

Thermal radiance measurement and spectral radiance computation for diesel exhaust gas species

5.1 INTRODUCTION

This Chapter documents the spectral radiance computation of diesel exhaust gas species using HITRAN data and verify with the total radiance measured by Thermal Imager. The objective of this work is to find out dominant gas species in the exhaust emission and their contribution to thermal signature of the exhaust. Using the high-resolution data on the absorption lines of gases available from the HITRAN open international database, transmission, absorption of radiation and spectral radiance are determined for the exhaust gas species - CO, NO, N₂O, and HC. The absorption coefficient and spectral radiance of these gases are investigated in Thermal IR region. Exhaust spectral radiance is calculated on the basis of IR absorption and emission of exhaust gases [Hilton M. *et al.*, 1997].

5.2 RADIANCE AND SPECTRAL RADIANCE

The radiance or radiative intensity is defined, as radiant flux per unit solid angle and unit area normal to the rays. Radiance is described that how radiation flux flow varies with respect to direction. The SI unit of radiance is W/m²-sr. The radiance is quantitatively defined with respect to radiation wavelength which is termed as a spectral radiance. The spectral radiance is defined, as radiance per unit wavelength in the radiation spectrum. The radiation characterization within a certain wavelength band of thermal IR is defined by spectral radiance. The SI unit of spectral radiance is W/m²-sr- μ m. Spectral radiance is an important parameter when selecting a source or gases for study, analysis and an application across a specific wavelength band of IR spectrum (3-5 μ m or 8-14 μ m). Generally, most radiation sources or gases exhibit variations in spectral radiance across the spectrum of radiation emission.

A perfect blackbody is one that absorbs all incident radiation and to remain in thermal equilibrium, the body must re-emit that radiation. The expression for spectral radiance, $I_{\lambda,b}(\lambda, T)$, of a perfect blackbody of temperature(T) in Kelvin and radiation wavelength (λ) in μ m is expressed by Planck's Law as equation 3.1 in Chapter 3.

The Planck's law is not exactly applicable to the exhaust smoke over an extended wavelength region. There are three processes such as absorption, reflection and transmission which can occur that prevent the exhaust gases from acting like a blackbody. However, it may approach the blackbody behaviour in certain spectral intervals. A non-blackbody emitter like gases can be described by its emissivity, however gases emissivity varies with its temperature. It is defined as the ratio of radiant emittance of gases to black body emittance at a specific temperature. Similarly, the spectral emissivity ϵ_{λ} , is the ratio of the spectral radiant power from exhaust gases to that from a blackbody at the same temperature and wavelength. The gaseous constituents of an engine exhaust smoke are spectrally selective emitters. The emissivity of the gases is calculated using Lambert- Beer Law, expressed by the equation 3.3 in Chapter 3.

5.3 RADIANCE MEASURED BY CALIBRTAED RADIOMETRIC THERMAL IMAGER

Broad-band radiance of diesel exhaust gases of Truck and Bus were measured using radiometric thermal imager. Radiance of exhaust gas of these diesel vehicles was measured under idle and accelerating conditions. Simultaneously, measurement of gas species concentration was carried out [Ronald G. *et al.*, 2005]. Variation in temperature of exhaust gas

species under engine running in idle and accelerating conditions shown in Table 4.6, 4.7, 4.9 and 4.10 are referred.

5.3.1 Radiance measurement of Truck exhaust smoke in idle engine running condition

Maximum, mean and minimum values of radiance of exhaust smoke were recorded under idle running of Truck for approximately 180 seconds. Figure 5.1 shows that the radiance does not vary much in idle engine running condition except for few peaks. The diesel fuel undergoes complete combustion. However, some unburnt HC gases and particulate matter gives rise to a few peaks in the recorded radiance. The engine conditions are also quite stable with time, which results in uniform smoke emission from exhaust pipe with constant temperature as shown in Figure 4.9. The influence of solar radiation on exhaust smoke is also negligibly small and the ambient wind causes marginal decrease in radiance of smoke exhaust.

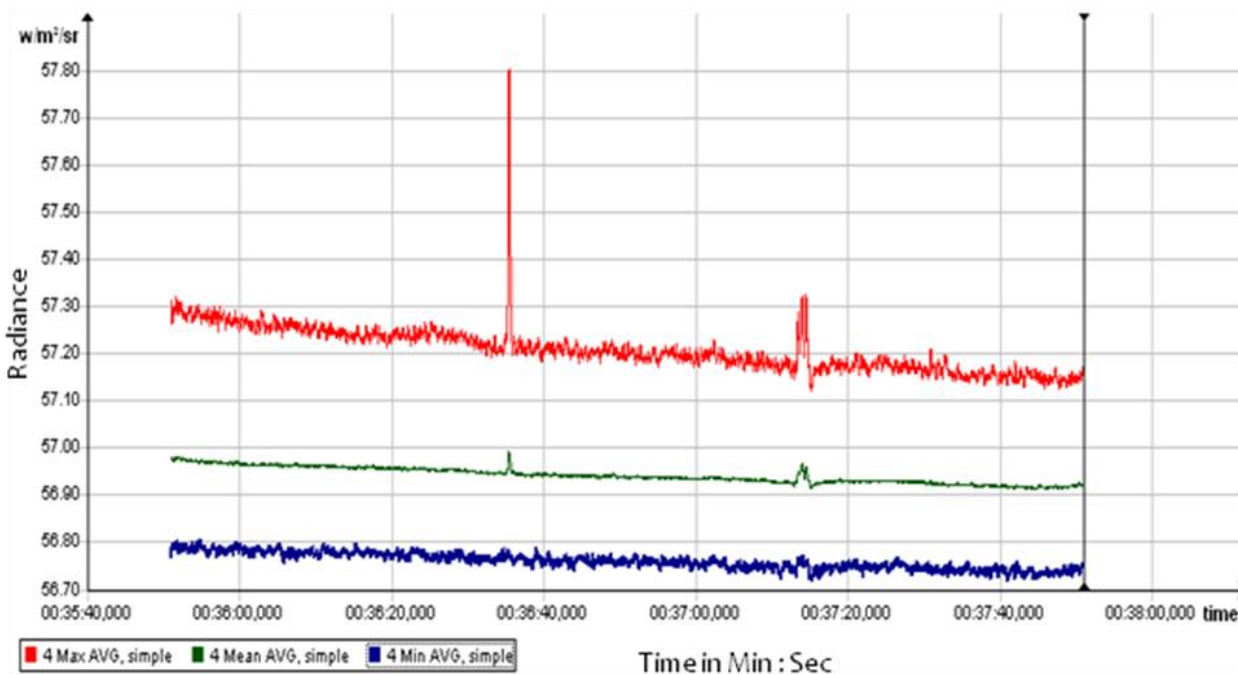


Figure 5.1: Radiance of exhaust gas of Truck with time under idle engine running condition

