Driving Cycle Construction of City Road for Hybrid Bus Based on Markov Process

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Abstract. By using the relevant theory of Markov chain, the actual driving data are compressed and reconstructed, and then the city road driving cycle is constructed based on characteristic parameters such as velocity, acceleration and gradient. In the process of constructing the driving cycle, corresponding state division principle and the evaluation criteria of characteristic parameters are designed against hybrid bus. The comparison results show that the driving cycle constructed using Markov processes can reflect the real driving characteristics on city roads.

Introduction

Driving cycle is a velocity-time trace that describes driving characteristics of specific vehicle in specific environment. Driving cycle has been an important parameter to estimate real-world vehicle emissions and fuel consumption which are evaluation criterions of power chain design. [1,2]

When vehicle is in motion, the driver changes the output power of vehicle's power chain and finally changes vehicle velocity. The vehicle state in the next second is only related with current road condition. Then we could say that this random variable follows Markov process. [3]

Compared with traditional construction method, the Markov driving cycle method better reflects the nature of velocity change. Random selection in traditional method is substituted by selection based on Markov transition matrix, and the accuracy of construction is improved. [4]

2 The original driving data collection

The required parameters of the original driving data collection are velocity, acceleration and gradient. This paper adopts the OXTS Inertial+ to measure velocity, acceleration and gradient of vehicle. These parameters are combined measured by Satellite-based Global Positioning System (GPS) and Inertial Navigation System. OXTS Inertial+ measurement accuracy is shown in table 1.

Table 1Measurement accuracy of the experimental equipment

Position Accuracy	Velocity Accuracy	Roll/Pitch	Acceleration			
			Bias	Linearity	Scale Factor	Range
2cm 1σ	0.05 km/hRMS	0.03° 1σ	10 mm/s² 1σ	0.01%	0.1% 1σ	100 m/s²

3 Data Preprocessing

The data preprocessing is consists of four steps: fragment division, state cluster division, estimation of the transition matrix and analysis of characteristic parameters.

3.1 Fragment Division

The fragments, which are the minimum unit of the driving cycle construction, are divided from the original driving data according to specific rules. These fragments will be used to analyze the change regulation of velocity.

3.1.1 The selection of velocity threshold

The object of this study is hybrid electric bus. The pure electric mode is often applied when the vehicle velocity is low. So if the vehicle velocity is lower than the selected velocity threshold, this sampling point should be divided into the fragment which we called “stop fragment”. Analyze all of sampling points, whose velocity is below 4Km/h, and the statistical data is shown in table 2

Table 2 Probability distribution of sampling points in low velocity

velocity range(Km/h)	0~0.4	0.4~0.7	0.7~1	1~1.5	1.5~2	2~2.5	2.5~3	3~3.5	3.5~4
Probability distribution	50.01%	17.32%	9.36%	7.85%	4.70%	3.36%	2.80%	2.42%	2.20%

It is obvious from table 2 that the sampling points whose velocity is less than 0.7Km/h account for 67.32% of all the sampling points. After comprehensive considered, 0.7Km/h is selected as the velocity threshold of stop fragment.

3.1.2 The selection of acceleration threshold

The acceleration threshold selection is as same as the velocity threshold. When vehicle travels at a uniform velocity, the vehicle’s acceleration fluctuated in a small range.

Table 3 Probability distribution of sampling points in stop fragments

absolute acceleration	0~0.05	0.05~0.1	0.1~0.15	0.15~0.2	0.2~0.25	0.25~0.3	0.3~0.35	>0.35
Probability distribution	82.09%	9.92%	2.59%	1.23%	0.75%	0.60%	0.49%	2.33%

As we can see from table 3, about 94.6% of accelerometer readings of the sampling points are between 0 and 0.15 when the vehicle is stationary. And it is acceptable that the acceleration threshold should be set to 0.15.

3.1.3 Basis of fragment division

The basis of fragment division is shown in Fig. 1.

