Emission Rates of Air Pollutants Exhausted from Railroad Diesel Engines

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Abstract

It is widely known that the railroad diesel locomotive engines emit significant amount of air pollutants. However, these engines are not equipped with any air pollutants reducing devices in Korea, resulting in the accumulative air pollution near the railroad. Because the pollutants emission from driving locomotive engines cannot be measured directly, the emission factors based on the amount of consumed fuel are widely used for the assumption of the total emission from these engines. In this study, we estimated the total air pollutants emission from a railroad diesel locomotive operated on Seoul-Busan Railway Line by using our new method (named as KR method). The actual driving pattern of Seoul-Busan Railway Line and the weighting factors for each power mode was reflected in our calculation to gain more accurate values. KR method can be used for any other railroad lines operated by the diesel locomotives in any countries to estimate the total air pollutants emissions if the simple information of driving pattern, driving power mode, and types of engine model can be provided.

Keywords: diesel locomotive engine, particulate matter, estimation, emission rates

1. Introduction

The air pollution from off-road vehicles has attracted much less interest than that from on-road vehicles because the number of the off-road engines is much less than that of on-road engines. The environmental impact of the air pollutants emissions from off-road ones was almost negligible when compared with those from on-road ones. However, the situation is reversed owing to the newly developed emission gas treatment equipments and more strict emission standards for the on-road vehicles, and the air pollution caused by the on-road ones has become a less serious problem when compared with that by off-road ones. Especially, the pollutants emission from the railroad diesel locomotives arises as one of the most important air polluting sources among the off-road vehicles.

Nowadays, governments have established the air prevention laws and the emission standards in order to regulate the air pollutants emissions from the railroad diesel locomotives (RDL). In United States, Tier 2 standards just began to be effective to RDL for the regulation of NOx, hydrocarbon, CO, and PM emissions in 2005 (US EPA, 1998; 2004). Tier 3 standards, which will take effect since 2007, were already prepared. Tier 3 standards recommend the use of NOx after-treatment and PM filter technologies to achieve the reduction of NOx and PM emissions (US EPA, 2004). As a result of these strong regulations, the interests in technologies for the reduction of pollutant emissions from RDL are gradually increasing worldwide (Andrew et al., 2000). Major engine manufacturers are also developing new engines satisfying more severe environmental regulations.

In Korea, the railroad transportation (excluding inner-city subway) occupied approximately 9 % of the total passenger transports by carrying more than 1 billion passengers in 2003 (Korea Transport Database, 2005). On some inter-city railroad lines (Seoul-Busan Line and Seoul-Mokpo Line) of Korea, the high-speed electric trains of 300 km/h, named as Korea Train eXpress (KTX), are operated since 2004. However, most of other inter-city lines (including the lines of high-speed train) are still operated by the conventional RDL equipped with large-sized diesel engines due to their own advantages (e.g., superior safety, higher energy efficiency, no need of electric wire, etc.). The diesel engines of RDL were reported to consume approximately 320 million liters of diesel oil in Korea in 2002 (Korea Railroad, 2003), followed by emitting of a huge amount of fine particulates causing severe air pollution. But, there is not any official announcement or regulations against the emissions from RDL in Korea at present. Therefore, the air pollutants are emitted from the exhaust pipes of RDL without any further treatment for the reduction of pollutants causing big air pollution problems.

To relieve this air pollution problem from RDL, the estimation of pollutants emission is necessary. The Korea National Institute of Environmental Research (1999, 1997) and Shin et al. (2003) reported the estimated results of emissions from RDL in Korea. However, the results were not close to the real values because all of these studies performed simple modelling with conventional air pollution exhaust models.
without the experimental measurement of emitted pollutants. We could estimate the emissions from RDE accurately by experimental measurement on Seoul-Busan Line of Korea because the types of RDL and the number of RDL operation mode are fixed. In this study, we developed a new emission estimation method (KR method) reflecting the real RDL operation on Seoul-Busan Line of Korea Railroad for the accurate estimation of emissions from RDL. The obtained results were compared with the values obtained by the method developed by United States Environmental Protection Agency (EPA method).

