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Comparative Study of VSP Binning Methods for Estimating Fuel consumptions of LDVs on Urban Roads

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Abstract. The micro-scale fuel consumption model is a tool commonly used to evaluate the effect of traffic flow conditions on vehicle fuel consumptions, which is an essential step in developing traffic management strategies for saving fuels. In developing any micro-scale fuel consumption model, the Vehicle Specific Power (VSP) binning method has been widely adopted in recent years as a fundamental approach. Existing studies have shown that the high distribution frequency when VSP=0 contributes to high fuel consumptions, so a question quickly emerged about whether VSP=0 should be designed as an independent VSP bin in the VSP binning method. This paper strives to compare different VSP binning methods for Light-Duty Vehicles (LDVs) on urban roads in Beijing in terms of their effects on the estimation of fuel consumptions. After collecting and processing field vehicle activity data and fuel consumption data, three VSP binning methods are proposed for the study. Then, total fuel consumptions and fuel consumption factors are calculated by using the proposed VSP binning methods as well as the second-by-second and average travel speed data. Finally, the estimation accuracy of total fuel consumptions and fuel consumption factors based on the three different VSP binning methods are compared for LDVs on urban roads. The study proves that an independent VSP bin at VSP=0 is indeed necessary, which can improve the estimation accuracy on both total fuel consumptions and fuel consumption factors.

Key words: Micro-Scale Fuel Consumption Model; VSP Binning Methods.

INTRODUCTION

Different traffic management, traffic control, and travel demand management policies can affect the vehicle fuel consumption by influencing traffic conditions of the road network. The micro-scale fuel consumption model has become an effective research tool to evaluate reductions of the fuel consumption as a result of implementing various policies. Basic inputs of a micro-scale fuel consumption model are traffic flow parameters, such as travel speed and traffic volume, so the model is usually able to reflect the effect of traffic flow conditions on the road fuel consumption.

In past decades, the average speed has been used directly to characterize vehicle activities in the fuel consumption model. With the application of advanced technologies for on-road fuel consumption and emission measurements, it has been found that mathematical relationships between the average travel speed and fuel consumptions are irregular. Nowadays, the power demand-based parameters, e.g. Vehicle Specific Power (VSP) and the logarithm of the Total Absolute Difference of the vehicle instantaneous speed Ln (TAD), begin to replace the average speed as the explanatory variable for fuel consumptions, especially in the micro-scale fuel consumption model. As the typical

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power demand-based parameter, the VSP (1) has been reported having strong correlations with vehicle fuel consumptions, thus has widely been applied in fuel consumption models.

Since VSP is an instantaneous parameter, its values need to be divided or partitioned into bins with a certain span for the purpose of the analysis (2). The VSP binning method defines operating mode bins based on VSP values with an attempt to refine fuel consumption estimates within each VSP bin using the typical regression analysis (3). Therefore, the determination of VSP bins is a critical issue in the fuel consumption modeling process (4).

In the determination of VSP bins, several key considerations should be taken into account. First, since VSP binning methods are used to acquire fuel consumption rates with the statistical method (5), the determination of VSP bins must also follow a statistical approach in order to minimize the error of fuel consumption rates. Second, operating characteristics of vehicle should be considered in the determination of VSP bins. Existing research has found that the fuel consumption rate when the vehicle is idling (i.e. VSP=0) is the lowest among all VSP bins (6), because the vehicle engine has no load in such condition. However, it has also been found that the data when VSP=0 has a high frequency, which then induce high emission contributions (4). So it is necessary to compare the difference between different VSP binning methods, especially methods with versus without an independent bin for VSP=0, e.g. idling condition. Finally, for different road types, frequencies of the idling are quite different. Therefore, VSP binning methods should also be studied for different road types.

To examine the difference between different VSP binning methods, total fuel consumptions and fuel consumption factors need to be compared for different VSP binning methods. The comparison of total fuel consumptions can determine the accuracy of the vehicle fuel consumption estimation for a certain road section or a driving cycle, while the comparison of fuel consumption factors can provide the accuracy of the estimation for different average speeds.