5.3.2 Radiance measurement of Truck exhaust smoke in accelerating engine running condition

The maximum, mean and minimum values of radiance of exhaust smoke were recorded under accelerating condition of Truck for approximately 180 Sec. Figure 5.2 shows that the radiance of exhaust smoke increases with the acceleration of the engine and decreases with the reducing speed of the engine. The Radiance of exhaust smoke increases in acceleration of engine due to increasing temperature and concentration of exhaust gas species. The diesel fuel undergoes complete combustion. However, some unburnt HC gases and particulate matter gives rise to a few peaks in the recorded radiance. As shown in Figure 4.10, the pattern of smoke emission from exhaust pipe does not vary uniformly with temperature, during engine acceleration. The influence of solar radiation on exhaust smoke is also negligibly small. The convective heat transfer between exhaust gases and air gets enhanced due to increase in ambient wind speed. This will result in decrease of radiation intensity of exhaust gases. The increase in ambient temperature of air will also increase the exhaust smoke radiance. It is due to the fact that increase in intake air temperature will result in increase in inside temperature of combustion chamber of the engine.

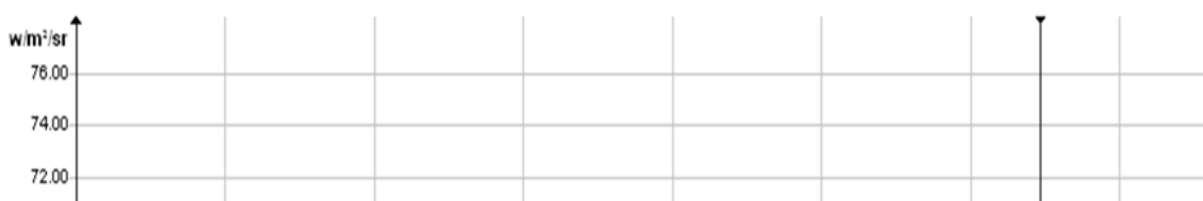


Figure 5.2: Radiance of exhaust gas of Truck with time under accelerating engine running condition

5.3.3 Radiance measurement of Bus exhaust smoke in idle engine running condition

Similar to the Truck, the radiance measurements of exhaust smoke was carried out for Bus under idle and accelerated engine running condition. Maximum, mean and minimum value of exhaust smoke radiance were recorded under idle running of Bus for approximately 180 Sec. **Figure 5.3** shows that the radiance does not vary much in idle engine running condition except for few peaks. The diesel fuel undergoes complete combustion. However, some unburnt HC gases and particulate matter gives rise to a few peaks in the recorded radiance. The engine conditions are also quite stable with time, which results in uniform smoke emission from exhaust pipe with constant temperature as shown in Figure 4.21. The influence of solar radiation on exhaust smoke is also negligibly small and the ambient wind causes marginal increase in radiance of smoke exhaust.

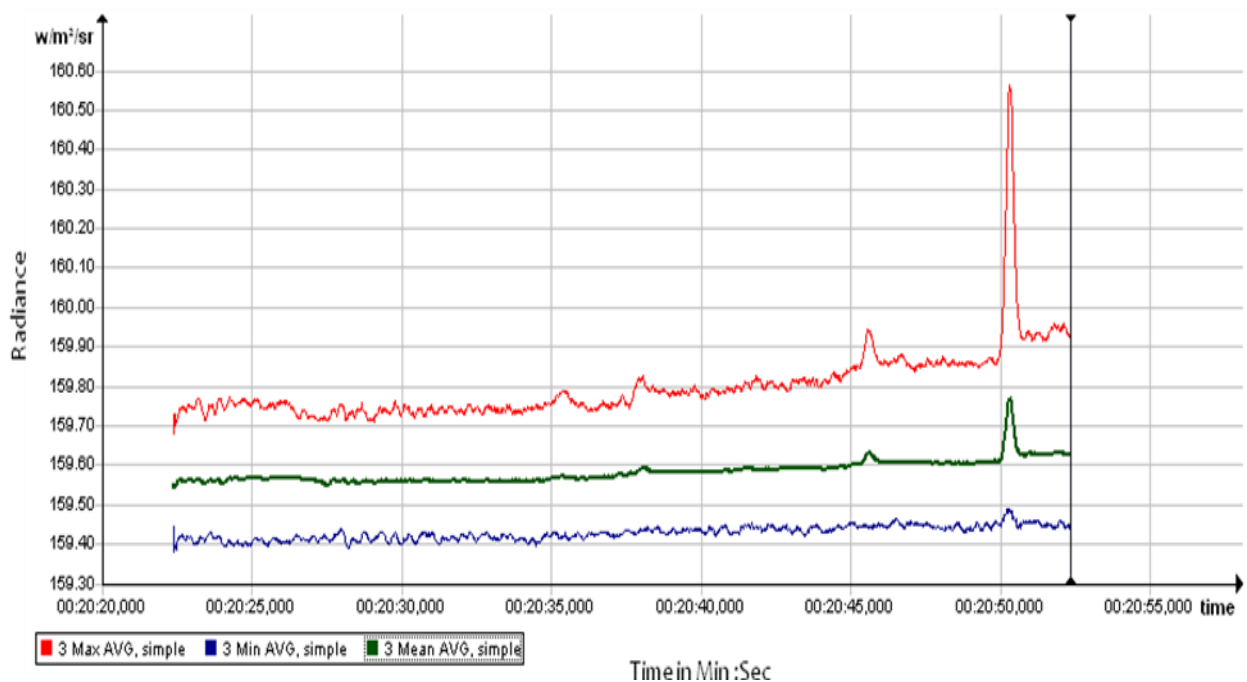


Figure 5.3: Radiance of exhaust gas of Bus with time under idle engine running condition

5.3.4 Radiance measurement of Bus exhaust smoke in accelerating engine running condition

The maximum, mean and minimum values of radiance of exhaust smoke were recorded under accelerating condition of Bus for approximately 180 Sec. **Figure 5.4** shows that the radiance of exhaust smoke increases with the acceleration of the engine and decreases with the reducing speed of the engine. The Radiance of exhaust smoke increases in acceleration of engine due to increasing temperature and concentration of exhaust gas species. The diesel fuel undergoes complete combustion. However, some unburnt HC gases and particulate matter gives rise to a few peaks in the recorded radiance. As shown in Figure 4.22, the pattern of smoke emission from exhaust pipe does not vary uniformly with temperature, during engine acceleration. The influence of solar radiation on exhaust smoke is also negligibly small.

