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Fuel Consumption Model for Trucks Based on Vehicle Specific Power

Tao Chen, Mengxue Li, Hongjing Feng, Bin Chen, and Yan Gao

ABSTRACT

To evaluate the efficiency of road traffic on mountainous highways, a method that captures the characteristics of road traffic on the basis of trucks is proposed. In previous studies of fuel consumption, parameters such as speed, acceleration, and power demand have been adopted to represent light-duty vehicle activities. However, they are not suitable for use for heavy-duty vehicles, especially for trucks on mountainous highways, due to the different number of shafts, quality variability, and other parameters. On the basis of data collected of trucks on Xihan mountainous highway, it was found that the time distribution in Vehicle specific power (VSP) bins, that is, the VSP bin distribution, can well represent the fuel consumption. Additionally, the combination of VSP bins and average instantaneous fuel consumption rates can represent fuel consumption of the whole driving routes. This paper develops a model for evaluating fuel consumption based on VSP distribution and average speed range by analyzing the relationship between VSP distribution and fuel consumption. Furthermore, the fuel consumption model is verified through a goodness of fit testing approach. A comparison of the estimated values, the values by using the VSP model of light duty vehicles, the values by using the VSP model in MOVES, and the real ones indicates that the proposed model performs well in evaluating fuel consumption on a mountainous highway and predicts a good fitting quality and effectiveness of the model. Finally, this paper provides recommendations and limitations for expansion of this study by including more vehicle types.

Keywords: VSP distribution; Fuel consumption model; Expressway in the mountain areas; Trucks
INTRODUCTION

With the deterioration of the global environment, fuel consumption is increasingly becoming an important factor that affects a nation's economy and environment. Effectively predicting and reducing the fuel consumption of motor vehicles on highways has become a major topic of current research. In recent years, a microscopic fuel consumption prediction model based on Vehicle Specific Power (VSP) has witnessed a rapid development. VSP-based approaches have recently been well accepted for fuel consumption and emission modeling. VSP was proposed to represent the instantaneous tractive power per unit of vehicle mass \((l, 2)\), it takes into account the power needed to overcome aerodynamic drag and rolling resistance of the vehicle, therefore the relationship between VSP and fuel consumption can be explained physically.

VSP distribution is often obtained from second-by-second speed, which is sometimes difficult to obtain. Using traffic acquisition methods, such as GPS phones, and video surveillance, can get abundant vehicle travel speed \((3)\). Thus, making use of VSP interval distribution model at different speeds can reflect the characteristics of the traffic flow and quantify fuel emissions.

Based on previous research, this paper collects data of driving behavior of different trucks when driving on a highway. Then we explore the relationship between VSP distribution of fully-loaded trucks, unloaded trucks, and fuel consumption. After that we establish calculation model based on the average fuel consumption rates and VSP distribution. Furthermore, the feasibility of VSP distribution model in predicting the fuel consumption of trucks in highway of mountain areas is validated. The comparison of the estimated indicators and the real values, the existing VSP fuel consumption models indicates that the proposed approach performs well in evaluating the fuel consumption. Thus, the model proposed in this paper can provide methodological guidance for real-time fuel consumption.

LITERATURE REVIEW

Several general approaches are usually considered in modeling fuel consumption and emissions all over the world: engine characteristics-based models, carbon balance-based models, and vehicle motion-based models. Typical examples of engine characteristics-based models are EcoGest \((4)\), ADVISOR \((5)\), Comprehension Model Emissions Model (CMEM) \((6)\), and Scania Truck and Road Simulation (STARS) \((7)\). The main inputs of these models are vehicle characteristics, engine parameters, and synthetic speed profiles, which are difficult to measure and predict. Many countries have developed the carbon balance method to calculate the instantaneous fuel consumption from the emissions of \(\text{CO}_2\), hydrocarbon (HC), and carbon monoxide (CO). The mass emissions of \(\text{CO}_2\), HC, and CO are from the tailpipe exhaust, and the corresponding vehicle speed and acceleration are reported on a second-by-second basis \((8, 9)\).

