7	30.6
$\overline{V}_2$ (kph)	24.4	23.8	41.6	27.1	24.1	39.4
τ (s)	84.4	77.3	70	45	50	97
M	21.2	28.8	6.0	1.0	2.0	5.0
S (%)	20.2	19.5	18.0	30.7	26.7	21.7
B (%)	29.7	31.5	33.1	18.5	24.4	34.2
K (%)	21.0	18.7	20.4	32.3	23.7	13.3
V (%)	29.1	30.3	28.5	18.5	25.2	30.8
a (m s^{-2})	0.765	0.798	0.61	0.75	0.67	0.54
d (m s^{-2})	0.782	0.829	0.70	0.75	0.65	0.60

Speed is an important criteria to measure traffic quality and is the most important factor influencing the emissions of the vehicle. The average travel speed ($\overline{V}_1$) is 19.6 kph, while the average running speed ($\overline{V}_2$) is 24.4 kph. The average travel speed of all the driving data is most similar to ECE, but average running speed is most similar to 10 Mode. We also find that the time percentage with the speed below 40 kph is 93.5% and the percentage of the segment with the average travel speed below 40 kph is 99.6%. The results reveal the fact that the speed of motorcycles in metropolitan Taipei is very low.

The mode of the vehicle can be divided into idling, accelerating, decelerating and constant speed. The percentage of idling time (**S**) is 20.2%, which is only longer than FTP75 and is most similar to 11 Mode. The time percentages of acceleration (**B**), constant speed (**K**) and deceleration (**V**) are 29.7, 21.0 and 29.1%, respectively, which are most similar to FTP75. This indicates that 58.7% of travel time of the motorcycle is in accelerating and decelerating mode, which is quite long compared to ECE and 10 Mode. The mean length of a driving period (τ) is 84.4 s. If the mean length of a driving period is short, it usually denotes that the traffic flow is congested or that the control of the traffic signals is not very good. We further analyze the distribution of the length of driving period and find that 81.8% of them are below 120 s.

As can be seen from the preceding description, motorcycles in use are often in accelerating or decelerating mode. If the average numbers of acceleration–deceleration changes within one driving period (**M**), average acceleration (**a**) and deceleration (**d**) are also rather high, it will indicate the driving behavior is of the aggressive type. The results show that the average acceleration (**a**) and deceleration (**d**) are higher than 0.765 m s^{-2}, and the average number of acceleration–deceleration changes within one driving period (**M**) is 21.2. They are higher than four well-known driving cycles. Therefore, it really indicates that the driving behavior in metropolitan Taipei is of the aggressive type. Besides, the average acceleration (**a**) and deceleration (**d**) are most similar to ECE and most dissimilar to 11 Mode.

Percentage probability of acceleration and speed of all the driving data is shown in Table 3. This matrix is obtained by subdividing the velocity field into 5-kph increments, and the acceleration field into 1 kph s^{-1} increments. When the probability matrix has been constructed, the entries are normalized on a percentage basis so that the total of all the acceleration–velocity entries add up to 100. It is found that most of the accelerations range from -3 kph s^{-1} to 3 kph s^{-1}.

It must be noted that the average travel speed, the average acceleration (**a**) and deceleration (**d**) of all the driving data are most similar to ECE. But the time percentages of four modes (**S**, B, **K**, **V**), mean length of a driving period (τ) and average numbers of acceleration–deceleration changes within one driving period (**M**) are most dissimilar to ECE.

5. TAIPEI MOTORCYCLE DRIVING CYCLE

The Taipei motorcycle driving cycle (TMDC) was developed according to the methodology described in Section 2 and is shown in Fig. 1. The factor analysis in Step 4 led to the identification of five main factor axes which explained 96% of the total variance. Then, the five factor scores derived from factor analysis were used to calculate the Euclidean distance.

Table 3. Percentage probability of acceleration and speed of all the driving data