OVERVIEW OF EXISTING STUDIES

Numerous parameters have been used in past studies in developing fuel consumption models. Hansen et al. (7) and Zachariadis and Samaras (8) used the speed and acceleration matrices to describe vehicle activities. Andre et al. (9) and Joumard et al. (10) developed a similar approach but both applied the product of the speed and acceleration to replace the acceleration rate. They used the combination of linear, quadratic, and cubic speed and acceleration terms for the development of the VT-Micro model by using the regression method. Barth et al. (11) developed the Comprehensive Modal Emission Model (CMEM), which used the power-demand modeling approach to estimate the fuel consumption and engine out emissions.

The concept of VSP was first proposed by Jiménez-Palacios (1), which is defined as the vehicle instantaneous tractive power per unit vehicle mass. This parameter could establish a better relationship between the vehicle fuel consumption and vehicle activities. Moreover, the VSP value can be easily obtained from the field test. Therefore, The VSP-based approach, also called the VSP binning method or approach, has widely been accepted in the fuel consumption modeling, which has already been adopted by the Motor Vehicle Emission Simulator (MOVES) (12) and International Vehicle Emissions (IVE) models (13).

The research team at North Carolina State University (NCSU) used a statistical technique known as the Hierarchical Tree-Based Regression (HTBR) to decide VSP bins (5). HTBR is an analytical technique that determines optimal points for splitting data to minimize the variability (5). The U.S. Environmental Protection Agency (EPA) developed the modeling method based upon 14 VSP bins, each divided into four strata representing two engine sizes and two odometer reading categories (3). This method is referred to as the “56-bin” method because of the 56 bins required (3).

Xu et al. (4) developed a new binning method with a total of 24 VSP bins resulted. In their method, both VSP intervals of VSP<0 and VSP=0 were each defined as an independent bin. This new method was validated by using the real world CO2 emission data collected in Beijing.

Song et al. (14) developed a VSP distribution model, which connected the average travel speed with the VSP distribution for LDVs on the urban restricted access roadway. In this model, the VSP distribution was shown to replicate a normal distribution. The mean of the VSP distribution was found strongly correlated with the VSP value when cruising at the average travel speed and the standard deviation of the VSP distribution could be expressed roughly as a power function of the average travel speed.

A review of existing studies has found that few efforts have been made to study the influence of different VSP binning methods, especially when considering VSP=0 as an independent bin, on the estimation of fuel consumptions. Thus, this paper strives to examine how different VSP binning methods for Light-Duty Vehicles (LDVs) affect fuel consumptions.

METHODOLOGY

The purpose of this paper is to compare different VSP binning methods in terms of their effect on the estimation of fuel consumptions. To this end, a total of 47,385 records of second-by-second GPS and fuel consumption data were collected from selected vehicles.

Data Source

The study conducted field tests for 6 different vehicles to collect second-by-second vehicle activity and fuel consumption data using a GPS device and a fuel consumption measurement system. The basic information of the tested vehicles is provided in Table 1. To avoid influences from different driving behaviors, the same driver was employed in all tests.

TABLE 1. Parameters of Tested Vehicles

Vehicle ID	Vehicle Brand	Vehicle Model	Vehicle Age	Gross Weight	Engine Size
1	CHERY	QQ	3	1,265 KG	1.1 L
2	Volkswagen	JETTA	4	1,545 KG	1.6 L
3	Volkswagen	SANTANA	3	1,560 KG	1.8 L
4	Volkswagen	PASSAT	4	1,700 KG	2.0 L
5	AUDI	A6L	2	2,185 KG	2.4 L
6	GM	GL8	3	2,470 KG	3.0 L

The Columbus V-900 Multifunction GPS Data Logger and the Flowtronic S8005C fuel consumption measurement system were used to collect vehicle activity and fuel consumption data in the tests. The measuring resolution and accuracy of Flowtronic S8005C fuel consumption measurement system is 4x10-3 ML and ±0.5%.

