Research on carbon dioxide emission factor characteristics of multi-type heavy-duty vehicles

Daoyuan Yang\textsuperscript{1}, Xinyu Zhang\textsuperscript{4}, Rui Wu\textsuperscript{1}, Yu Liu\textsuperscript{2,3}, Hanzhengnan Yu\textsuperscript{2,3}, Xi Hu\textsuperscript{2,3}, Kunqi Ma\textsuperscript{2,3}, Yongkai Liang\textsuperscript{2,3}, Hang Xu\textsuperscript{2,3} and Hao Zhang\textsuperscript{2,3,4}

\textsuperscript{1}Laboratory of transport pollution control and monitoring technology, Transport planning and research institute, Ministry of transport department, Beijing, 100028, China
\textsuperscript{2}China Automotive Technology & Research Center Co., Ltd., Tianjin, 300300, China
\textsuperscript{3}CATARC Automotive Test Center (Tianjin) Co., Ltd., Tianjin, 300300, China
\textsuperscript{4}School of Mechanical Engineering, Hebei University of Technology, Tianjin, 300401, China

Abstract. CO\textsubscript{2} emissions from heavy-duty vehicles are an important source of greenhouse gases in the transportation sector. However, there is a lack of in-depth research on the characteristics of CO\textsubscript{2} emission factors of multiple types of heavy-duty vehicles. The paper conducts a study on the characteristics of carbon dioxide emission factors of multi-type heavy-duty vehicles, with a focus on tractors, heavy-duty trucks, and dump trucks. A method based on C-WTVC for VSP-Bin interval division is proposed to establish a unified bin interval for heavy-duty vehicles, and calculate the CO\textsubscript{2} emission factors of different types of heavy-duty vehicles. The study indicates that the carbon dioxide emission factors of tractors are mainly distributed in suburb and highway intervals. The carbon dioxide emission factors of heavy-duty trucks are distributed across three intervals. The CO\textsubscript{2} emission factors of dump trucks are concentrated in suburb intervals.

1. Introduction

Against the backdrop of increasingly severe global climate change and continuously rising environmental temperatures, the greenhouse gas emissions from the transportation industry have attracted widespread social attention\cite{1}. As important players in the transportation industry, the carbon dioxide emissions from heavy-duty vehicles cannot be ignored. According to relevant studies\cite{2}, China's mobile sources of pollution generate approximately 1 billion tons of CO\textsubscript{2} emissions annually, with heavy-duty vehicles contributing about 39.7%. Heavy-duty vehicles have become a main source of CO\textsubscript{2} emissions. However, due to the diverse uses of heavy-duty vehicles, different types of heavy-duty vehicles may have variations in their driving conditions. In the national standard GB/T27840-2021 \cite{3}, Heavy-duty vehicles are classified into various types such as tractors, heavy-duty trucks, and dump trucks. Tractors mainly operate under suburb and highway conditions. Dump trucks primarily operate under suburb conditions. Heavy-duty trucks, however, encompass urban, suburb, and highway driving conditions. Variations in driving conditions will lead to differences in the CO\textsubscript{2} emission characteristics of different types of heavy-duty vehicles. Such differences will pose challenges for carbon emission control in heavy-duty vehicles and even greenhouse gas control in the transportation industry. Therefore, conducting research on the CO\textsubscript{2} emission characteristics of different types of heavy-duty vehicles is of significant importance. It supports greenhouse gas emission control in the transportation industry and the implementation of national carbon emission policies.