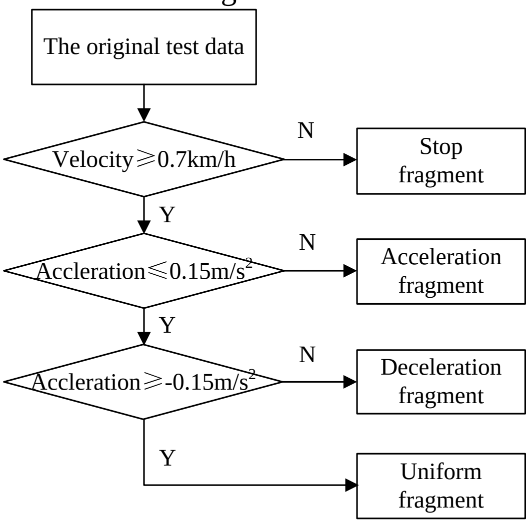

Figure 1 Basis of Fragment Division

3.2 State cluster division

3.2.1 Calculation for the rode power and the nominal velocity

To completely descript the driving condition, the road power is introduced as an important basis of state cluster division. Road power, calculated in Eq. 1, captures the combined effects of rolling resistance, aerodynamic resistance, acceleration resistance and gradient resistance.

$$\begin{cases} P_{0(a\le 0.15)} = \dfrac{1}{\eta_T}\left(\dfrac{Gfu_a}{3600} + \dfrac{Giu_a}{3600} + \dfrac{C_D A u_a^3}{76140}\right), \quad a \le 0.15 \\ P_{0(a>0.15)} = \dfrac{1}{\eta_T}\left(\dfrac{Gfu_a}{3600} + \dfrac{Giu_a}{3600} + \dfrac{C_D A u_a^3}{76140} + \dfrac{\delta m u_a}{3600}\dfrac{du}{dt}\right), a > 0.15 \end{cases} \tag{1}$$

Road power is not a direct parameter to divide the original data, and we need a velocity parameter to be the division criterion. Nominal velocity, calculated in Eq. 2, is a good choice. where u is the vehicle nominal velocity.

$$\begin{cases} P_{(a\le 0.15)} = \frac{1}{\eta_T}(\frac{Gfu}{3600} + \frac{C_D Au^3}{76140}) = P_{0(a\le 0.15)}, a \le 0.15 \\ P_{(a>0.15)} = \frac{1}{\eta_T}(\frac{Gfu}{3600} + \frac{C_D Au^3}{76140} + \frac{\delta mu}{3600}\frac{du}{dt}) = P_{0(a>0.15)}, a > 0.15 \end{cases} \quad (2)$$

3.2.2 State cluster division

According to the vehicle nominal velocity discussed above, the average nominal velocity of each fragment can be calculated. According to the average velocity, all the fragments are labeled by 7 state clusters: (-∞,5],[5,15],[15,25],[25,35],[35,45],[45,55],[55,∞]. The state clusters are collections of fragments with similar average velocity characteristics.

3.3 Estimation of the transition matrix

Vehicle's driving condition translates from one state to another along with the time. The transition matrix is estimated by counting the translation of state in the original data. The expression of elements in the transition matrix is shown in Eq. 3.

$$T = \begin{pmatrix} 0.7432 & 0.1879 & 0.0508 & 0.0167 & 0.0014 & 0 & 0 \\ 0.1123 & 0.6732 & 0.1796 & 0.0304 & 0.0043 & 0.0002 & 0 \\ 0.0284 & 0.1520 & 0.6023 & 0.1790 & 0.0331 & 0.0042 & 0.0010 \\ 0.0159 & 0.0220 & 0.2054 & 0.5245 & 0.1955 & 0.0329 & 0.0039 \\ 0.0023 & 0.0024 & 0.0328 & 0.2587 & 0.4789 & 0.1890 & 0.0359 \\ 0.0003 & 0.0002 & 0.0057 & 0.0585 & 0.3689 & 0.3925 & 0.1739 \\ 0 & 0 & 0.0010 & 0.0158 & 0.1041 & 0.3684 & 0.5108 \end{pmatrix} \qquad p_{ij} = \frac{N_{ij}}{\sum_j N_{ij}} \quad (3)$$

where N_{ij} is the number of individuals in state i at time t-1 and j at time t.