In 1999 J. L. Jimenez-Palacios proposed the concept of VSP and applied it to describe the demand of instantaneous power of light-duty vehicles. In order to overcome the rolling resistance and air resistance, VSP is the output power the engine needed to increase the vehicle kinetic energy and potential energy. The source formula was presented as Equation \((1)\). According to the features of light vehicles, the typical
parameters, such as $C_r$, $C_d$, $A$, $m$, etc, were set and the light-vehicle VSP model was finally gotten as Equation (2)\(^2\):

$$VSP = gv(f + i) + \delta av + 0.5C_dA\rho v^3 / m \quad (1)$$

$$VSP = v \times (1.1a + 0.132) + 0.000302v^3 \quad (2)$$

where $v$ is vehicle speed (m/s), $a$ is vehicle acceleration (m/s\(^2\)), $g$ is the acceleration of gravity (9.8 m/s\(^2\)), $\rho$ is the air density (kg/m\(^3\)), $f$ is the friction coefficient, $i$ is the road slope, $\delta$ is the mass scaling factor, $C_d$ is the air resistance coefficient, $A$ is the windward area (m\(^2\)), $m$ is the vehicle mass (kg).

The typical driving motion-based models include: Nam developed the Physical Emissions Rate Estimator (PERE), which uses vehicle parameters and second-by-second driving traces as inputs and estimates second-by-second fuel consumption rates (10). The University of California divided VSP into intervals and uses different emission factors to calculate the pollutants (11, 12). The Motor Vehicle Emission Simulator (MOVES), released by the US Environmental Protection Agency (EPA), was based on second-by-second measurements of vehicle fuel use and emissions obtained either using dynamometers in a laboratory or from real world data from Portable Emissions Measurement System (PEMS) (13, 14, 15). Ahn et al. proposed a statistical model based on regression analysis for fuel consumption as a function of speed and acceleration (16). Frey et al. took the average fuel consumption rates under different VSP bins to calculate the fuel consumption on diesel engines (17, 18, 19). Sun et al. developed a fuel consumption model based on the VSP of light-duty vehicles and found a significant linear relationship between fuel consumption and VSP in every specific speed range (20). A PEMS built by the Department of Environmental Science and Engineering of Tsinghua University was used to explore the influence of driving patterns on fuel consumption on passenger cars and built a VSP-based model (21). Based on the VSP distribution data of Beijing expressway and non-expressway, peak and off-peak hours, Song put forward the concept of standard fuel consumption rate (22, 23, 24). Tu developed a dynamic quantization algorithm to calculate the fuel consumption of floating cars on a fast road (25). For heavy-duty vehicles, there is no uniform model or formula of VSP. The International Vehicle Emission model applied the VSP model of light-duty vehicles to heavy-duty vehicles (12). Based on the emission model of heavy-duty vehicles, P. Andrei set the typical parameters of truck-tractors, box-type trucks and buses and got the VSP model of heavy-duty vehicles (26). The EPA has presented the different formula of VSP for light-duty vehicles and heavy-duty vehicles. For heavy-duty vehicles, the mass was set as 12020kg. The coefficients of the formula in this model were very different from other VSP model (27). Based on the tonnage classification of heavy-duty vehicles, MOVES has set the different coefficient values in different tonnage (28).

On the basis of the review of existing fuel consumption models presented above, instantaneous or modal emissions have focused primarily on developing these varieties of light-duty vehicles, with less effort devoted to heavy-duty vehicles, especially trucks on mountainous highways. Although heavy-duty vehicles currently make up only a fraction of the total vehicle population, they are major contributors to the entire emissions
inventory. Additionally, it is generally believed that trucks will offer earlier opportunities for public implementation of automated operations compared to passenger cars. Thus, there is a need for a robust fuel consumption model for trucks on mountain area highways. Studies on the VSP distribution on mountain area highways are eager to find solutions for the variability of roads and environmental factors on mountain highway traffic. For trucks, due to the different number of shaft types and quality variability, a discussion of the relationship between VSP and fuel consumption for different qualities of trucks should be analyzed separately.