2. Method

2.1. Estimation by EPA Method

In EPA method, the emission factors multiplied by the fuel combustion means the averaged emission values (kg of pollutants/kg of fuel burned) of each pollutants (Equation 1).

\[ ER = FC \times EF \quad (1) \]

Where, ER (emission rate) is the total annual emissions (metric-ton/year), FC is the total annual fuel consumptions (kℓ/year), EF is the emission factor (g/ℓ). The unit can be presented as metric-ton/year by multiplying the obtained values presented as metric-ton/year by the conversion factor of 1.1. To calculate the total annual emissions from RDL, the information on the number of RDL, the annual fuel consumption rates of diesel for each train types and line types, and the mode of RDL operation (e.g., line-haul and switch modes) is required.

2.2. Concept of KR Method

EPA method is widely used for the simple estimation of the emissions from RDL. However, it is certainly erroneous because the variation of RDL notch and RDL operation mode during the driving of RDL was not considered at all. In United States, RDL does not have to change its notch frequently because the railways of United States were mostly constructed as a shape of a beeline on flat plain terrain. However, the geographical condition of Korea is quite different from that of United States. Because the railways were constructed as shape of a relatively steep and curve lines in Korea (more than 70% of Korean area is mountains), RDL should change its notch so often. Therefore, it is not appropriate to apply EPA method to Korea without any compensation. In this study, we estimated the emission of RDL operated in Seoul-Busan Line, the busiest lines of Korea, by our KR method based on the analysis of the driving pattern of RDL and the calculation of the weighted averaged emission values for each notch. RDL is operated mostly in line-haul mode with quite small operation frequency in switch mode. In case of line-haul mode, new emission factors were applied. However, in case of switch mode, because more than 70% of switch mode is operated in idle mode (1st notch), and its using frequency is quite small when compared with that of line-haul mode, the emission factors of EPA method was applied without change. The emission factors for NOx and CO was estimated based on the ratings of engine, temperature of emitted gases, the concentrations of each pollutants in the emitted gases, and the frequency in use of each notch and mode.

2.3. Calculation of Weighting Factors

The weighting factors for emissions from RDL can be calculated by using working cycle mode. The emission rates (g/bhp-hr) of pollutants (NOx, CO) for each mode can be estimated by using weighting factors for each mode (Table 1) and Equation 2.

\[ E_{idd} = \sum (M_i(F_j))/\sum (BHP) (F_j) \]

where, \( E_{idd} \) is emission rates (g/bhp-hr) of pollutants i based on brake characteristics, \( M_i \) is emission rates of pollutants i for j mode, \( F_j \) is weighting factor of for j mode, and \( BHP \) is brake horsepower for j mode.

The brake horsepower (BHP) means the power of RDL, and it can be calculated as following Equation (3).

\[ BHP = HP_{out}/A_{eff} + HP_{acc} \]

where, \( HP_{out} \) is the horse power at AC generator or generator, \( A_{eff} \) is the Efficiency of AC generator or generator (%), and \( HP_{acc} \) is the Auxiliary rates.
The values of \( HP_{out} \), \( A_{eff} \), and \( HP_{acc} \) can be obtained by carrying out a dynamic engine test at each torque. The emission rates of \( i \) pollutant at \( j \) mode can be obtained by using of the emission rates in dry (Equation 5) and wet condition (Equation 6) as follows:

\[
M_{ij} \text{(wet)} = \left( \frac{D_i}{10^6} \right) \left( D_{\text{Vol}} \right) \left( \frac{M_{Wi}}{V_m} \right) \tag{5}
\]

\[
M_{ij} \text{(dry)} = \left( \frac{W_i}{10^6} \right) \left( W_{\text{Vol}} \right) \left( \frac{M_{Wi}}{V_m} \right) \tag{6}
\]

where, \( D_i \) and \( W_i \) are the concentrations (ppm or ppmc) of pollutants \( i \) under dry and wet condition, respectively, \( M_{Wi} \) is the molecular weight (g/mol) of pollutants, \( D_{\text{Vol}} \) and \( W_{\text{Vol}} \) are the total amount (ft\(^3/\)hr) of emissions flowed under dry and wet condition, respectively, and \( V_m \) is molar volume (ft\(^3/\)mol) of gas under ambient temperature and pressure.