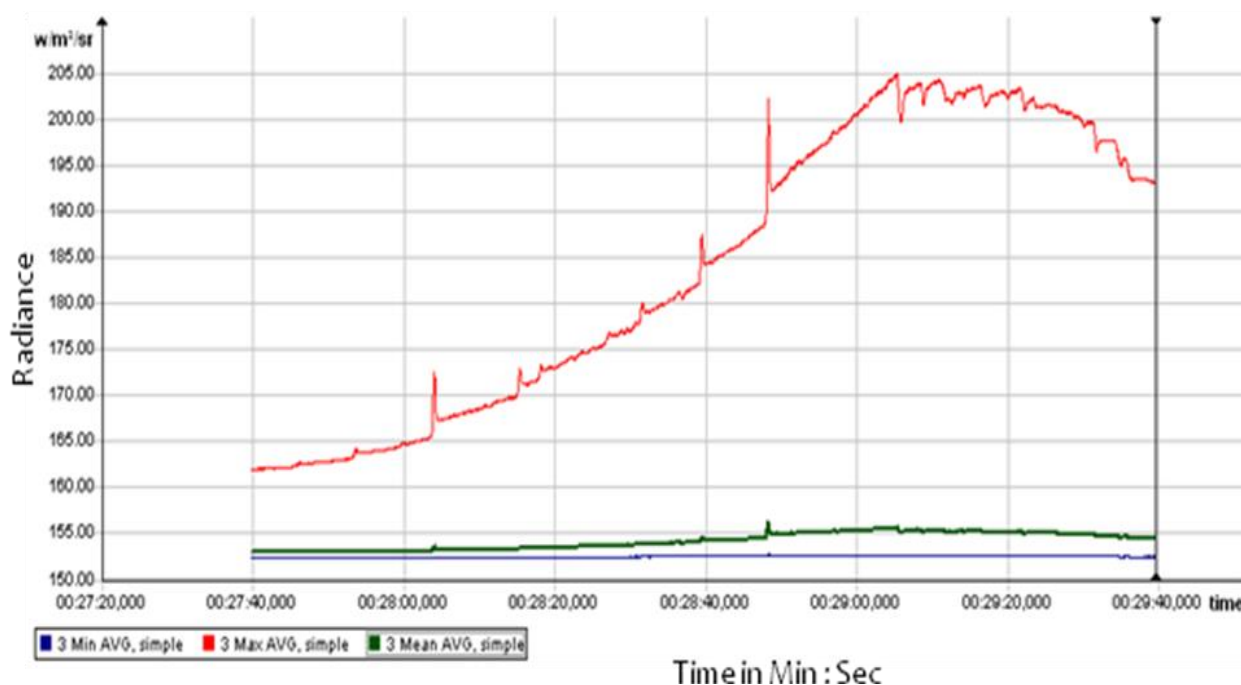


Figure 5.4: Radiance of exhaust gas of Bus with time under accelerating engine condition

5.4 HITRAN MOLECULAR SPECTROSCOPIC DATA

There are several computer models that compute very precise transmission spectra of IR radiation within the atmosphere, the most well-known being the Low Resolution Transmittance (LOWTRAN), Moderate Resolution Transmittance (MODTRAN), or High Resolution Transmittance (HITRAN) codes. These are radiative transfer models for the atmosphere. They incorporate absorption as well as scattering constants for all relevant gaseous species in the atmosphere, and they also include vertical distributions of the constituents, in order to provide an adequate modeling for the gas attenuation. LOWTRAN is a low-resolution propagation model and computer code for predicting atmospheric transmittance and background radiance. MODTRAN is similar to LOWTRAN, but with better spectral resolution. Similarly, HITRAN works with even higher spectral resolution. The 2004 HITRAN model included 17, 34,469 spectral lines for as many as 37 different molecules. However, only limited number of spectral lines pertaining to a few gas species is applicable for predicting atmospheric transmittance in the thermal IR bands [Vollmer and Mollmann, 2010].

The HITRAN database is not expected to be appropriate at high temperature, because it was originally devised for simulating the transmission and the emission of light under atmospheric pressure at low temperatures. Exhaust gas species CO, NO, NO₂, HC database using Java Hawks software was generated for transmissibility and spectral radiance calculation. As the exhaust gas species CO, NO, NO₂, HC have voluminous spectral lines data, the data could not be enclosed as annexure.

5.5 COMPUTATION OF SPECTRAL INTENSITY OF GAS SPECIES

5.5.1 Attenuation of Radiation by a low temperature gas

The attenuation losses of IR radiation passing through a gas are described by Bouguer's law (sometimes also called *Lambert-Beer's law*), which states that the change in radiance passing through matter as a function of length L is given by

$$I(\tau) = I_0(\lambda) \cdot e^{-\tau(\lambda, c, L)} \quad (5.1)$$

Here I_0 defines the radiance entering the matter. Radiation in terms of transmission $T(\tau) = I(\tau)/I_0$ in atmosphere decreases exponentially with increasing optical thickness which is represented by Eq. (5.1). The quantity $\tau(\lambda, c, L)$ is known as the optical thickness of the gas. It depends on wavelength λ , gas concentration c , and length L of optical path through the gas. The gas concentration may be written in a number of ways. It may be given as $\rho = m/V$, that is, mass per volume (kg m^{-3}), as number density $n = N/V$, that is, number of molecules per unit volume (in m^{-3}) or as pressure p (in hPa or atm), since according to the ideal gas law, p is proportional to number density n . For a gas of constant density n (molecules per unit volume) over the whole optical path, τ can be written in two different ways as

$$\tau(\lambda, c, L) = \sigma_{\text{ext}}(\lambda) \cdot n \cdot L = k(\lambda) \cdot p \cdot L \quad (5.2)$$

where the extinction cross section $\sigma_{\text{ext}}(\lambda)$ accounts for scattering as well as absorption losses. Herein only absorption features are considered. $k(\lambda)$ is the spectral gas absorption coefficient, usually given in units of $1/(\text{atm m})$. Once $k(\lambda)$ is known, one may quantitatively calculate the transmission $T(\lambda, p, L) = I(\lambda, p, L)/I_0(\lambda)$ of radiation through any gas of given pressure p and dimension L from Eq. (5.1). Here, Eqs (5.1) and (5.2) are the key for any quantitative analysis of gas absorption: one needs to know the absorption coefficient $k(\lambda)$ very precisely. Then, it is easy to compute the portion of transmitted radiation through a gas of given length at given pressure. We note that the situation may be more complex, for example, if the gas is not distributed homogeneously. In this case the optical thickness is calculated from

$$\tau(\lambda) = \int \sigma(\lambda) \cdot n(x) dx = \int k(\lambda) \cdot p(x) dx \quad (5.3)$$

that is, contributions must be summed up over the total length of the optical path, which is considered. In the following section, the equation with the absorption constant k is used.