**DATA COLLECTION**

Source data were collected from four trucks that traveled on the Xihan highway in China in the free flow of working condition. Xihan highway is one of sections of G5 highway in Shaanxi province. We took the sections K1133 – K1176 for experiments. The test sections were 44km, and the grade slope were 1°~5°. The tested cars included two Shanqi Delong M3000 trucks and two Shanqi Delong X3000 trucks in China. Table 1 lists the basic parameters of these vehicles. Using a Weichai CAN bus adapter to monitor vehicle ECU, we exported parameters such as engine speed, instantaneous speed, fuel injection quantity and output torque, and torque load rate. A video collector was used to record vehicle driving modes and the driving routes on the highway at the same time. Figure 1 illustrates the testing routes on the mountainous highway. Instantaneous driving behavior and engine operating mode data were then obtained. By subsequent data processing, the VSP distribution, transient VSP, instantaneous fuel consumption rates, and other data were calculated.

**Table 1 Basic parameters of tested vehicles**

<table>
<thead>
<tr>
<th>Test date</th>
<th>Maker</th>
<th>Test vehicles</th>
<th>Axis</th>
<th>Total mass(t)</th>
<th>Engine type</th>
</tr>
</thead>
<tbody>
<tr>
<td>04-12-2016</td>
<td>Shanqi</td>
<td>SX42564T324</td>
<td>6</td>
<td>15</td>
<td>Weichai WP12.375E40</td>
</tr>
<tr>
<td>04-13-2016</td>
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<td>40</td>
<td>Weichai WP12.375E40</td>
</tr>
<tr>
<td>04-14-2016</td>
<td>Shanqi</td>
<td>SX4256GR279</td>
<td>6</td>
<td>38.6</td>
<td>Weichai WP10.336E40</td>
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<td>6</td>
<td>15</td>
<td>Weichai WP10.336E40</td>
</tr>
<tr>
<td>05-23-2016</td>
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<td>53.1</td>
<td>Weichai WP10.336E40</td>
</tr>
<tr>
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<td>Shanqi</td>
<td>SX42564T324</td>
<td>6</td>
<td>15</td>
<td>Weichai WP12.375E40</td>
</tr>
<tr>
<td>05-24-2016</td>
<td>Shanqi</td>
<td>SX4256GR279</td>
<td>6</td>
<td>14.5</td>
<td>Weichai WP10.336E40</td>
</tr>
</tbody>
</table>
Figure 1: Testing routes on mountainous highway

METHODOLOGY
Characteristics of road traffic using VSP bin distribution

As we can see that the VSP models introduced above of light-duty vehicles and the heavy-duty vehicles are all affected by air density, air drag coefficient, rolling resistance coefficient, the windward area, acceleration of gravity, vehicle mass and road slope. Based on the difference comparison of the existing VSP models, we have analyzed the appearance of heavy-duty vehicles in China, and we have analyzed the above VSP models and the weight range division in MOVES. Then we calibrated these parameters of six-axis heavy-duty vehicles in our nation. We took the median vehicle mass in this paper. The air density was set as 1.29kg/m$^3$ under the normal atmospheric pressure. The windward area was the projection area in the driving direction and it was calculated by the width and the height of the vehicle. The air drag coefficient was calculated based on wind tunnel experiment and the aerodynamics formula. It was generally in 0.3~1.0. The rolling resistance coefficient was the ratio of the tire rolling resistance and the vehicle load. It was generally in 0.01~0.03. The road slop was replaced with $i$. The suitable algorithm of VSP for six-axis trucks can be obtained as follows (29).

When the vehicle is unloaded, that is the vehicle mass of six-axis trucks are 8~15kg,

$$VSP = v \times (1.1a + 9.807 \times i + 0.2646) + 0.00029 \times v^3$$

(3)

where $C_R=0.027$, $C_D=0.88$, $A=8.59m^2$, and $i$ is road grade.

When the vehicle is packed up with cargo, that is the six-axis vehicle mass are over 29kg.

$$VSP = v \times (1.1a + 9.807 \times i + 0.265) + 0.0000745 \times v^3$$

(4)

where $C_R=0.027$, $C_D=0.88$, $A=8.59m^2$, and $i$ is road grade.