In existing research on CO\textsubscript{2} emissions from heavy-duty vehicles, the emission characteristics of heavy-duty vehicles are mainly analyzed by calculating CO\textsubscript{2} emission factors, and these factors are used to measure the emission levels of heavy-duty vehicles. The data sources mainly rely on remote monitoring data of heavy-duty vehicles\cite{4-5} and actual on-road driving data from PEMS\cite{6-7}. The analysis methods mainly involve the use of the moving average window method\cite{8} and Bin interval division methods such as VSP-Bin\cite{9}. The focus of the data analysis is also primarily on the overall CO\textsubscript{2} emission characteristics of heavy-duty vehicles. There is little in-depth research conducted by experts and scholars on the CO\textsubscript{2} emission factor characteristics of different types of heavy-duty vehicles. To address this, the study focuses on tractors, heavy-duty trucks, and dump trucks, and conducts research on the CO\textsubscript{2} emission factor characteristics of different types of heavy-duty vehicles. A VSP-Bin interval division method based on C-WTVC is proposed. Using the current standard in China for heavy-duty commercial vehicle operating conditions, C-WTVC, as a reference, a unified Bin interval for heavy-duty vehicles is constructed to calculate the CO\textsubscript{2} emission factors of different types of heavy-duty vehicles. Based on this, the study reveals the characteristics of CO\textsubscript{2} emission factors for multiple types of heavy-duty vehicles.
providing theoretical guidance for greenhouse gas emission control in the transportation industry.

2. Materials & methods

Different types of heavy-duty vehicles are subjected to CO₂ emission data collection experiments to provide data support for the research. Simultaneously, a method for calculating CO₂ emission factors for heavy-duty vehicles is proposed to conduct research on the characteristics of CO₂ emission factors for different types of heavy-duty vehicles.

2.1. Data source

The heavy-duty vehicles selected for the study have diesel fuel type, meet the China VI emissions standard, and have a tonnage exceeding 12.5 tons, as shown in table 1.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Usage</th>
<th>Tonnage</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>tractor</td>
<td>42t, 49t</td>
<td>three each</td>
</tr>
<tr>
<td>2</td>
<td>heavy truck</td>
<td>18t, 31t</td>
<td>three each</td>
</tr>
<tr>
<td>3</td>
<td>dump truck</td>
<td>31t</td>
<td>three</td>
</tr>
</tbody>
</table>

The selected heavy-duty vehicle models include tractors, heavy trucks, and dump trucks. Among them, both tractors and heavy trucks have two different tonnages. Three vehicles were selected for each vehicle type and each tonnage category, totaling 15 heavy-duty vehicles. Emission collection tests were conducted on a heavy-duty chassis dynamometer. The heavy-duty chassis dynamometer is used to simulate road load and vehicle speed, while the incremental method is employed to calculate vehicle acceleration, as shown in equation (1). The equipment is used to collect the vehicle's CO₂ emission rate (unit: g/s). During the experiment, C-WTVC was selected as the reference operating condition according to national standards. The emission collection test for each vehicle was conducted three times.

\[ a_i = \frac{v_{i+1} - v_i}{7.2} \quad (1) \]

2.2. Analysis method

Using the current standard heavy-duty vehicle operating condition, C-WTVC, as a benchmark, and vehicle specific power (VSP) as a variable, the C-WTVC condition is divided to establish a VSP-Bin interval partitioning method based on C-WTVC. Through comparative analysis of the operating characteristics of different types of heavy-duty vehicles and the CO₂ emission factor values in each Bin interval, the study is conducted on the characteristics of CO₂ emission factors of different types of heavy-duty vehicles.

2.2.1. Based on the VSP-Bin intervals of C-WTVC

VSP, proposed by Jimenez-Palacios in 1998, is a variable used to characterize the instantaneous output power per unit mass of motor vehicles [10]. It typically represents an indicator of the output power of a vehicle's engine when overcoming driving resistance. The calculation method for VSP refers to the heavy-duty vehicle VSP calculation formula presented in Reference [11], as shown in equation (2). The analysis of CO₂ emission characteristics of vehicles using VSP can effectively avoid the influence of changes in vehicle tonnage status on emission results, thus reflecting the true emission characteristics of vehicles more accurately.

\[ VSP = v(1.1a + 0.044) + 0.0022v^3 \quad (2) \]

The C-WTVC operating conditions are divided into urban conditions, suburb conditions, and highway conditions, as shown in figure 1. Therefore, based on the C-WTVC, the VSP-Bin intervals can be divided into five categories overall: braking interval, idle interval, urban interval, suburb interval, and highway interval. Among them, the braking interval encompasses all data with VSP less than 0. The idle interval includes all data with vehicle speeds less than 0.5 km/h.