5.5.2 Spectral radiance computation for Truck exhaust gas CO under idle engine running condition

Using equation No. 5.2

$$\text{Optical thickness of gas, } \tau(\lambda, c, L) = \sigma_{\text{ext}}(\lambda) \cdot n \cdot L$$

Where, extinction cross section $\sigma_{\text{ext}}(\lambda)$ accounts for scattering as well as absorption losses,
(in $\text{cm}^2/\text{molecule}$)

n is number density $n = N/V$, that is, number of molecules per unit volume
(in $\text{molecule}/\text{cm}^3$),

N - Avogadro's Number = 6.023×10^{23} molecules/mole

L - Optical path through the gas in cm

Average gas (CO) concentration (c, in ppm) is calculated from **Table 4.6**

$$\begin{aligned} \text{Average gas (CO) concentration (c, in ppm)} &= \frac{\text{Number density (n) in molecules/cm}^3 \times \text{molecular mass}}{\text{molecular volume} \times N} \\ n &= \frac{474.16 \times 38 / 10^6 \times 6.023 \times 10^{23}}{1.085 \times 10^{22} \text{ molecules/cm}^3} \quad [\text{ppm} = \text{g/m}^3] \end{aligned}$$

Optical path through the gas (L) = 5 cm (Approx)

Optical thickness of gas $\tau(\lambda, c, L)$ is computed on the basis of the extinction cross section $\sigma_{\text{ext}}(\lambda)$ value obtained from the HITRAN database .

Thereafter, using gas transmissivity Equation 5.1, transmission $T(\tau) = I(\tau)/I_0 = e^{-\tau(\lambda, c, L)}$ and emissivity $\varepsilon = 1 - e^{-\tau(\lambda, c, L)}$ is computed.

Spectral radiance $I_{\lambda, e}(\lambda)$ in $\text{W/m}^2 \mu\text{m}$ is calculated using Equation No. 3.2

Average gas temperature of gas mixture is taken from **Table 4.6**, $T = 62^\circ\text{C}$ (335 K)
spectral radiance $I_{\lambda, e}(\lambda)$ in $\text{W/m}^2 \mu\text{m}$ is computed as below.

$$I_{\lambda, e}(\lambda) = I_{\lambda, b}(\lambda) [1 - e^{-\tau(\lambda, c, L)}]$$

Similarly, spectral radiance is computed for NO, NO₂ and HC during idle engine running condition of Truck. Average gas concentration value is taken from **Table 4.6** of NO, NO₂ and HC as 136, 144 and 100 ppm, respectively at average temp 335 K. Number density (n), in molecules/cm³ is calculated as below.

$$n \text{ for NO} = 2.4619 \times 10^{21} \text{ molecules/cm}^3$$

$$n \text{ for NO}_2 = 3.9688 \times 10^{21} \text{ molecules/cm}^3$$

$$n \text{ for HC} = 7.8299 \times 10^{20} \text{ molecules/cm}^3$$

Computed spectral radiance data is used to plot the graph for comparison of spectral radiance with accelerating condition of engine of Truck.

5.5.3 Spectral radiance computation for Truck exhaust gas species under accelerating engine running condition

Average concentration of Truck exhaust gases CO, NO, NO₂ and HC under accelerating condition is taken from **Table 4.7**. Average gas concentration for exhaust gases CO, NO, NO₂ and HC during accelerating engine running condition of Truck are 812, 145, 152 and 292 ppm respectively at average temperature 492 K. Number density (n), in molecules/cm³ is calculated as below:

$$n \text{ for CO} = 1.8591 \times 10^{22} \text{ molecules/cm}^3$$

$$n \text{ for NO} = 2.6186 \times 10^{21} \text{ molecules/cm}^3$$

$$n \text{ for NO}_2 = 4.209 \times 10^{21} \text{ molecules/cm}^3$$

$$n \text{ for HC} = 2.2837 \times 10^{21} \text{ molecules/cm}^3$$

Spectral radiance is computed for exhaust species CO, NO, NO₂ and HC using equations (5.1) & (5.2) in similar way as computed for idle engine running condition shown in **section 5.4.2**.

Spectral radiance comparison graph in idle and accelerating condition of Truck is shown in **Section 5.6**.

5.5.4 Spectral radiance computation for Bus exhaust gas CO under idle engine running condition

Spectral radiance of Bus exhaust gas species in idle running condition is computed as per method described in Section 5.4.2. Average gas (CO) concentration (c, in ppm) is taken from **Table 4.9**

$$\begin{aligned} \text{Number density (n) in molecules/cm}^3 &= \\ \text{Average gas (CO) concentration (c, in ppm)} \times \text{molecular mass/molecular volume} \times N & \\ n = 403.92 \times 28 / 10^6 \times 6.023 \times 10^{23} & \quad [\text{ppm} = \text{g/m}^3] \\ = 6.812 \times 10^{21} \text{ molecules/cm}^3 & \end{aligned}$$

$$\text{Optical path through the gas (L)} = 5 \text{ cm (Approx)}$$

Spectral radiance $I_{\lambda,e}(\lambda)$ in $\text{W/m}^2 \mu\text{m}$ is computed using Equation (3.2). Average gas temperature of gas mixture is taken from **Table 4.9** as $T = 62^\circ \text{C}$ (335 K). Spectral radiance $I_{\lambda,e}(\lambda)$ computation results are shown in the graph in Section 6.5.

$$I_{\lambda,e}(\lambda) = I_{\lambda,e}(\lambda) [1 - e^{-\tau(\lambda,c,L)}]$$

Similarly, spectral radiance is computed for NO, NO₂ and HC during idle engine running condition of Bus. Average gas concentration value is taken from **Table 4.9** for NO, NO₂ and HC, as 91, 95 and 100 ppm respectively at average temperature 359 K. Number density (n), in molecules/cm³ is calculated as below:

$$n \text{ for NO} = 1.637 \times 10^{21} \text{ molecules/cm}^3$$

$$n \text{ for NO}_2 = 2.637 \times 10^{21} \text{ molecules/cm}^3$$

$$n \text{ for HC} = 7.8299 \times 10^{20} \text{ molecules/cm}^3$$

Computed spectral radiance data is used to plot the graph for comparison of spectral radiance with accelerating condition of engine of Truck in **Section 5.6**.