Raw data records from the GPS and the on-road fuel consumption measurement system consist of the longitude, latitude, time, instantaneous speed and fuel rate on a second-by-second basis.

Two tests were conducted for each tested vehicle, and all the tests were performed in peak hour. Second-by-second vehicle activity and fuel consumption data in the first test were used to develop fuel consumptions with different VSP binning methods, and the data in the second test were used to examine the estimation accuracy of fuel consumptions based on different VSP binning methods. After the process of the data quality control, a total of 47,385 records of valid second-by-second vehicle activity and fuel consumptions data were identified for this study. Based on continuous points for each test, all records were divided into 789 speed trajectories, which are defined as 60 seconds of continuous speed data. Then, all speed trajectories are grouped into 36 average speed bins at a step length of 2 km/h.

VSP Binning Methods

In this study, the basic logic in estimating fuel consumptions is to divide the entire vehicle operations into smaller VSP bins, and then aggregate fuel consumptions of all VSP bins (14) to estimate total fuel consumptions. The fuel consumption in each VSP bin is obtained by multiplying the VSP distribution frequency for that bin by the fuel consumption rate in that bin. In existing studies, the equation for calculating the VSP for LDVs is as shown in Equation (1) (14).

$$VSP = v \cdot [1.1 \cdot a + 9.81 \cdot grade(\%) + 0.132] + 0.000302 \cdot v^3 \tag{1}$$

Where v is the instantaneous speed, a is the acceleration, and grade stands for the grade of the slope on the road. Since the terrain is flat in the test route, the influence of this parameter is assumed to be zero in this paper.