<table>
<thead>
<tr>
<th>VSP (kw/ton)</th>
<th>Braking interval</th>
<th>Idle interval</th>
<th>Urban interval (Bin2*)</th>
<th>Suburb interval (Bin3*)</th>
<th>Highway interval (Bin4*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSP&lt;1</td>
<td>Bin0</td>
<td>Bin1</td>
<td>Bin21</td>
<td>Bin31</td>
<td>-</td>
</tr>
<tr>
<td>1≤VSP&lt;3</td>
<td>Bin21</td>
<td>Bin22</td>
<td>Bin23</td>
<td>Bin33</td>
<td>Bin35</td>
</tr>
<tr>
<td>3≤VSP&lt;5</td>
<td>Bin22</td>
<td>Bin23</td>
<td>Bin24</td>
<td>Bin34</td>
<td>Bin36</td>
</tr>
<tr>
<td>5≤VSP&lt;7</td>
<td>Bin23</td>
<td>Bin24</td>
<td>Bin25</td>
<td>Bin35</td>
<td>Bin37</td>
</tr>
<tr>
<td>7≤VSP&lt;10</td>
<td>Bin24</td>
<td>-</td>
<td>Bin36</td>
<td>Bin37</td>
<td>Bin38</td>
</tr>
<tr>
<td>10≤VSP&lt;13</td>
<td>Bin25</td>
<td>-</td>
<td>Bin37</td>
<td>Bin38</td>
<td>Bin39</td>
</tr>
<tr>
<td>13≤VSP&lt;16</td>
<td>Bin26</td>
<td>-</td>
<td>Bin38</td>
<td>Bin39</td>
<td>Bin40</td>
</tr>
<tr>
<td>16≤VSP&lt;18</td>
<td>Bin27</td>
<td>-</td>
<td>Bin39</td>
<td>Bin40</td>
<td>Bin41</td>
</tr>
<tr>
<td>VSP&gt;18</td>
<td>Bin28</td>
<td>-</td>
<td>Bin40</td>
<td>Bin41</td>
<td>Bin42</td>
</tr>
<tr>
<td>VSP&gt;19</td>
<td>Bin29</td>
<td>-</td>
<td>Bin41</td>
<td>Bin42</td>
<td>Bin43</td>
</tr>
<tr>
<td>28≤VSP&lt;29</td>
<td>Bin30</td>
<td>-</td>
<td>Bin42</td>
<td>Bin43</td>
<td>Bin44</td>
</tr>
<tr>
<td>29≤VSP&lt;30</td>
<td>Bin31</td>
<td>-</td>
<td>Bin43</td>
<td>Bin44</td>
<td>Bin45</td>
</tr>
<tr>
<td>VSP≥30</td>
<td>Bin32</td>
<td>-</td>
<td>Bin44</td>
<td>Bin45</td>
<td>-</td>
</tr>
</tbody>
</table>
The urban, suburb, and highway intervals are determined based on the division of C-WTVC operating conditions, excluding data from the braking and idle intervals. Detailed information on the VSP-Bin intervals based on C-WTVC is presented in table 2.

Figure 1. C-WTVC driving cycle.