The calculation results T, a 7×7 matrix, is shown below:

3.4 Calculation for PM

PM (Performance Measure) characterize the difference between the original data and alternative driving cycles that have been constructed. We define the final representative cycle to be the one that has the lowest value of PM. The calculation for PM is consists of three steps:

(1) We obtain a n×16 matrix, denoted by M, by counting characteristic parameters of every alternative driving cycle. And then denote M_0 as the characteristic parameters matrix of the original data. The parameters, shown in table 4, typically describe the characteristics of the average driving behavior in term of velocity, acceleration and road power, etc. [5]

Table 4 Characteristic parameters of the original data

	Characteristic Parameters	statistic		Characteristic Parameters	statistic
1	Proportion of stop time	24.09%	9	Maximum acceleration	4.507
2	Proportion of uniform velocity	19.91%	10	Acceleration standard deviation	0.5944
3	Proportion of acceleration	30.31%	11	Minimum gradient	-4.59%
4	Proportion of deceleration	25.69%	12	Maximum gradient	5.61%
5	Velocity standard deviation	13.67	13	Average gradient	0.54%
6	Maximum velocity	53.762	14	Minimum road power	-32.6027
7	Average velocity	14.8962	15	Maximum road power	627.1849
8	Minimum acceleration	-5.399	16	Average road power	24.7528

(2) Note that in table 4, the ranges of characteristic parameters are totally different. Without normalization, the PM value would be dominated by one or two characteristic parameter that has a large value range. The expression is shown in Eq. 4

$$\begin{cases} pm = \left| M_{(n\times16)} - (1,1\cdots,1)^{T}_{(n\times1)} \times M_{0(1\times16)} \right| \\ PM_{(k,i)} = \dfrac{pm_{(k,i)} - pm_{i\min}}{pm_{i\max} - pm_{i\min}}, k \in (1,n), \quad i \in (1,16) \end{cases} \tag{4}$$

(3) The final PM of the kth alternative driving cycle is obtained by integrating elements of row k in matrix PM.

4 Driving Cycle Construction

In this study, the entire driving cycle is divided into three parts: starting part, middle part and ending part. According to the theory of Markov chain, the probability of the current state s_t depends only on the previous state s_{t-1}. In the starting part and the ending part, however, the movement trend of vehicle has been determined, and the method based on Markov theory is not applicable.

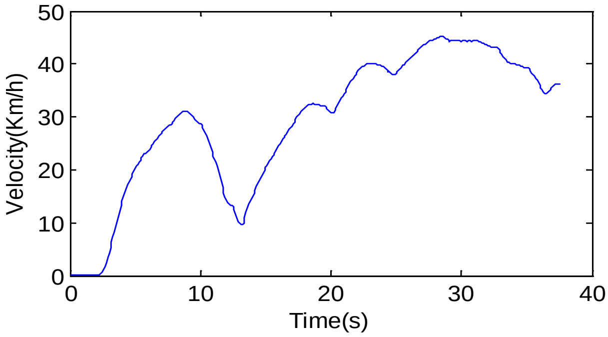

Figure 2 The selected starting part

4.1 Selection of starting part

The selection of starting part is divided into 2 steps. First, according to specific rules, select all alternative starting part from the original data. The duration of each alternative starting part last 60s-120s. Second, calculate the PM value of each part, and the part having the lowest PM value will be chosen as the final starting part.

According to the related literature at home and abroad, the duration of starting part is set to 75s. The selection rules are shown below:

(1) Set the checkpoint is at time t. All velocities of sampling points in the range of (t-5,t) are less than velocity threshold (0.7 Km/h).

(2) All velocities of sampling points in the range of (t,t+10) are more than velocity threshold (0.7 Km/h).