Table 1. Weighting factors for calculating emission rates emitted from RDL (USEPA, 1998).

<table>
<thead>
<tr>
<th>Throttle notch</th>
<th>Test mode</th>
<th>Locomotive without multiple idle notches</th>
<th>Locomotive equipped with multiple idle notches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Line-haul</td>
<td>Switch</td>
</tr>
<tr>
<td>Low Idle</td>
<td>1a</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Normal Idle</td>
<td>1</td>
<td>0.380</td>
<td>0.598</td>
</tr>
<tr>
<td>Dynamic brake</td>
<td>2</td>
<td>0.125</td>
<td>0.000</td>
</tr>
<tr>
<td>Notch 1</td>
<td>3</td>
<td>0.065</td>
<td>0.124</td>
</tr>
<tr>
<td>Notch 2</td>
<td>4</td>
<td>0.065</td>
<td>0.123</td>
</tr>
<tr>
<td>Notch 3</td>
<td>5</td>
<td>0.052</td>
<td>0.058</td>
</tr>
<tr>
<td>Notch 4</td>
<td>6</td>
<td>0.044</td>
<td>0.036</td>
</tr>
<tr>
<td>Notch 5</td>
<td>7</td>
<td>0.033</td>
<td>0.036</td>
</tr>
<tr>
<td>Notch 6</td>
<td>8</td>
<td>0.039</td>
<td>0.015</td>
</tr>
<tr>
<td>Notch 7</td>
<td>9</td>
<td>0.030</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.162</td>
<td>0.008</td>
</tr>
</tbody>
</table>

2.4. Estimation by KR Method

The total amount of emissions from RDE was obtained by summing up the emissions during the operation. The emission rates can be calculated by following equation 7 (Jung, 1999).

\[
ER = NC \times RP \times AR \times RT \times EF \tag{7}
\]

where, \( ER \) is total annual emissions (g/yr), \( NC \) is the number of RDL, \( RP \) is ratio weighted average rated power (kW) of each RDL, \( AR \) is average power ratio of working and rated power (%), \( RT \) is annual average operation hours (hr/yr), and \( EF \) is the intensified emission factor (g/kW-h).

The driving patterns of RDL are important in estimating the emissions because it shows how RDL is actually operated on the railway tracks. The run curve of RDL provides the RDL driver with the information on terrain, gradient, turning radius, and recommended notch, so that the driving can be optimized. The engine ratings are strongly dependent on the driving habit of each RDL driver. However, because the difference between each driver is not that large, the emissions of pollutants exhausted from each RDL are largely similar. Therefore, we can assume that the emissions from each RDL are same, and we can calculate the emissions by simply monitoring the emissions from one RDL in operation.

In this study, Seoul-Busan Line of Korea was selected as a representative line, because it is the longest (444.3 km), and the most frequently operated line in Korea. We analysed the run curve of Seoul-Busan Line to develop KR method appropriate for the terrain of Korea. We divided the Seoul-Busan Line into 4 sections with 100 km length for each section, and then prepared a driving pattern based on the driving information of each section.

2.5. Characterization of Exhaust Gases

Measurement of the exhaust gases from RDL was performed in accordance with SAE standard J177 (SAE, 1995). The engine was ignited, and warmed-up for > 10 min under rated speed and load condition to reach its stable state. The engine rating was 2.3 % of the maximum engine load, and the rpm was 315 under the
steady state condition. The engine was run under various engine load condition for > 20 min. The engine load was 2.3 % at idle mode, 11.2 % at 2 notch, 33 % at 4 notch, 59.1 % at 6 notch, and 100 % at 8 notch. The concentrations of CO, CO₂, NO, NO₂, and HC of the exhausted gases were continuously monitored. The data collected during the last 3 min was averaged and recorded. Further details of the measurement procedure were described by Park (2003).