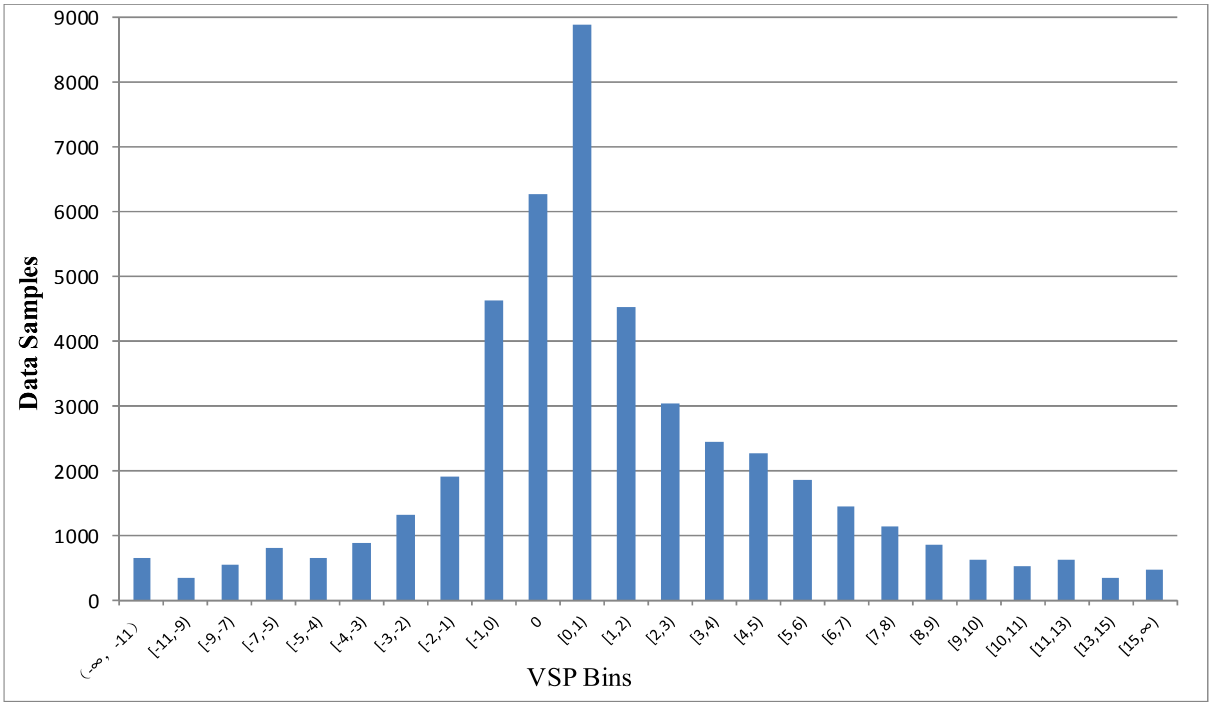

FIGURE 1. VSP distribution of all the field second-by-second data

It is shown that the VSP value in the range of (0,1) has the highest VSP distribution frequency and data samples, and VSP=0 accounts for the second highest one. In order to estimate fuel consumptions in this study, we propose the following three VSP binning methods.

VSP Binning Method A

In the previous study, a binning approach was used as provided in Equation (2), in which the VSP data were first binned into an equal 1 kW/ton interval and then the average fuel consumption rate within each bin was calculated (15). This approach is used as the first VSP binning method in this study.

$$VSP \in [i-0.5, i+0.5), VSP\ bin = i, (\text{ n is consecutive integer from -24 to 24}) \tag{2}$$

VSP Binning Method B

This second proposed VSP binning method is the same as VSP binning method A, except that the VSP interval when VSP=0 is defined as an independent bin. Table 2 shows sample frequencies of all the field second-by-second data with VSP binning method B.

VSP Binning Method C

Previous study (4) developed principles for developing VSP binning methods: (1) VSP bins should have statistically significant different average fuel consumptions rates from one another; and (2) no single VSP bin should dominate the estimation of total fuel consumptions. Based on above two principles and the consideration of the independent VSP bin at VSP=0 in this study, VSP binning method C is proposed as shown in Table 3, which shows sample frequencies of all the field second-by-second data with VSP binning method C.

TABLE 2. Sample Frequency Based on VSP Binning Method B

Bin ID	VSP Bin	Frequency	Bin ID	V S	Frequency	Bin ID	VSP Bin	Frequency
1	[-24.5,-23.5)	0.05%	18	[-7.5,-6.5)	0.58%	35	[7.5,8.5)	1.69%
2	[-23.5,-22.5)	0.02%	19	[-6.5,-5.5)	0.67%	36	[8.5,9.5)	1.15%
3	[-22.5,-21.5)	0.02%	20	[-5.5,-4.5)	1.03%	37	[9.5,10.5)	0.95%
4	[-21.5,-20.5)	0.02%	21	[-4.5,-3.5)	1.40%	38	[10.5,11.5)	0.62%
5	[-20.5,-19.5)	0.02%	22	[-3.5,-2.5)	1.86%	39	[11.5,12.5)	0.43%
6	[-19.5,-18.5)	0.03%	23	[-2.5,-1.5)	3.01%	40	[12.5,13.5)	0.38%
7	[-18.5,-17.5)	0.08%	24	[-1.5,-0.5)	9.78%	41	[13.5,14.5)	0.24%
8	[-17.5,-16.5)	0.07%	25	[-0.5,0)	5.27%	42	[14.5,15.5)	0.19%
9	[-16.5,-15.5)	0.10%	26	0	13.33%	43	[15.5,16.5)	0.17%
10	[-15.5,-14.5)	0.10%	27	(0,0.5)	8.28%	44	[16.5,17.5)	0.14%
11	[-14.5,-13.5)	0.12%	28	[0.5,1.5)	17.33%	45	[17.5,18.5)	0.09%
12	[-13.5,-12.5)	0.18%	29	[1.5,2.5)	7.34%	46	[18.5,19.5)	0.06%
13	[-12.5,-11.5)	0.17%	30	[2.5,3.5)	5.80%	47	[19.5,20.5)	0.02%
14	[-11.5,-10.5)	0.31%	31	[3.5,4.5)	5.46%	48	[20.5,21.5)	0.07%
15	[-10.5,-9.5)	0.35%	32	[4.5,5.5)	4.41%	49	[21.5,22.5)	0.06%
16	[-9.5,-8.5)	0.38%	33	[5.5,6.5)	3.04%	50	[22.5,23.5)	0.02%
17	[-8.5,-7.5)	0.55%	34	[6.5,7.5)	2.52%	51	[23.5,24.5)	0.03%