Acc/speed	0	1–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	51–55	56–60	61–65	> 66	Sum
> 7	0.11	0.12	0.12	0.10	0.10	0.08	0.04	0.04	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.75
7	0.06	0.06	0.09	0.09	0.07	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.49
6	0.12	0.10	0.14	0.14	0.19	0.15	0.08	0.06	0.04	0.01	0.01	0.01	0.00	0.00	0.00	1.05
5	0.08	0.20	0.36	0.29	0.27	0.35	0.19	0.17	0.06	0.03	0.02	0.01	0.00	0.00	0.00	2.03
4	0.13	0.09	0.29	0.27	0.39	0.41	0.26	0.16	0.16	0.05	0.02	0.02	0.00	0.00	0.00	2.24
3	0.25	0.33	0.61	0.90	0.94	1.12	0.95	0.69	0.31	0.17	0.10	0.05	0.02	0.01	0.00	6.43
2	0.01	0.30	0.70	0.84	1.27	1.81	1.66	1.47	0.74	0.28	0.23	0.11	0.05	0.02	0.00	9.49
1	0.43	0.19	0.50	0.63	0.76	1.13	1.19	1.12	0.65	0.35	0.13	0.09	0.04	0.01	0.01	7.22
0	19.94	0.56	1.51	1.73	2.23	3.44	3.84	3.75	2.13	1.00	0.56	0.31	0.14	0.05	0.02	41.21
−1	0.00	0.63	0.59	0.46	0.72	1.28	0.84	1.19	0.58	0.21	0.21	0.08	0.03	0.02	0.01	6.84
−2	0.00	0.21	0.74	0.96	0.97	1.15	1.66	1.33	0.95	0.50	0.17	0.14	0.06	0.02	0.01	8.89
−3	0.00	0.43	0.67	0.62	0.91	1.16	0.89	0.87	0.56	0.19	0.14	0.08	0.03	0.01	0.01	6.56
−4	0.00	0.20	0.20	0.27	0.30	0.36	0.30	0.26	0.18	0.12	0.04	0.02	0.01	0.01	0.00	2.26
−5	0.00	0.08	0.21	0.36	0.30	0.29	0.40	0.21	0.18	0.07	0.03	0.02	0.01	0.01	0.00	2.18
−6	0.00	0.00	0.15	0.09	0.15	0.26	0.15	0.13	0.09	0.04	0.02	0.01	0.01	0.00	0.00	1.10
−7	0.00	0.00	0.05	0.05	0.07	0.10	0.06	0.06	0.04	0.02	0.01	0.00	0.00	0.00	0.00	0.48
< −7	0.00	0.00	0.05	0.10	0.10	0.13	0.14	0.10	0.08	0.04	0.02	0.02	0.01	0.00	0.00	0.78
Sum	21.13	3.48	6.99	7.89	9.73	13.27	12.68	11.63	6.79	3.08	1.72	0.97	0.41	0.17	0.05	100

Unit of acceleration: kph s^{-1}; unit of speed: kph.

The values of 11 criteria and the average travel speed of TMDC are shown in the third column of Table 2. As shown in Table 2, most criteria of TMDC are rather close to those of all the driving data. The difference between the average travel speed, the most important criterion, of all the driving data and TMDC is only 0.2 kph, only about 1.03% compared to all the driving data. Nine criteria (excluding average numbers of acceleration–deceleration changes within one driving period, time percentage at constant speeds and mean length of a driving period) differ less than 7% from all the driving data. Only one criterion (average numbers of acceleration–deceleration changes within one driving period, M) differs more than 40% from all the driving data. Besides, TMDC still retains the relationships between the values of criteria of all the driving data and ECE, described in Section 4.

Differences of percentage probability of speed and acceleration are often used to compare two different driving cycles (e.g. Milkins and Watson, 1983). Differences of percentage probability between all the driving data and TMDC are shown in Table 4. Only two entries are greater than 1%, and three entries are smaller than −1%. The largest difference (−1.9%) occurs in the entry where acceleration equals 2 kph s^{-1} and speed equals 31–35 kph. The second largest difference (−1.65%) occurs in the entry where acceleration equals 1 kph s^{-1} and speed equals 26–30 kph. If we define the total square difference of percentage probability as eqn (2), the total square difference of percentage probability of TMDC and all the driving data is equal to 22.37. The total

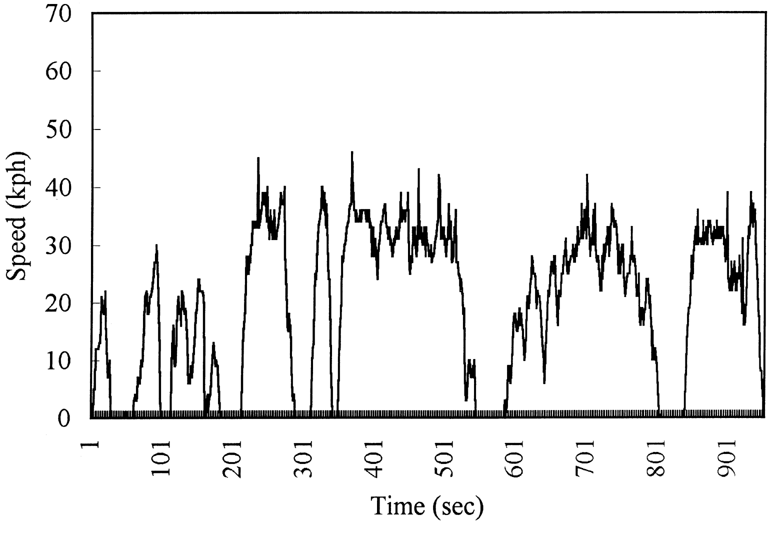

Fig. 1. Taipei motorcycle driving cycle.