3. Results and Discussion

3.1. Emissions Estimated by EPA Method

3.1.1. Fuel Consumptions
The emission rates from RDL for each line type and train type were estimated by applying emission factors of EPA method from the fuel consumption data (Table 2). Here, the fuel consumptions of each line are the sum of fuel consumption at each mode. The operation pattern of the train was used for the estimation of emissions. In Table 3, the fuel consumptions of each train type and each operation mode (line-haul mode and switch mode) were presented. The table shows that the fuel consumption of diesel locomotive in line-haul mode is much bigger than that of any other type of car both in line-haul and switch mode. In case of diesel locomotive, most of the fuel was consumed in line-haul mode (83.5 %), while only a small portion (16.5 %) was done in switch mode. However, in case of other cars, fuel consumption in switch mode was higher than that in line-haul mode.

Table 2. Emission rates for the locomotives (US EPA, 1998).

<table>
<thead>
<tr>
<th>Mode</th>
<th>CO</th>
<th>NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line-haul</td>
<td>1.28</td>
<td>7.04</td>
</tr>
<tr>
<td></td>
<td>g/bhp-hr</td>
<td>g/l</td>
</tr>
<tr>
<td>Switch</td>
<td>1.83</td>
<td>10.07</td>
</tr>
</tbody>
</table>

Table 3. Fuel consumptions (ℓ) for each train type.

<table>
<thead>
<tr>
<th>Type</th>
<th>Line-haul mode</th>
<th>Switch mode</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel locomotive</td>
<td>215,632,657</td>
<td>42,623,695</td>
<td>258,256,352</td>
</tr>
<tr>
<td>General rail car</td>
<td>4,135,702</td>
<td>12,257,062</td>
<td>16,392,764</td>
</tr>
<tr>
<td>Other rail car</td>
<td>18,031,326</td>
<td>34,532,785</td>
<td>52,564,111</td>
</tr>
<tr>
<td>Special rail car</td>
<td>17,588</td>
<td>19,506</td>
<td>37,094</td>
</tr>
</tbody>
</table>

3.1.2. Emissions from Seoul-Busan Line
The emissions of pollutants exhausted from the all RDL of Korea were estimated by EPA method. The total emitted NOx was calculated to be 28,117 tons with 18,705 tons (66.5%) in line-haul mode and 9,412 tons (33.5 %) in switch mode. In Seoul-Busan Line, the total NOx emission was estimated to be 14,612 tons, which implies about 52 % of NOx emission of Korean RDL was done on Seoul-Busan Line.

The total emitted CO was estimated to be 2,832 tons with 1,842 tons (65 %) in line-haul mode and 991 tons (35 %) in switch mode. As the similar case of NOx emission, Seoul-Busan Line was calculated to emit 1,476 tons of CO, which corresponds to 52.1 % of the all CO emission from Korean RDL in operation.

3.2. Emissions Estimated by KR Method

3.2.1. Assumptions
In order to estimate the emissions of RDL, the emission factors should be calculated first. The emission factors of KR method were obtained by applying the measured emissions of Korean RDL at each notch and mode. In this study, for the exact estimation of total emissions, the driving patterns of RDL on Seoul-Busan Line were analysed by referring the real run curve data of Korean RDL. As previously mentioned, we assumed that the emissions from each RDL are same, and we can calculate the emissions by simply monitoring the emissions from one RDL in operation.

Prior to the development of KR method, it was assumed that the Run Curve of diesel locomotives corresponded to the frequency rates of notch on service. The Seoul-Busan Line was selected on the KR method, which was applied to the other line uniformly as well. While the use frequency rates of notch is determined by the time in case of EPA method, it was decided by the distance on KR mode developed in this study. Additionally, there is no consideration of the additional emission rates generated during accelerating
and decelerating of diesel locomotive for calculate the total amount of emissions, and the emissions when stopping by station as well.

Gyeongbu-Line can be divided into up and down line, the operating rates of the diesel locomotives change with each notch more or less. This is why results from the load of engine that change with a gradient all over the line. Nonetheless, it was almost the same regardless of up and down line as reviewing the operating rates on each notch in relation of round-trip. After all, the sum of operating rates both up and down line will make the average value between them without fluctuating dramatically.