5.5.5 Spectral radiance computation for Bus exhaust gas species under accelerating engine running condition

Average concentration of exhaust gases during Truck in accelerating condition is taken from **Table 4.10**. Average gas concentration for exhaust gases CO, NO, NO₂ and HC during accelerating engine running condition of Truck are 1170, 153, 161 and 350 ppm respectively at average temperature of 495 K. Number density (n), in molecules/cm³ is calculated as below.

$$n \text{ for CO} = 1.9729 \times 10^{22} \text{ molecules/cm}^3$$

$$n \text{ for NO} = 2.7676 \times 10^{21} \text{ molecules/cm}^3$$

$$n \text{ for NO}_2 = 4.4537 \times 10^{21} \text{ molecules/cm}^3$$

$$n \text{ for HC} = 2.7405 \times 10^{21} \text{ molecules/cm}^3$$

Spectral radiance is computed for exhaust gas species CO, NO, NO₂ and HC using equations (5.1) & (5.2) in similar way as computed for idle engine running condition shown in **Section 5.4.2**. Spectral radiance comparison graph in idle and accelerating condition of Truck is shown in **Section 5.6**.

5.6 EXHAUST GAS SPECTRAL RADIANCE ANALYSIS OF TRUCK

Spectral radiance of exhaust gas species is calculated as explained in Section 5.5 using HITRAN data. Spectral radiance of gas species CO, NO, NO₂ and HC in thermal IR band is shown in Figures 5.5, 5.6, 5.7 and 5.8, respectively. It is observed that spectral radiance of gas species is less in idle engine running condition than that in accelerating engine condition. It is due to increase in gas temperature as well as concentration of gas species during engine acceleration. CO contributes maximum in the total spectral radiance of gas mixture as shown in **Figure 5.5**. NO₂ contribution is very less in comparison to other exhaust gases as shown in **Figure 5.6**.

5.6.1 Spectral radiance of exhaust gas species under idle & accelerated engine running condition of Truck

Spectral radiance distribution of exhaust gas species CO, HC, NO and NO₂ in the waveband is shown in **Figures 5.5, 5.6, 5.7 and 5.8**, respectively.

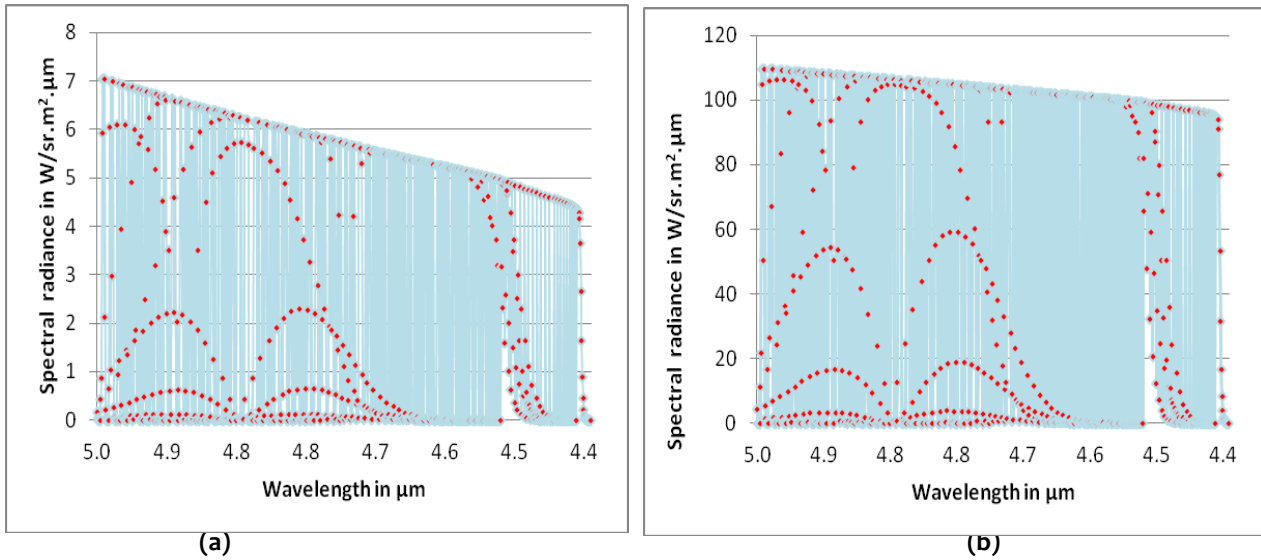


Figure 5.5 : (a) Spectral radiance, $I_{\lambda,e}(\lambda)$ of CO under idle engine running condition of Truck (b) Spectral radiance, $I_{\lambda,e}(\lambda)$ of CO under accelerating engine condition of Truck