Table 4. Differences of percentage probability between all the driving data and TMDC

Acc/speed	0	1–5	6–10	11–15	16–20	21–25	26–30	31–35	36–40	41–45	46–50	51–55	56–60	61–65	> 66
> 7	0.01	0.12	0.12	0.00	−0.01	0.08	−0.17	−0.28	−0.09	0.01	0.01	0.00	0.00	0.00	0.00
7	0.06	−0.05	0.09	0.09	0.07	−0.05	−0.07	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
6	0.02	−0.01	−0.07	0.14	−0.02	−0.27	−0.02	−0.26	0.04	0.01	0.01	0.01	0.00	0.00	0.00
5	−0.03	−0.11	0.04	0.29	−0.04	0.13	−0.23	−0.25	0.06	0.03	0.02	0.01	0.00	0.00	0.00
4	−0.08	0.09	−0.13	−0.36	0.28	−0.32	−0.27	−0.05	0.05	0.05	0.02	0.02	0.00	0.00	0.00
3	−0.17	−0.09	−0.23	0.16	0.10	−0.35	−0.53	−0.26	−0.11	0.17	0.10	0.05	0.02	0.01	0.01
2	0.01	0.20	0.07	0.63	0.00	0.65	0.29	−1.90	0.53	0.28	0.23	0.11	0.05	0.02	0.00
1	0.33	−0.44	0.08	−0.01	0.13	0.28	−1.65	−0.14	0.23	0.35	0.13	0.09	0.04	0.01	0.01
0	1.31	−0.70	−0.07	0.99	0.76	−0.24	0.58	−1.20	−0.50	1.00	0.56	0.31	0.14	0.05	0.02
−1	0.00	0.11	−0.36	0.15	−0.33	−0.19	−0.32	−0.71	0.37	0.21	0.21	0.08	0.03	0.02	0.01
−2	0.00	0.00	0.22	0.44	−0.08	−0.32	0.30	0.28	−0.21	0.39	0.17	0.14	0.06	0.02	0.01
−3	0.00	0.11	−0.06	0.40	0.28	−0.32	−0.69	−0.81	−0.60	0.19	0.14	0.08	0.03	0.01	0.01
−4	0.00	−0.02	−0.22	0.16	0.19	0.26	−0.02	−0.16	−0.03	0.12	0.04	0.02	0.01	0.01	0.00
−5	0.00	−0.13	0.00	−0.17	0.20	0.29	−0.02	−0.63	−0.13	0.07	0.03	0.02	0.01	0.01	0.00
−6	0.00	0.00	0.05	0.09	0.05	0.05	0.15	0.02	−0.33	−0.06	0.02	0.01	0.01	0.00	0.00
−7	0.00	0.00	0.05	0.05	−0.14	0.00	−0.04	0.06	−0.27	0.02	−0.09	0.00	0.00	0.00	0.00
< −7	0.00	0.00	−0.06	−0.01	−0.01	0.13	0.14	−0.01	−0.34	−0.17	0.02	0.02	0.01	0.00	0.00

Unit of acceleration: kph/s; unit of speed: kph.

square difference of percentage probability of TMDC and other well-known driving cycles, such as FTP75 and ECE, are also shown in Table 5. Noteworthy is the good correspondence between TMDC and all the driving data. This indicates that TMDC is a good representative driving cycle compared to the other well-known driving cycles.

$$DIF_{jk} = \sum_{i} (P_{ij} - P_{ik})^2 \tag{2}$$

where DIF_{ij} is the total square difference of percentage probability and P_{ij} is the percentage probability of i entry of j driving cycle.

If we cannot collect more driving cycle data, the characteristics of the representative driving cycle developed by the methodology may differ from all the driving data, though the characteristics of the representative driving cycle are most similar to all the driving data compared to the other driving cycles. Therefore, it is suggested that the sample size of driving cycles collected must be as large as possible.

The average travel speed, the average acceleration and deceleration of TMDC are most similar to ECE. The time percentages of four modes, mean length of a driving period and average numbers of acceleration–deceleration changes within one driving period are most dissimilar to ECE. So, it is interesting to know what are the emissions and fuel economy of TMDC and ECE.