Table 4 shows the rates of operating on each notch in Seoul-Busan Line. Based on this, the idle (1 notch) of 37.9 % is the maximum and 31.2 % in case of 8 notch. It is analysed that idle (1 notch) and 8 notch occupied approximately 70 %, whereas it is relatively low less than 10% on the other notches.

Table 4. Estimated driving patterns of diesel locomotives on the Gyeongbu-Line.

<table>
<thead>
<tr>
<th>Notch</th>
<th>0(1)</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~100</td>
<td>34.3</td>
<td>4.0</td>
<td>4.6</td>
<td>8.5</td>
<td>9.4</td>
<td>3.0</td>
<td>2.3</td>
<td>33.9</td>
</tr>
<tr>
<td>100~200</td>
<td>43.8</td>
<td>3.0</td>
<td>4.4</td>
<td>5.6</td>
<td>3.6</td>
<td>3.1</td>
<td>7.1</td>
<td>29.4</td>
</tr>
<tr>
<td>200~300</td>
<td>38.5</td>
<td>8.1</td>
<td>5.7</td>
<td>9.0</td>
<td>6.5</td>
<td>3.5</td>
<td>3.7</td>
<td>25.0</td>
</tr>
<tr>
<td>300~400</td>
<td>34.9</td>
<td>3.2</td>
<td>4.3</td>
<td>5.2</td>
<td>4.4</td>
<td>6.1</td>
<td>5.3</td>
<td>36.6</td>
</tr>
<tr>
<td>Avg.</td>
<td>37.9</td>
<td>4.6</td>
<td>4.8</td>
<td>7.0</td>
<td>6.0</td>
<td>3.9</td>
<td>4.6</td>
<td>31.2</td>
</tr>
</tbody>
</table>

3.2.2. Emission Factory by KR Method

The driving patterns of diesel locomotives on the Seoul-Busan Line were analysed and the operating rates were studied for each notch as line-haul mode. Meanwhile, the switch mode is that the vehicles mainly stop by a station or maintenance area or travel at a short distance in low gear of which idle (1 notch) occupies 70%. As indicated earlier, there is no the Run Curve regarding switch mode in Korea because notch can be controlled by operators at their discretion depending on situations and the operating rates of EPA is used in this paper. Therefore, the emission factors of NOx and CO were developed with the engine rates, the temperature, the concentrations and emissions of pollutants, etc.

The concentration of NOx increased up to the maximum as 6,207 g/hr at 8 notch with loads. But, it decreased up to the maximum 9.95 g/bhp-hr with load increased and then was the minimum 1.91 g/bhp-hr on 6 notch with idle (1notch). This indicates that the emissions rates are the maximum with idle. The emission factor (g/bhp-hr) was calculated as 5.08 g/bhp-hr in line-haul mode and 7.91 g/bhp-hr in case of switch mode. The emission factor of KR means the emission factor of NOx related to engine power of diesel locomotives per unit and hour, which were 26.4 g/ℓ and 41.2 g/ℓ in line-haul mode and in switch mode respectively. Emission rates (g/hr) of CO was 907 g/hr with idle and the maximum was 4,162 g/hr on 6 notch while engine load increase but it decreased to 1,991 g/hr at 8 notch. The emission factor (g/bhp-hr) of CO was resulted in 2.15 g/bhp-hr in line-haul mode and 3.3 g/bhp-hr in switch mode. The calculation of an emission was conducted by the factor of KR (g/ℓ) which was 11.2 g/ton line-haul mode and 17.2 g/ton on switch mode.

3.2.3. Emission Rates for Seoul-Busan Line

Table 5 shows the results of the emission factor by applying it to the fuel consumption data. The total amount of NOx exhausted for one year was 10,958.8 tons and the amount of emissions by line-haul mode was 6,906.4 tons, approximately 63 % of the entire emission. Meanwhile, it was estimated that NOx of 4,052.4 tons, 37%, was exhausted by switch mode. The emission rates from the Seoul-Busan Line were approximately NOx of 50%. The total amount of CO was 4,622 tons and 2,930 tons of them consumed by line-haul mode which occupied 63.4 %. And it was estimated that CO emissions by switch mode was 1,692.0 tons, 36.6 %. CO also considerably emitted on major lines in Korea.