TABLE 3. Sample Frequency Based on VSP Binning Method C

Bin ID	VSP Bin	Frequency	Bin ID	VSP Bin	Frequency	Bin ID	VSP Bin	Frequency
1	(-∞, -11)	1.39%	9	[-1, 0)	9.81%	17	[6, 7)	3.06%
2	[-11, -9)	0.76%	10	0	13.33%	18	[7, 8)	2.42%
3	[-9, -7)	1.17%	11	[0, 1)	18.84%	19	[8, 9)	1.84%
4	[-7, -5)	1.72%	12	[1, 2)	9.59%	20	[9, 10)	1.35%
5	[-5, -4)	1.39%	13	[2, 3)	6.44%	21	[10, 11)	1.11%
6	[-4, -3)	1.86%	14	[3, 4)	5.19%	22	[11, 13)	1.34%
7	[-3, -2)	2.79%	15	[4, 5)	4.83%	23	[13, 15)	0.76%
8	[-2, -1)	4.05%	16	[5, 6)	3.93%	24	[15, +∞)	1.03%

VSP Distribution Model

Second-by-second data are not always available in estimating fuel consumptions. Nevertheless, the average speed data are always readily available. The previous study has developed the relationship between the second-by-second speed and the corresponding VSP distribution and average speeds (14), which was basically viewed as a VSP distribution model used to reversely derive VSP distribution frequencies given average speeds. Based on the existing study, VSP distribution patterns for LDVs on urban roads follow a statistical normal distribution. The mean of the normal distribution equals the VSP at the average travel speed, and the standard deviation can be expressed roughly as a linear function of the average travel speed (16). Then, the average travel speed for each speed trajectory can be used to derive VSP distribution frequencies by using the VSP distribution model, as shown in Equation (3).

$$f(VSP) = \frac{1}{\sigma_L\sqrt{2\pi}} e^{-\frac{(VSP-\mu_L)^2}{2\sigma_L{}^2}}$$

$$\mu_L = 0.132 * \bar{v} + 0.000302\bar{v}^3$$
$$\sigma_L = 1.382 * \bar{v}^{0.3961} \quad (3)$$

Where f (VSP) is the density function for the VSP distribution, $\bar{v}$ is the average travel speed in the unit of m/s, μ_L is the mean VSP value, and σ_L is the standard deviation of VSP distributions.

COMPARISONS AND DISCUSSIONS

Comparison of Total Fuel Consumptions

To compare total fuel consumptions estimated based on different VSP binning methods, total fuel consumptions for each field test were calculated and compared with the field fuel consumptions data. The comparison process is designed as follows:

Step 1: According to three VSP binning methods, the second-by-second speed and fuel consumption data are divided into VSP bins. Then, the average fuel consumption per second in each VSP bin becomes the fuel consumption rate for the tested vehicle.

Step 2: Sum up fuel consumption rates according to second-by-second instantaneous VSP values to obtain the fuel consumption estimation based on different VSP binning methods.

Step 3: Compare total fuel consumptions between estimated values based on different VSP binning methods and the field collected fuel consumption data.

Table 4 shows estimation errors of total fuel consumptions for each test based on three VSP binning methods.