6. EMISSIONS AND FUEL ECONOMY

One purpose of this study is to ascertain the emissions and fuel economy of TMDC. We took 45 motorcycles to test in the laboratory, including 29 with two-stroke engines and 16 with four-stroke engines randomly selected according to the proportions of brands and ages. The distribution of engine capacity and age of these 45 motorcycles is shown in Table 6. The number of motorcycles with age under 3 years, 4–6 years and over 7 years are 18, 18 and 9, respectively. The number of two-stroke engine motorcycles with engine capacity of under 50, 80–100 and over 120 c.c. are 22, 5 and 2, respectively, while the number of four-stroke engine motorcycles is 16. Because four-stroke engine motorcycles with engine capacity under 50 c.c. were not developed until 1996 in Taiwan,

Table 5. The total square difference of percentage probability of TMDC and other well-known driving cycles

	TMDC	ECE	FTP75	10 Mode	11 Mode
All the driving data	22.37	517.35	158.34	362.34	302.26
TMDC	—	543.07	189.79	416.45	358.71
ECE	—	—	718.77	850.17	743.19
FTP75	—	—	—	513.85	293.99
10 Mode	—	—	—	—	514.93

Table 6. Distribution of engine capacity and age of motorcycles

Engine type	Engine capacity (c.c.)	Age (year)			Total
		Under 3	4–6	Over 7	
2-stroke	Under 50	7	10	5	22
	80–100	2	2	1	5
	Over 120	—	1	1	2
4-stroke	Over 120	9	5	2	16
Total		18	18	9	45

most four-stroke engine motorcycles are over 120 c.c. Furthermore, motorcycles with engine capacity of over 150 c.c. are not permitted to be imported; therefore, in Taiwan almost all motorcycles are under 150 c.c.

Each motorcycle was tested both by TMDC and ECE-40 with chassis dynamometer. A total of 90 tests were conducted. The testing procedure of TMDC was similar to ECE-40, but four ECE cycles were replaced by TMDC. The emissions tested by TMDC and ECE are shown in Table 7.

As shown in Table 7, the mean emissions of CO, HC and NOx of the whole 45 motorcycles tested by TMDC are equal to 10.6, 4.586 and 0.091 g/km, respectively, while the mean emissions tested by ECE are 9.928, 3.892 and 0.081 g/km, respectively. At the same time, the mean emissions of CO, HC and NOx of the motorcycles with two-stroke engine or four-stroke engine tested by TMDC are also higher than the mean emissions tested by ECE. It is clear that the emissions tested by TMDC are higher than ECE. Comparing the motorcycles with two-stroke engines and four-stroke engines, we find that the CO and HC emissions of two-stroke engines are higher than four-stroke engines, but NOx of two-stroke engines is lower than four-stroke-engines.

Furthermore, we took the emission tested by TMDC as dependent variable and that of ECE as independent variable to conduct regression equations. The results are shown in Table 8. The t values of independent variable are greater than 1.96 in each equation. This indicates they are quite significant. Most values of R^2 are higher than 0.80. Only the R^2 of the equation describing the HC emission of four-stroke engine motorcycles tested by TMDC and ECE are lower than 0.7. As a whole, there are highly linear relationships between the emissions of TMDC and ECE.

For all 45 motorcycles, the CO emission tested by TMDC is equal to 0.88 times the emission tested by ECE plus 1.862 g/km, which is equal to 19% of the mean emission tested by ECE. The NOx emission tested by TMDC is 12.7% higher than that of ECE. The HC emission tested by TMDC is almost equal to 1.025 times the emission tested by ECE plus 0.595 g/km, which is equal to 15% of the mean emission tested by ECE. The previous results indicate that the emissions tested by TMDC and ECE are significantly different. The relationships still remain when

Table 7. Emissions and fuel economy of TMDC and ECE

Vehicle type	Item	TMDC				ECE			
		CO (g/km)	HC (g/km)	NO_x (g/km)	Fuel (km/litre)	CO (g/km)	HC (g/km)	NO_x (g/km)	Fuel (km/litre)
Both (45)	Mean	10.600	4.586	0.091	36.78	9.928	3.892	0.081	36.95
	Standard deviation	6.303	4.226	0.100	7.20	6.940	4.085	0.087	6.16
	Max.	31.955	21.563	0.390	53.70	34.528	21.690	0.330	49.37
	Min.	1.970	0.670	0.007	16.60	2.280	0.580	0.005	16.10
2-stroke (29)	Mean	11.369	6.275	0.037	34.77	10.608	5.552	0.031	35.68
	Standard deviation	7.200	4.428	0.049	7.31	7.972	4.261	0.039	6.99
	Max.	31.955	21.563	0.262	53.20	34.528	21.690	0.207	49.37
	Min.	1.970	1.790	0.007	16.60	2.280	1.880	0.005	16.10
4-stroke (16)	Mean	9.205	1.524	0.189	40.43	8.695	0.883	0.171	39.25
	Standard deviation	4.069	0.512	0.097	5.52	4.487	0.261	0.077	3.40
	Max.	17.250	2.540	0.390	53.70	18.810	1.460	0.330	46.60
	Min.	3.970	0.670	0.040	33.12	3.550	0.580	0.040	32.44