(3) When two criteria above are met, record this checkpoint and select all sampling points in the range of (t-5,t+69) as the alternative starting part.

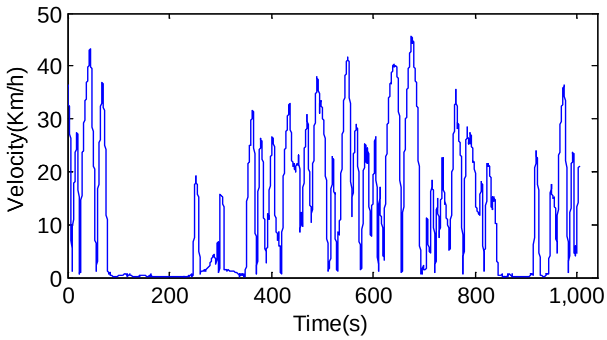

Figure 3 The selected middle part

4.2 Construction of middle part

The construction of middle part is a typical process solved by Monte Carlo method. Once a fragment is selected, its state as well as terminal velocity are identified. A random number is generated to determinate the next fragment's state based on the probability of the corresponding row in the transition matrix.

Before calculating the PM value, the alternative middle part should be combined with the selected starting part. The one who has the lowest PM value will be chosen as the final middle part.

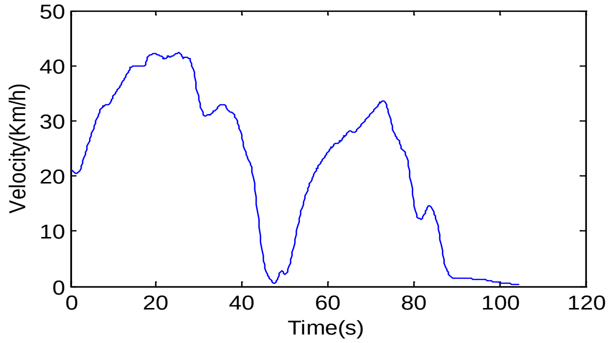

Figure 4 The selected ending part

4.3 Selection of ending part

The ending part selection method is as same as the starting part's. The selection rules are shown below:

(1) Set the checkpoint is at time t. All velocities of sampling points in the range of (t-10, t) are more than velocity threshold (0.7 Km/h).

(2) All velocities of sampling points in the range of (t, t+5) are less than velocity threshold.

(3) When two criteria above are met, record this checkpoint and select all sampling points in the range of (t-114, t+5).

(4) Check all sampling points in the range of (t-114, t+5). If there is such a point that the velocity of this point is very close to the terminal velocity of middle part, record this point, note it by t_0, and select all sampling points in the range of (t_0, t+5) as the alternative ending part.

Finally, calculate the PM value of each alternative ending part, and choose the cycle that has the lowest PM value to be the final ending part.

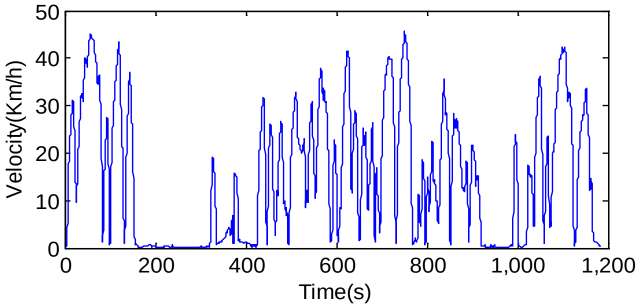

Figure 5 The final driving cycle for hybrid bus

4.4 Construction of driving cycle

Construct the final driving cycle by combining the starting part, the middle part and the ending part selected above to be a complete velocity-time curve.

5 Conclusions

1 The mathematical statistics theories related with Markov chain are used to construct a driving cycle of city road for hybrid bus. And a new method to divide vehicle state clusters is proposed during the construction process.

2 A special method for PM calculation, which eliminates differences caused by non-uniform unit between different characteristic parameters, guarantees the reasonability of part selection.

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