TABLE 4. Comparison of Estimation Errors of Total Fuel Consumptions with Different VSP Binning Methods

Test ID	Total Field Fuel Consumption (ML)	VSP Binning Method A		VSP Binning Method B		VSP Binning Method C	
		Total (ML)	Error	Total (ML)	Error	Total (ML)	Error
2	1852	1985	7.18%	1934	4.43%	1941	4.81%
4	2408	2381	1.12%	2401	0.29%	2418	0.42%
6	2183	2060	5.63%	2080	4.72%	2093	4.12%
8	3738	3623	3.08%	3652	2.30%	3648	2.41%
10	3393	3338	1.62%	3352	1.21%	3402	0.27%
12	3837	3732	2.74%	3749	2.29%	3771	1.72%
Average Error		3.56%		2.54%		2.29%	

It is shown from Table 4 that the VSP binning approach C exhibits a higher accuracy on fuel consumption estimations than VSP binning method A and method B. Estimation errors between VSP binning method B and C are relatively close.

Comparison of Fuel Consumption Factors

The following is the process to compare fuel consumption factors.

Step 1: Calculate the average speed value for each speed trajectory by the second-by-second speed data, and then group speed trajectories into 36 bins by their average travel speeds at an interval of 2 km/h.

Step 2: Derive the field fuel consumption data and calculate fuel consumptions by the field data and estimated values based on three VSP binning methods. Sum up the distance travelled at each average speed bin, and calculate speed specific fuel consumption factors by the field data and estimated values based on three VSP binning methods.

Step 3: Compare fuel consumption factors for each tested vehicle between estimated values based on different VSP binning methods and the field collected fuel consumption data.

By taking the tested vehicle 2 as an example, Table 5 shows the estimations errors of fuel consumption factors between different fuel consumption estimations based on three VSP binning methods at different average speed bins.

TABLE 5. Estimations Errors of Fuel Consumption Factors with Different VSP Binning Methods at Different Average Speed Bins

Average Speed Bin(Km/h)	VSP Binning Method A	VSP Binning Method B	VSP Binning Method C
0-10	12.32%	11.40%	11.10%
10-20	11.28%	11.15%	11.02%
20-30	11.78%	10.73%	10.72%

According to the data in Table 5, in the low average speed interval (less than 10 km/h), average estimation errors based on three VSP binning methods are 12.32%, 11.4% and 11.1%. In the high average speed interval (higher than 10 km/h), average estimation errors are 11.53%, 10.94% and 10.87%.

In statistics, the mean squared error (MSE) of an estimator is used to quantify the difference between values implied by an estimator and the true value. A low MSE means a high accuracy of the estimator. By using fuel consumption factors derived from the field data as the true value, the MSE of fuel consumption factors based on three VSP binning methods were calculated. Figure 2 shows the resulting MSEs of fuel consumption factors for each tested vehicle.