Subsequently, within the urban interval, suburb interval, and high-speed interval, further subdivided Bin intervals are established, with the time sharing conforming to a normal distribution, where , Time sharing rate refers to the proportion of the duration of data in a certain interval to the total duration. Here, the establishment process of the Bin interval in the urban interval is taken as an example. Specifically: first, within the urban interval, refine the interval based on VSP equals 1 kW/ton to obtain subdivided urban intervals; then, randomly merge the adjacent subdivided urban intervals with varying numbers of intervals to obtain merged subdivided urban intervals; subsequently, use a normal distribution test to calculate whether the obtained merged subdivided urban intervals follow a normal distribution, and simultaneously determine if the total number of intervals in the current merged subdivided urban intervals is less than or equal to 9. If it does not meet either condition, re-randomly merge until the conditions are met. Finally, within the urban interval, build subdivided Bin intervals with time sharing rate conforming to a normal distribution. The suburb and highway intervals follow the same process. Lastly, based on the VSP-Bin interval of C-WTVC, as shown in figure 2, the normal distribution fitting coefficients of the time sharing rate for the urban, suburb, and highway Bin intervals are 0.86, 0.89, and 0.97, respectively.

Figure 2. Based on the C-WTVC’s VSP-Bin intervals.

Furthermore, to calculate the CO₂ emission factors, it is necessary to compute the mileage sharing rate for each Bin interval. The mileage sharing rate refers to the proportion of the mileage of each Bin interval to the total mileage of the driving cycle. Since the mileage of idle driving conditions is zero, its mileage sharing rate is set to 1.

2.2.2. CO₂ mission factor calculation

Based on the constructed VSP-Bin intervals and using the obtained CO₂ emission data for heavy-duty vehicles, calculate the CO₂ emission factors. According to the type of heavy-duty vehicle usage, the experimental research objects are divided into three categories: tractor units, heavy trucks, and dump trucks. Taking the tractor unit as an example, allocate all the experimental data of the tractor units to the VSP-Bin intervals constructed in 2.2.1. Calculate the CO₂ baseline emission factor for each Bin interval (except for idle intervals) using equation (3). Since the driving mileage in idle intervals is zero, the baseline emission factor for idle intervals is replaced by the CO₂ emission rate, as shown in equation (4).

\[
EFbase_j = \frac{\sum_i \Delta T_j \times \frac{v_j}{3600}}{\sum_i \Delta v_j / 3600}
\]

\[
ER_{\text{Bin1}} = \frac{\sum_{i} \Delta T_{ji} \times \frac{v_{ji}}{3600}}{\Delta T_{\text{bin1}}}
\]

where , , is the baseline emission factor of the vehicle in the -th Bin interval, unit: (g/km); is the emission rate of the vehicle in the -th second within the -th Bin interval, unit: (g/s); is the vehicle speed in the -th second within the -th Bin interval, unit: (km/h); is the vehicle operating duration in the -th Bin interval; is the CO₂ emission rate of idle intervals, unit: (g/s); is the CO₂ emission rate in the -th second within idle intervals, unit: (g/s); is the vehicle operating duration in idle intervals.

Calculate the comprehensive CO₂ emission factor for tractor units using equation (5).

\[
EF = \sum_{j} EF_{\text{base}, j} \times \Delta L_j + T_{\text{cycle,Bin1}} \times ER_{\text{Bin1}} / L_{\text{cycle, sum}}
\]

where , , is the comprehensive CO₂ emission factor, unit (g/km); is all Bin intervals; is the mileage sharing rate of the -th Bin interval; is the duration of idle intervals in the driving cycle; is the duration of idle intervals in the driving cycle.

Following the above steps, the carbon dioxide emission factor for tractor units can be calculated. The calculation process for heavy-duty trucks and dump trucks is similar.

3. Results and Discussion

The CO₂ emission factor calculation method proposed for heavy vehicles can be used to calculate the CO₂ emission data obtained from experiments for different types of heavy vehicles, thereby obtaining the numerical values of the CO₂ emission factors for different types of heavy vehicles. As shown in figure 3, it displays the numerical values of the CO₂ emission factors for three types of heavy vehicles.
vehicles, including tractor units, heavy trucks, and dump trucks.

Figure 3. Tractor, heavy trucks, and dump trucks’ CO\textsubscript{2} emission factors.