As shown in Equations (3) and (4), by using parameters for certain vehicle types, VSP can be calculated from the vehicle speed, acceleration, and road grade, which are
easily obtained from field data. Studies have shown that VSP distribution can better reflect the relationship between VSP and the instantaneous fuel consumption rate of vehicles under different driving modes (30, 31, 32). VSP distribution is the proportion of vehicles under different VSP intervals, which can reflect the features of vehicle power and the fuel consumption characteristics. To avoid the random errors that could come from the use of the second-by-second data collected from the field test, the binning approach was applied in this analysis. Based on the clustering method of VSP, the VSP data were binned into bins of 1kw/t, as shown in Equation (5). Figures 2 and 3 illustrate the VSP distribution rates in each VSP bin of unloaded trucks and loaded trucks separately. The VSP distribution rates show that the unloaded trucks have a wider range of VSP bins than that of loaded trucks, and the relationship of VSP bins and VSP distribution rates obey the normal distribution, which is in accordance with the previous studies (25).

\[
\text{VSP Bin=n, } \forall: \text{VSP} \in [n, n+1) \tag{5}
\]

where \(n\) is the VSP bin number.

---

**Figure 2** VSP distribution rates of unloaded trucks

**Figure 3** VSP distribution rates of loaded trucks

**Average instantaneous fuel consumption and VSP bin distribution of network**

The instantaneous fuel consumption rates can be calculated based on the datasets of the unloaded trucks and loaded trucks. The instantaneous fuel consumption rates of unloaded trucks is calculated ranges from 0kw/t to 16kw/t, and the loaded trucks is
calculated from 0kw/t to 6kw/t, respectively. It was found that the instantaneous fuel consumption rates from the tested vehicles have good linear relationship with the VSP bin distribution, as shown in Figures 4 and 5.

![Figure 4 Instantaneous fuel consumption rates of unloaded trucks](image)

![Figure 5 Instantaneous fuel consumption rates of loaded trucks](image)

The analysis presented above provided instantaneous fuel consumption rates with VSP bins. In reality, engine size, vehicle type, and vehicle mass have considerable influence on instantaneous fuel consumption (24,33). To eliminate these effects and to reflect the obvious relationship between fuel consumption with VSP, we termed the average instantaneous fuel consumption, in which the instantaneous fuel consumption was calculated by arithmetic mean value, that was the average fuel consumption per VSP bin. With the VSP bin increases, the average instantaneous fuel consumption rates increase as well, as illustrated in Figures 6 and 7.
Based on the Figure 2, 4, 6, we can see that the peak is located in the 7kw/t-9kw/t in the VSP Bin range distribution. As the VSP Bin range increases, the average instantaneous fuel consumption rate is also gradually increased.

Based on the Figure 3, 5, 7, we can see that the peak is located in the 2 kw/t-3 kw/t in the VSP Bin range distribution. As the VSP Bin range increases, the average instantaneous fuel consumption rate is also gradually increased.

The difference of fuel consumption model between the loaded trucks and the unloaded trucks mainly lies in VSP Bin number and the rate range of the average instantaneous fuel consumption. The loaded trucks have a wider mass change. In this paper, the mass of the loaded trucks were about 55t, while the mass of the unloaded trucks were nearly 14t. So the VSP of the loaded trucks was far less than the VSP of the unloaded trucks. The influence factors of automobile fuel economy show that with the increase of automobile quality, the more resistance needed to overcome. The worse condition of the fuel economy leads to the unloaded vehicles a lower average fuel consumption than loaded trucks in the same VSP intervals.

**Fuel consumption model of VSP bin distribution**

On the basis of the analysis presented above, the maximum VSP of loaded trucks
is far less than the VSP value. The average fuel consumption rates of unloaded trucks is far less than the loaded one under the same VSP interval. Previous studies mainly focused on light-duty vehicles, and the quality difference had little effects on the fuel consumption model, such that the shaft type and quality differences have significant influence on the relationship between VSP and fuel consumption of trucks. By the VSP distribution and the relationship between the average instantaneous fuel consumption rates of the loaded and unloaded trucks, we get the following calculation models.