Table 5. Emission rates of NOx, CO on the all of Korean railroads estimated by KR method.

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>Emission rates (short ton/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Line-haul</td>
</tr>
<tr>
<td>NOx</td>
<td>6,906.4</td>
</tr>
<tr>
<td>CO</td>
<td>2,930.0</td>
</tr>
</tbody>
</table>
3.3. Comparison of EPA and KR Method

3.3.1. Comparison of Emission Factors

EPA method has a characteristic that the ratio of idle is high (57.0 %) and the ratio of 8 notch is low (16.2 %) with the average weighted on each notch per hour. In case of the KR method, the weighted value by each notch can be obtained by analysing the actual driving patterns condition with the distance of average weighted by each notch in Seoul-Busan line. Idle ratio is 37.1 % that is similar level of 35.4 % on the rate of 8 notch. When the emission factors (g/ℓ) by EPA and KR methods were compared, the NOx emission factor by KR method (26.4 g/ℓ in line-haul mode and 41.2 g/ℓ in switch mode) was turned out to be a little bit lower than that by EPA method (40.7 g/ℓ in line-haul mode and 60.50 g/ℓ in switch mode), whereas in case of CO, the values of KR method (11.2 g/ℓ in line-haul mode and 17.2 g/ℓ in switch mode) is a little higher than that of EPA method (12.1 g/ℓ in line-haul mode and 13.75 g/ℓ in switch mode).

3.3.2. Comparison of Emission Rates

Table 6 represents the results of the emission rates using EPA and KR method compared each other. The emission rates of NOx calculated using EPA method was as much as approximately 2.6 times of that by KR method while the emissions of CO by KR method was much more than that using EPA method by 1.6 times. There is a big difference among two methods because of the different emission factors. The EPA method that was developed based on the flat configuration of ground of USA. That is, it will be more efficient and proper to use the KR method which was developed in reference to that of Korea Railway lines.

<table>
<thead>
<tr>
<th>Method</th>
<th>EPA (short ton/year)</th>
<th>KoRail (short ton/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pollutants</td>
<td>Line-haul</td>
<td>Switch</td>
</tr>
<tr>
<td>NOx</td>
<td>18,704.7</td>
<td>9,412.3</td>
</tr>
<tr>
<td>CO</td>
<td>1,841.7</td>
<td>990.6</td>
</tr>
</tbody>
</table>

3.4. Emission Factor of RDL

The emissions of pollutants per distance (g/km) were calculated with using fuel consumptions from one diesel locomotive in up and down line of Seoul-Busan Line. The amount of diesel fuel consumed for one diesel locomotive of 1-configuration to travel on down line (Seoul → Busan section) was 1,372.6ℓ. Dividing this quantity by the moving distance of 444.3 km, the fuel consumption efficiency is 3.1 ℓ/km. Also, on up line (Busan → Seoul section), it is 3.3 ℓ/km by dividing diesel fuel of 1,463.5 ℓ by 444.3 km and then the average of fuel consumption efficiency on up and down line can be 3.2 ℓ/km. The emission factors of NOx and CO were 84.5 g/km and 35.84 g/km, respectively by multiplying fuel consumptions by the emission factor from line-haul mode.

4. Conclusion

The characteristics of emissions of pollutants from engines of diesel locomotives were analysed and identified by testing for the pollutants to be controlled throughout 10 times. And, based on the results of concentrations, it was suggested that the new method will be replaced with EPA method so that it can be applied to the RDL in Korea adequately and efficiently in the future. The emission factor from KR method resulted in the operating rates by analysing the driving patterns of diesel locomotives on the Seoul-Busan Line on each notch for line-haul mode. In case of switch mode, the operating rates from each notch by EPA method were used due to the constraints such as insufficient data and various parameters in Korea.

Acknowledgments

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