For the braking interval (Bin0), the CO\textsubscript{2} emission factors are as follows: The minimum for tractor units is 432.2 g/km, the maximum for dump trucks is 665.1 g/km, and heavy trucks fall in between with 629.2 g/km. For the idle interval (Bin1), the CO\textsubscript{2} emission rates are provided in figure 3. Tractor units, heavy trucks, and dump trucks have similar CO\textsubscript{2} emission factors, measuring 19.8 g/s, 14.8 g/s, and 18.6 g/s respectively. Additionally, in the urban interval (Bin2*), suburb interval (Bin3*), and highway interval (Bin4*), the CO\textsubscript{2} emission factors for the three types of heavy vehicles are mainly concentrated in the suburb interval. The CO\textsubscript{2} emission factors for tractor units are primarily distributed in the suburb and highway intervals. Heavy trucks have CO\textsubscript{2} emission factors distributed across all three intervals. Dump trucks’ CO\textsubscript{2} emission factors are concentrated in the suburb interval.

Using equation (6), calculate the CO\textsubscript{2} emission factors for different types of heavy vehicles in urban intervals, suburb intervals, and highway intervals. The calculation results are shown in figure 4.

\[ EF_i = \sum_{j} EF_{\text{base},j} \times \Delta L_{j} / \Delta L_{\text{sum},j} \]  

(6)

where, \( i \) is the urban interval, suburb interval, or highway interval; \( EF \) the CO\textsubscript{2} emission factor for a specific interval, units: (g/km); \( N_i \) is all the Bin intervals in a specific interval; \( \Delta L_{j} \) is the mileage sharing rate for the jth Bin interval; \( \Delta L_{\text{sum},j} \) is the sum of mileage sharing rate for a specific interval.

Figure 4. The CO\textsubscript{2} emission factors for different types of heavy vehicles in urban intervals, suburb intervals, and highway intervals.

As shown in figure 4, in suburb and highway intervals, the CO\textsubscript{2} emission factor for tractor units is significantly higher than that for heavy trucks. In the suburb interval, the CO\textsubscript{2} emission factor for dump trucks falls between the other two types of heavy vehicles. Additionally, for the CO\textsubscript{2} emission factor of heavy trucks, it follows the order: urban interval > suburb interval > highway interval. Studies indicate that heavy trucks have the lowest CO\textsubscript{2} emission factor among the three types of heavy vehicles. Tractor units have the highest CO\textsubscript{2} emission factor among the three types of heavy vehicles. Furthermore, while focusing on the CO\textsubscript{2} emissions of tractor units, attention should also be given to dump trucks operating frequently in suburb conditions.

4. Conclusions

The paper focuses on tractor units, heavy trucks, and dump trucks to study the characteristics of CO\textsubscript{2} emission factors for different types of heavy vehicles. It proposes a VSP-Bin interval division method based on C-WTVC, using China’s current standard for heavy commercial vehicle driving conditions (C-WTVC) as a reference to establish a unified set of heavy vehicle Bin intervals and calculate the CO\textsubscript{2} emission factors for different types of heavy vehicles. The research findings are as follows:

(1) Across urban intervals, suburb intervals, and highway intervals, the CO\textsubscript{2} emission factors for the three types of heavy vehicles are primarily distributed in the suburb intervals. The CO\textsubscript{2} emission factors for tractor units are mainly distributed in the suburb and highway intervals. Heavy trucks exhibit CO\textsubscript{2} emission factor distribution across all three intervals. Dump trucks have their CO\textsubscript{2} emission factors concentrated in the suburb intervals.

(2) With the increase of VSPA value or engine torque percentage value, the CO\textsubscript{2} emission factor value also increases correspondingly. At medium and high rotational speed, the CO\textsubscript{2} emission factor is small. At low rotational speed, the CO\textsubscript{2} emission factor increases.

Acknowledgment

Open Research Topic Funding from the Laboratory of Transport Pollution Control and Monitoring Technology ((2024)JH-F008).

References

regression and the double exponential smoothing model. Sustainability, 12(21), 9152.


3. GB/T 27840-2021, Fuel consumption test methods for heavy-duty commercial vehicles.