Based on the definition of VSP distribution explained above, Equation (6) is the calculation of VSP distribution rates:

$$R_{i,j} = \frac{N_{i,j}}{N_j}$$  \hspace{1cm} (6)

where $R_{i,j}$ is the $i$ VSP distribution rate in the $j$ speed binary. $N_j$ is the total number of VSP in the $j$ speed binary, $N_{i,j}$ is the number of VSP in the $j$ speed binary, $i$ is the VSP distribution, $j$ is the speed binary.

Equation (7) is the calculation of the average instantaneous fuel consumption in different VSP distributions:

$$f_{iVSP} = \frac{\sum f_{iVSP, transient}}{n}$$  \hspace{1cm} (7)

where $f_{iVSP}$ is the average instantaneous fuel consumption, $f_{iVSP, transient}$ is the instantaneous fuel consumption of second-by-second VSP in the $i$ VSP distribution. $n$ is the number of second-by-second VSP in the $i$ VSP distribution.

The average fuel consumption rate in the $j$ speed binary was calculated as follows.

$$f_{jASI, \text{links}} = \sum_i f_{iVSP} \times R_{i,j}$$  \hspace{1cm} (8)

where $f_{jASI, \text{links}}$ is the average fuel consumption rate in the $j$ speed binary.

Equation (9) is the calculation of the average fuel consumption in the $j$ speed binary. The corresponding fuel consumption of the average speed binary is the multiply of the average fuel consumption rate and the traveling time:

$$F_{jASI, \text{links}} = T_j \times f_{jASI, \text{links}}$$  \hspace{1cm} (9)

where $T_j$ is the traveling time in the speed intervals.

The whole fuel consumption is the accumulation of the fuel consumption in different average speed distribution.

$$F_{\text{links}} = \sum F_{jASI, \text{links}} = \sum T_j \times f_{jASI, \text{links}}$$  \hspace{1cm} (10)

where $F_{\text{links}}$ is the fuel consumption.

So, the overall fuel consumption model of the vehicle in the process of the running period is established, which can realize the fuel consumption prediction of trucks on the highways in the mountains based on the theory of VSP distribution and the average speed.

**MODEL VERIFICATION**
To verify the applicability of the VSP and fuel consumption model of the above six-axis unloaded trucks and six-axis loaded trucks, typical routes within the mountain highway sections were selected. Making use of the test data and statistic information of each routes, the prediction value of average fuel consumption rates and fuel consumption of each route were compared with the measured value of corresponding one, based on the prediction value of average fuel consumption of each route in different average speed range that was calculated by the method put forward in the previous section, then analyzing the relative error. The comparison results are shown in Tables 2 and 3.

As shown in Tables 2 and 3, error exists in the prediction value and the measured value of average fuel consumption rate and fuel consumption, but within 10%, indicating that the above fuel consumption model can be used to depict the fuel consumption characterization of six-axis unloaded trucks and six-axis loaded trucks.

By comparing the fuel consumption model for trucks proposed in this paper, the traditional light-duty vehicle fuel consumption model, the heavy-duty fuel consumption model in MOVES, and the measured fuel consumption, we have gotten the error comparison of loaded trucks and unloaded trucks as following. The results showed that the proposed truck fuel consumption model has a better fitting degree and smaller relative error. The comparison are as Figure 8 and Figure 9.