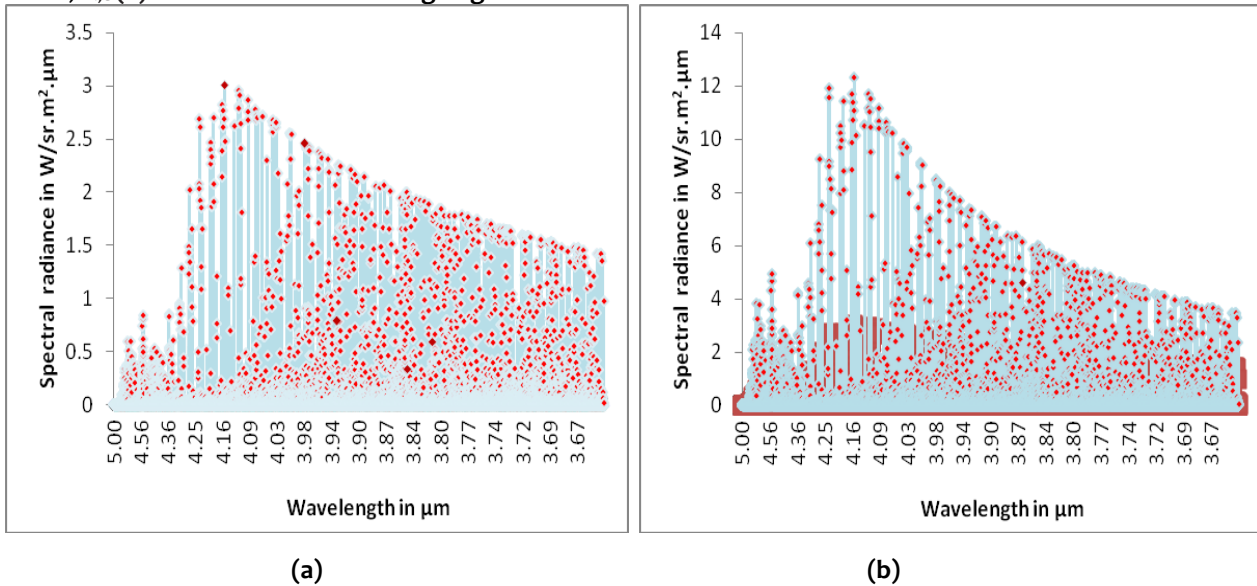
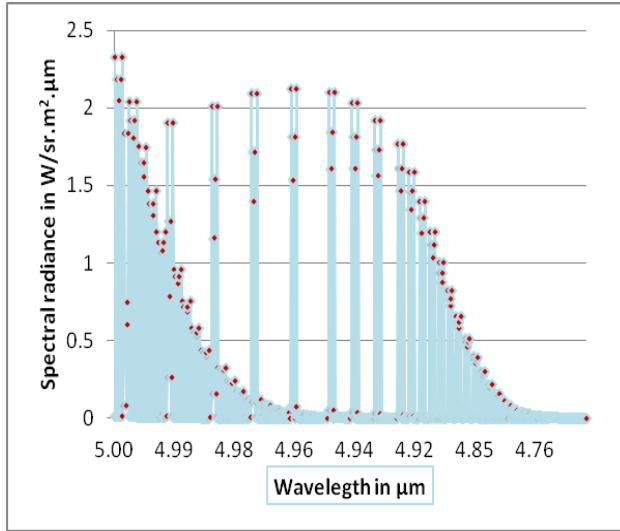
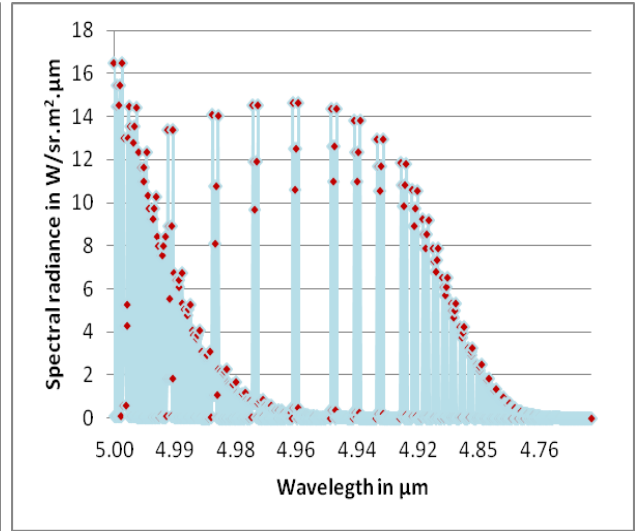


Figure 5.6 : (a) Spectral radiance, $I_{\lambda,e}(\lambda)$ of HC under idle engine running condition of Truck (b) Spectral radiance, $I_{\lambda,e}(\lambda)$ of HC under accelerating engine condition of Truck

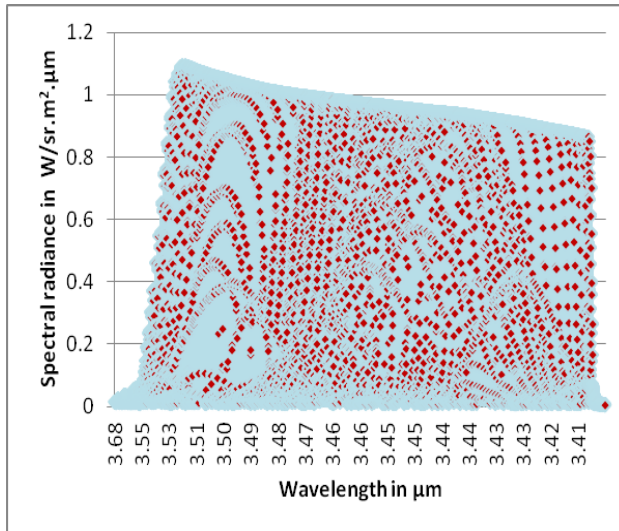


(a)

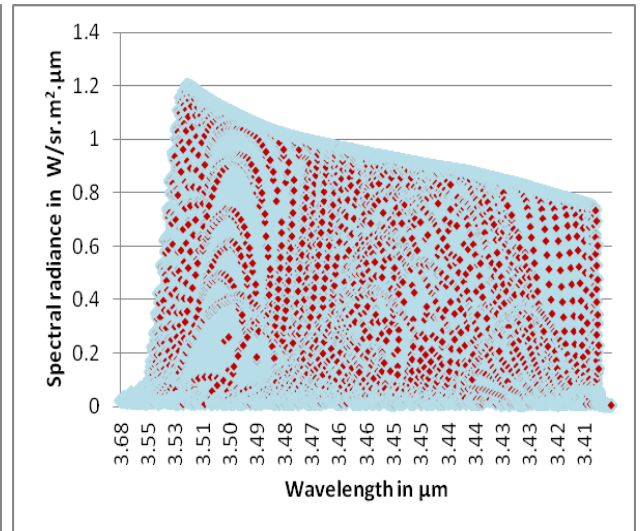


(b)

Figure 5.7 : (a) Spectral radiance, $I_{\lambda,e}(\lambda)$ of NO under idle engine running condition of Truck (b) Spectral radiance, $I_{\lambda,e}(\lambda)$ of NO under accelerating engine condition of Truck



(a)



(b)

Figure 5.8 : (a) Spectral radiance, $I_{\lambda,e}(\lambda)$ of NO₂ under idle engine running condition of Truck (b) Spectral radiance, $I_{\lambda,e}(\lambda)$ of NO₂ under accelerating engine condition of Truck

5.6.2 Results and discussion

Spectral radiance of exhaust gas emission is spread over wavelength band as shown in **Figures 5.5, 5.6, 5.7 and 5.8**. Maximum spectral radiance value at specific wavelength is summarised below in **Table 5.1**.

Table 5.1: Spectral radiance of Truck exhaust gas emissions

S. No.	Diesel exhaust Gas species	Maximum spectral radiance in idling engine condition (in W/sr.m ² .μm)	Maximum spectral radiance in accelerating engine condition (in W/sr.m ² .μm)
1.	CO	7 at wavelength 5 μm	110 at wavelength 5 μm
2.	HC	3 at wavelength 4.16 μm	12 at wavelength 4.16 μm
3.	NO	2.4 at wavelength 5 μm	16.5 at wavelength 5 μm
4.	NO ₂	1.1 at wavelength 3.54 μm	1.2 at wavelength 3.54 μm

Spectral radiance contribution of CO is maximum and NO₂ contribution is minimum in comparison to other two gas species, HC and NO.