Table 8. Regression equation

Pollutant (fuel)	Vehicle type	A		B		R^2
CO	Both	1.862	(4.51)	0.880	(25.73)	0.939
	2-stroke	2.073	(3.74)	0.876	(20.82)	0.941
	4-stroke	1.629	(2.49)	0.871	(12.96)	0.923
HC	Both	0.595	(5.05)	1.025	(48.82)	0.982
	2-stroke	0.567	(2.77)	1.028	(34.92)	0.978
	4-stroke	0.263	(0.80)	1.428	(3.97)	0.530
NO_x	Both	0.0002	(0.05)	1.127	(28.73)	0.951
	2-stroke	−0.001	(−0.44)	1.249	(23.13)	0.952
	4-stroke	−0.013	(−0.58)	1.178	(9.91)	0.875
Fuel	Both	−2.904	(−1.10)	1.074	(15.28)	0.844
	2-stroke	−0.579	(−0.25)	0.991	(15.32)	0.897
	4-stroke	−12.268	(−1.28)	1.343	(5.51)	0.684

Function type is $\mathrm{TMDC}_{ij} = A + B \times ECE_{ij}$; where TMDC_{ij} is the i pollutant emission (fuel economy) of j vehicle type tested by TMDC, and ECE_{ij} is the i pollutant emission (fuel economy) of j vehicle type tested by ECE.

we compare the equation describing the emissions of two-stroke engine or four-stroke engine motorcycles.

Fuel economy tested by TMDC and ECE can be derived by carbon balance method. The results are shown in Table 7. It was found that the mean value of the 45 motorcycles tested by TMDC is 36.78 km/litre, and 36.95 km/litre for ECE. Also, it is found that the fuel economy of two-stroke engine motorcycles tested by TMDC is lower than tested by ECE, but the fuel economy of four-stroke engine motorcycles tested by TMDC is higher than tested by ECE. This indicates that the four-stroke engine motorcycle is more effective in fuel consumption during use in metropolitan Taipei than the two-stroke engine motorcycle.

We also took the fuel economy tested by TMDC as dependent variable and that of ECE as independent variable to conduct regression equations. The results are shown in Table 8. The independent variable is quite significant, since t values are greater than 1.96. The R^2 of the two equations describing all 45 motorcycles and two-stroke engine motorcycles tested by TMDC and ECE is higher than 0.8. This indicates they fit quite well. Only the R^2 of the equation describing the fuel economy of four-stroke engine motorcycles tested by TMDC and ECE is lower than 0.7. As a whole, there are highly linear relationships between the fuel economy of TMDC and ECE.

7. CONCLUSIONS AND RECOMMENDATIONS

This study proposed a methodology to develop a representative driving cycle of metropolitan Taipei. After collecting extensive driving cycle data of metropolitan Taipei, we developed TMDC. The methodology was proved to be a good methodology by comparing the characteristics of the TMDC and all the driving data. The characteristics of TMDC are high average acceleration and deceleration, high acceleration–deceleration changes and low average travel speed.

Forty-five motorcycles, including 29 with two-stroke engines and 16 with four-stroke engines, were tested in a laboratory by using TMDC and ECE. The results reveal that the emissions of motorcycles tested by TMDC are higher than those tested by ECE, regardless of whether they are two-stroke engines or four-stroke engines. The fuel economy of the two-stroke engine motorcycles tested by TMDC is lower than that tested by ECE, but the fuel economy of the four-stroke engine motorcycles tested by TMDC is higher than that tested by ECE. A linear regression of TMDC in terms of ECE emissions shows them to be highly correlated, as is fuel economy. The CO and HC emissions of two-stroke engine motorcycles are higher than four-stroke engine motorcycles, and the NOx emission of two-stroke engine motorcycles is lower than four-stroke engine motorcycles, regardless of whether they are tested by TMDC or ECE.

If the sample size of driving cycle is limited, the representative driving cycle developed by the methodology proposed in this study may not reflect the characteristics of the whole sample. Therefore, it is suggested that the sample size of driving cycle collected must be as large as possible.

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