<table>
<thead>
<tr>
<th>Route</th>
<th>Route sections</th>
<th>Predicted average fuel consumption rates(g/s)</th>
<th>Measured average fuel consumption rates(L)</th>
<th>Predicted fuel consumption (L)</th>
<th>Measured fuel consumption (L)</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>K1137+011~K1137+614</td>
<td>9.79</td>
<td>10.14</td>
<td>0.363</td>
<td>0.376</td>
<td>3.46%</td>
</tr>
<tr>
<td>2</td>
<td>K1144+397~K1144+824</td>
<td>9.97</td>
<td>10.67</td>
<td>0.25</td>
<td>0.268</td>
<td>6.72%</td>
</tr>
<tr>
<td>3</td>
<td>K1146+006~K1146+357</td>
<td>6.55</td>
<td>7.13</td>
<td>0.1804</td>
<td>0.1965</td>
<td>8.19%</td>
</tr>
<tr>
<td>4</td>
<td>K1150+593~K1150+799</td>
<td>7.68</td>
<td>8.38</td>
<td>0.124</td>
<td>0.135</td>
<td>8.15%</td>
</tr>
<tr>
<td>5</td>
<td>K1150+949~K1151+760</td>
<td>9.49</td>
<td>8.47</td>
<td>0.4546</td>
<td>0.4151</td>
<td>9.5%</td>
</tr>
<tr>
<td>6</td>
<td>K1152+013~K1152+166</td>
<td>10.11</td>
<td>10.57</td>
<td>0.103</td>
<td>0.107</td>
<td>3.73%</td>
</tr>
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</table>
Table 3 Prediction and measured value of fuel consumption of loaded trucks

<table>
<thead>
<tr>
<th>Route</th>
<th>Route sections</th>
<th>Predicted average fuel consumption rates (g/s)</th>
<th>Measured average fuel consumption rates (g/s)</th>
<th>Predicted fuel consumption (L)</th>
<th>Measured fuel consumption (L)</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.1239</td>
<td>0.1218</td>
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</tr>
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<td>2</td>
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<td>8.85</td>
<td>8.02</td>
<td>0.092</td>
<td>0.086</td>
<td>6.98%</td>
</tr>
<tr>
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<td>8.479</td>
<td>0.1028</td>
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</tr>
<tr>
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<td>9.124</td>
<td>0.085</td>
<td>0.082</td>
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<td>10</td>
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<tr>
<td>6</td>
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<td>10.18</td>
<td>10.51</td>
<td>0.11</td>
<td>0.1136</td>
<td>3.17%</td>
</tr>
</tbody>
</table>

Figure 8 The relative error comparison of the fuel consumption models of unloaded trucks

Figure 9 The relative error comparison of the fuel consumption models of loaded trucks

DISCUSSION
On the basis of the large amount of real-world fuel consumption and traffic data, we analyzed the relationship between VSP and fuel consumption. The practical fuel consumption model of six-axis unloaded trucks and fully-loaded trucks was proposed. The proposed approach can help transportation planners and decision-makers to evaluate road traffic fuel economy. It can also be a good reference for traffic managements. The main findings in this study can be summarized as follows:

1. The instantaneous fuel consumption rates and the VSP show a good linear relation. When the VSP bin increases, the average instantaneous fuel consumption rate increases as well.

2. For a traffic network, the VSP bin distribution can reflect the fuel consumption of trucks, and the combination of VSP bin distribution and average travel speed can reflect the fuel consumption.

3. A fuel consumption model of trucks on mountain highways was proposed and verified. Therefore, it is recommended that this model be used as the basis for the estimation of fuel efficiency of road traffic.

4. The difference of the fuel consumption of loaded trucks and the unloaded trucks were gotten. The unloaded vehicles have a lower average fuel consumption than loaded trucks in the same VSP intervals.

5. The model proposed was compared with the existing approaches to calculate the fuel consumption of trucks. The results showed that the proposed truck fuel consumption model has a better fitting degree and smaller relative error.

The limitations of this study that would need further improvements still exist. First, it was assumed that trucks are the only type, and different shafts of trucks were not discussed. Further studies should be focused on different shafts of trucks and should divide truck type into more detail. We only analyzed the VSP model of loaded trucks and unloaded trucks in this paper. The application to passenger cars should also be considered. For model improvement, a study of the validation and calibration of the data for other vehicle types and technologies is needed. Second, more case studies on more trucks need to be conducted to define and classify fuel efficiency. Third, although the use of GPS is desirable, speed data for traffic in the field are more extensively available from detectors. Therefore, further studies are needed to understand how detector speeds could be used to estimate fuel consumption. Finally, fuel consumption was determined under the assumption that a vehicle consumes fuel only when moving at a certain distance at a certain speed. Fuel consumption during deceleration, idle, and other driving modes was not taken into account. Accurate studies should be present in future work.
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