5.7 EXHAUST GAS SPECTRAL RADIANCE ANALYSIS OF BUS

Spectral radiance of exhaust gas species is calculated as explained in **Section 5.5** using HITRAN data. Spectral radiance of gas species CO, NO, NO₂ and HC thermal IR waveband is shown in **Figures 5.9, 5.10, 5.11 and 5.12**, respectively. It is observed that spectral radiance of gas species is less in idle engine running condition in comparison to that in accelerating engine condition. It is due to increase in gas temperature as well as concentration of gas species under engine acceleration. CO contributes maximum in total spectral radiance of gas mixture as shown in Figure 5.9. NO₂ contribution is very less in comparison to other exhaust gases as shown in **Figure 5.12**.

5.7.1 Spectral radiance of Bus exhaust gas species under idle & accelerated engine running condition

Spectral radiance distribution of exhaust gas species CO, HC, NO and NO₂ over the wavelength band is shown in **Figures 5.9, 5.10, 5.11 and 5.12**, respectively.

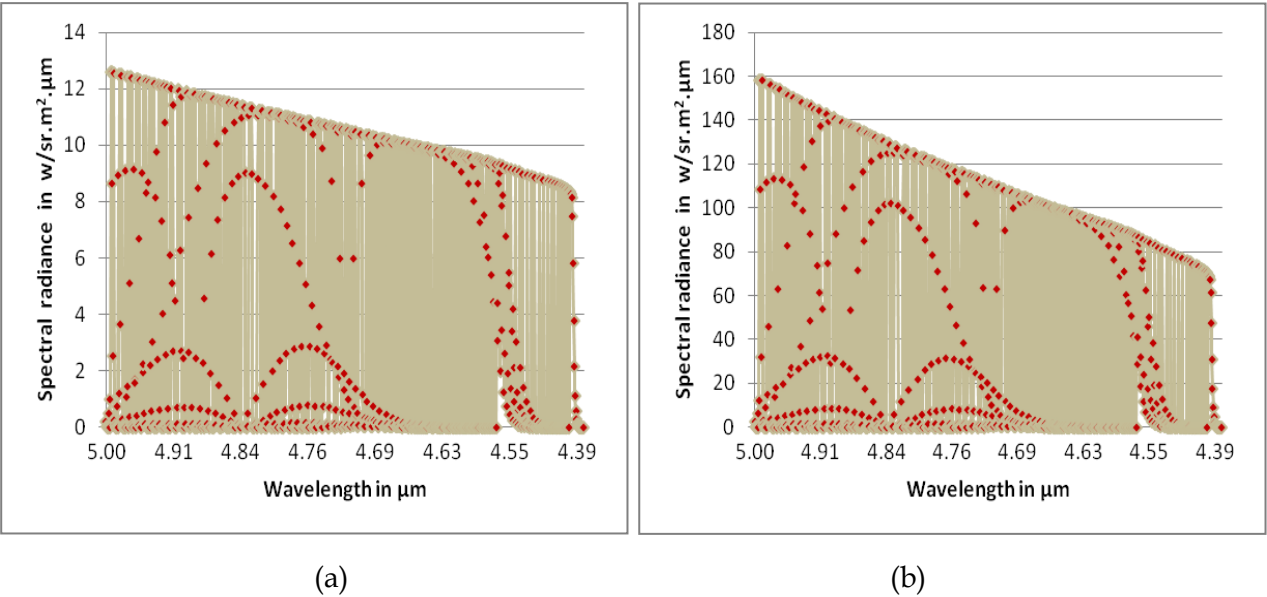
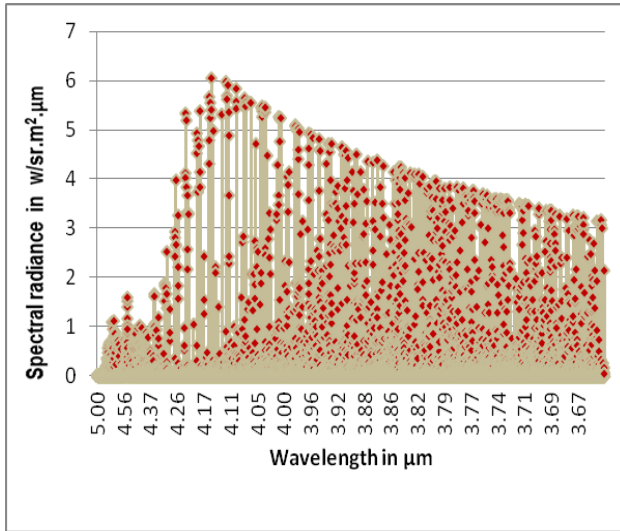
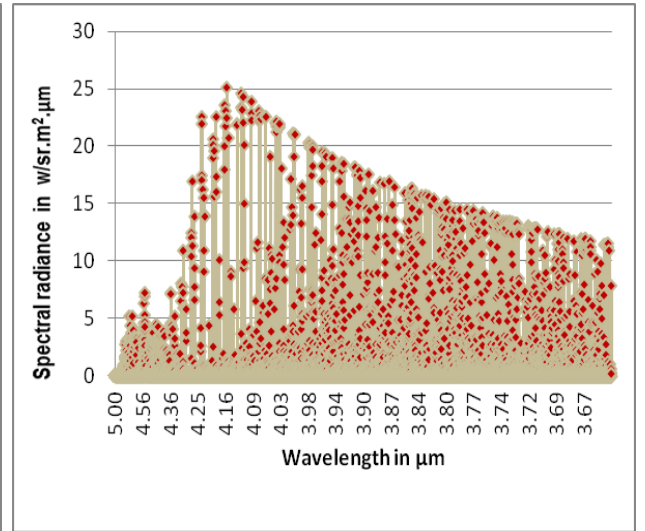


Figure 5.9 : (a)Spectral radiance, $I_{\lambda,e}(\lambda)$ of CO under idle engine running condition of Bus (b) Spectral radiance, $I_{\lambda,e}(\lambda)$ of CO under accelerating engine condition of Bus

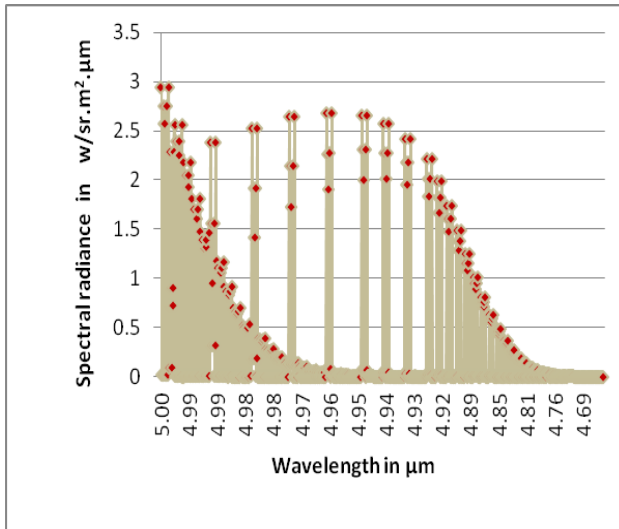


(a)