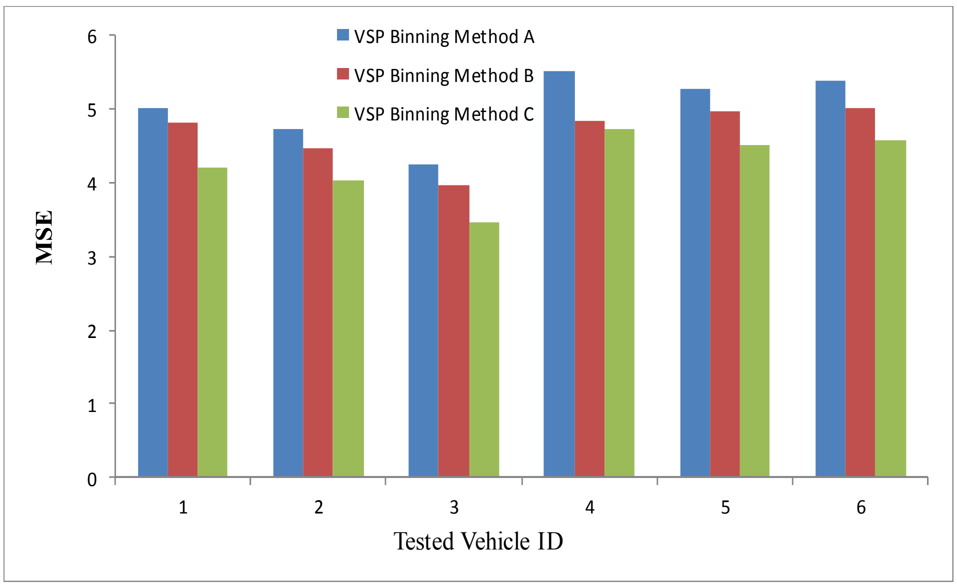

FIGURE 2. Comparison of variances of fuel consumption factors between different VSP binning methods

It is shown from Figure 2 that the MSE of fuel consumption factors based on VSP binning method C is the lowest of the three VSP binning approaches. It implies that VSP binning method C would be more accurate on estimating fuel consumption factors than other two methods.

Comparison of Estimations Based on Average Travel Speed

The VSP distribution model in Equation (3) makes it possible to estimate fuel consumptions by using the average speed for each speed trajectory. Fuel consumption estimations based on the average speed were calculated and compared with the field data. The process is described as follows:

Step 1: Apply the average travel speed for each speed trajectory to the VSP distribution model to estimate the VSP distribution for each speed trajectory, and then combine the calculated VSP distribution with the fuel consumption rate based on different VSP binning methods to derive the fuel consumption.

Step 2: The estimation of the fuel consumption for the VSP bin when VSP=0 is multiplying the bin frequency by the fuel consumption rate at VSP=0 for each average speed.

Step 3: Compare errors between the field fuel consumption and fuel consumption estimations, as shown in Table 6.

TABLE 6. Comparison of Estimations of Total Fuel Consumptions with Different VSP Binning Methods Based on Average Travel Speed

Test ID	Total Field Fuel Consumption (ML)	VSP Binning Method A		VSP Binning Method B		VSP Binning Method C	
		Total (ML)	Error	Total (ML)	Error	Total (ML)	Error
2	1852	1654	10.69%	1663	10.23%	1828	1.30%
4	2408	2817	16.99%	2797	16.17%	2812	16.78%
6	2183	2193	0.46%	2192	0.41%	2375	8.80%
8	3738	4112	10.01%	4100	9.68%	4129	10.46%
10	3393	3443	1.47%	3440	1.38%	3521	3.77%
12	3837	3993	4.07%	3985	3.87%	4087	6.52%
Average Error		7.28%		6.96%		7.94%	

It is shown from Table 6 that VSP binning method B exhibits a higher accuracy on fuel consumption estimations when the average travel speed is used as the major input. Although errors from VSP binning method C are higher most of the times, they are not that different from those from VSP binning methods A and B.

CONCLUSIONS

Main findings of this paper are summarized as follows:

1. In estimating total fuel consumptions and fuel consumption factors with second-by-second and average travel speed data, the design of an independent VSP bin for VSP=0 can improve the estimation accuracy.

2. In the estimation of fuel consumption factors at the low average speed (less than 10 km/h), the estimation error based on VSP bins without the designation of an independent VSP bin for VSP=0 is higher than that at the higher speed. It may be caused by the fact that the vehicle has more idling time at the low average speed section, which leads to higher errors without the independent VSP bin for VSP=0.

3. Estimation errors of VSP binning methods B and C vary in estimating total fuel consumptions and fuel consumption factors by using different inputs. However, errors are not quite different. Given that VSP binning method C may improve the computational efficiency because of its less number of VSP bins, it would be a more acceptable VSP binning method in applications.

For further study, two recommendations are provided. The first is regarding how to choose the appropriate sample size of second-by-second data for the micro-scale fuel consumption modeling. The second is to study VSP binning methods for different vehicle types and road types.

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