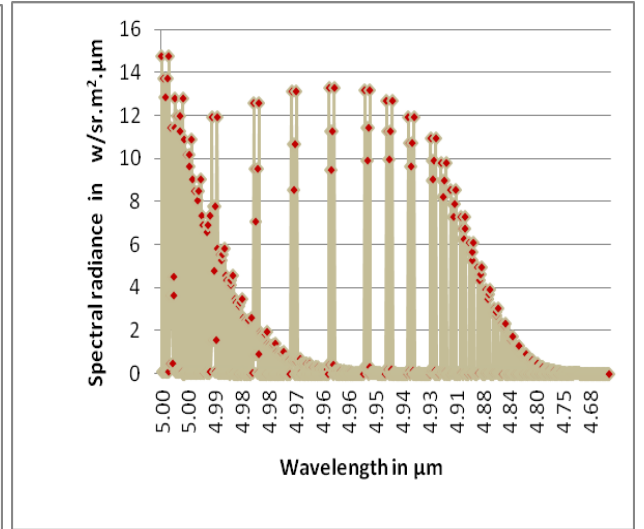


(b)

Figure 5.10 : (a) Spectral radiance, $I_{\lambda,e}(\lambda)$ of HC under idle engine running condition of Bus (b) Spectral radiance, $I_{\lambda,e}(\lambda)$ of HC under accelerating engine condition of Bus

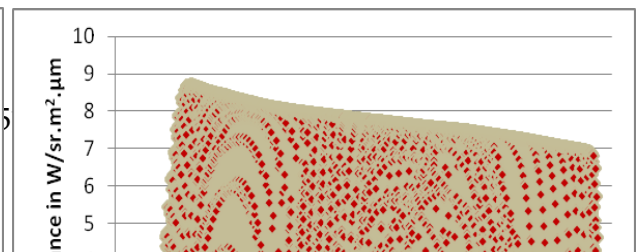
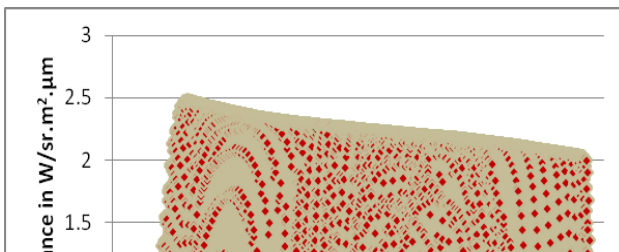


(a)



(b)

Figure 5.11 : (a) Spectral radiance, $I_{\lambda,e}(\lambda)$ of NO under idle engine running condition of Bus (b) Spectral radiance, $I_{\lambda,e}(\lambda)$ of NO under accelerating engine condition of Bus



(a)

(b)

Figure 5.12: (a) Spectral radiance, $I_{\lambda,e}(\lambda)$ of NO₂ under idle engine running condition of Bus
(b) Spectral radiance, $I_{\lambda,e}(\lambda)$ of NO₂ under accelerating engine condition of Bus

5.7.2 Results and discussions

Spectral radiance of exhaust emissions is spread over wavelength band as shown in **Figures 5.9, 5.10, 5.11 and 5.12**. Maximum spectral radiance value at specific wavelengths is summarised in **Table 5.2**.

Table 5.2: Spectral radiance of Bus exhaust gas emissions

S. No.	Diesel exhaust Gas species	Maximum spectral radiance in idling engine condition (in W/sr.m ² .μm)	Maximum spectral radiance in accelerating engine condition (in W/sr.m ² .μm)
1.	CO	12.5 at wavelength 5 μm	160 at wavelength 5 μm
2.	HC	6 at wavelength 4.16 μm	25 at wavelength 4.16 μm
3.	NO	3 at wavelength 5 μm	15 at wavelength 5 μm
4.	NO ₂	2.5 at wavelength 3.54 μm	8.9 at wavelength 3.54 μm

Spectral radiance contribution of CO is maximum and NO₂ contribution is minimum in comparison to other gas species, HC and NO.

5.8 SUMMARY

Spectral radiance of diesel exhaust emissions such as CO, HC, NO and NO₂ of two vehicles are calculated using HITRAN database. Total radiance of diesel exhaust emission of vehicles is also measured using radiometric thermal imager. Important observations of analysis are summarised below:

1. It is observed that measured total radiance of exhaust smoke of Truck by radiometric thermal imager in 3-5 μm waveband under acceleration of engine has maximum value of 63 W/sr. m² as shown in **Figure 5.2**.
2. It is noticed that measured total radiance of exhaust smoke of Bus by radiometric thermal imager in 3-5 μm waveband under acceleration of engine has maximum value of 205 W/sr. m² as shown in **Figure 5.4**. The outcome of the study confirms that radiance of exhaust smoke

is mainly depends on the temperature and concentration of exhaust gas species. In addition, radiance of exhaust smoke is influenced by the ambient air temperature and wind speed also.

3. The spectral radiance calculated using HITRAN database has also confirmed that diesel exhaust emission spectral radiance of Bus is more than exhaust emissions spectral radiance of Truck. Calculated spectral radiance is given in **Table 5.1** and **Table 5.2**.
4. The spectral radiance contribution of CO is maximum in comparison to other gas species under engine idling and acceleration of both Bus and Truck.
5. The spectral radiance contribution of NO₂ is minimum in comparison to other gas species under engine idling and acceleration of both Bus and Truck.
6. It can be said that visualization of diesel exhaust emission in the thermal IR image acquired using radiometric thermal imager is mainly due to CO, which has more predominant thermal emission and absorption in MWIR 3-5 μm waveband.
7. From the figures 5.5 to 5.12, the IR signature contribution of each constituent of exhaust gas is highly wavelength selective and confined to only in the following sub-bands in MWIR (3-5 μm).

CO: 4.4 - 5 μm

HC: 3.67- 5 μm

NO: 4.76 - 5.00 μm

NO₂: 3.41 - 3.68 μm

The constituents of exhaust gas species of diesel engine of truck/ bus primarily generate IR signature in the MWIR band (3-5 μm).

8. The important finding of the study is that the thermal signature of the exhaust of engine is dependent on constituent gas elements and exhaust temperature. This is a valuable input for simulating thermal signature of exhaust smoke of engines in the decoys of military vehicles. This mandates the use of similar type of fuel for mimicking the thermal signature of diesel engine of the military vehicles.

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