Chapter 14
Visibility

Abstract Visibility is very important for evacuation during a fire and, therefore, a very important parameter for fire safety in a tunnel. There are different methods for estimating the visibility in smoke-filled spaces, using mass-specific extinction coefficient or the mass optical density. For both methodologies there are experimental values available for some materials of interest. First, the mass extinction coefficient methodology is presented and at the end compared and correlated to the mass optical density methodology. Values of these parameters for selected materials are presented and conversion of values for one of the parameters into the other is discussed. Finally, the effect on the walking speed during egress is discussed.

Keywords Visibility · Extinction coefficient · Optical density · Egress

14.1 Introduction

Fire safety in tunnels relies to a large extent on the principle of self-evacuation. Visibility is one of the most important parameter affecting the possibilities for safe egress. Although reduced visibility in itself does not lead to incapacitation, visibility is an important parameter in tenability analysis. With the most common criteria used for visibility, the "tenability limits" for visibility are in most cases reached before similar limits are reached for other parameters of interest (gas concentrations, temperature, and radiation) as shown in Chap. 15. Therefore, good knowledge of visibility phenomena and the processes affecting it are very important for the safety of escaping people.

As with other parameters relating to perception, it is not easy to find a single mathematical equation describing the relation between visibility and smoke density. The situation is complicated by the fact that the typical size and shape of the particles in smoke from fires varies and depends on the burnt material and combustion conditions [1, 2]. This has led to different suggestions about how to calculate visibility, that is, how to relate a measurable (or estimated) physical parameter to visibility. In the next section different approaches are presented, compared, and discussed.

H. Ingason et al., *Tunnel Fire Dynamics,* DOI 10.1007/978-1-4939-2199-7_14

14.2 Different Methods of Predicting Visibility

One common way to express the smoke density is by the extinction coefficient, C_s (1/m):

$$C_s = \frac{1}{L}\ln\left(\frac{I_0}{I}\right) \tag{14.1}$$

where I_0 is the intensity of the incident light, I is the intensity of the light through smoke, and L is the path length of the light (m).

The relationship between the transmitted and incident intensities is a function of the mass-specific extinction coefficient of smoke σ (m^2/kg), the mass concentration of smoke, ρ_{sm} (kg/m^3), and L (m) as expressed by Bouguer's law [3]:

$$\frac{I}{I_0} = \exp(-\sigma\rho_{sm}L) \tag{14.2}$$

Jin [4, 5] developed several relationships between the visibility (V_s) and the extinction coefficient. For a *light-emitting sign* the relationship is given as:

$$V_s \approx \frac{1}{C_s}\ln\left(\frac{B_{EO}}{\delta_c k\Pi}\right) \tag{14.3}$$

where,

B_{EO}	brightness of the sign (cd/m^2)
δ_c	contrast threshold of signs in smoke at the obscuration level (-)
$k = \sigma_s/C_s$	
$C_s = \sigma_s + \sigma_{ab}$	extinction coefficient (1/m)
σ_s	scattering coefficient (1/m)
σ_{ab}	absorption coefficient (1/m)
Π	$1/\pi$ of mean illuminance of light radiating from all directions in smoke (m/m^2)

The contrast threshold (δ_c) is in the range 0.01–0.05, and a value of 0.02 is often used (For example, ISO 13571). For *reflecting signs* the corresponding equation can be written as [4, 5]:

$$V_s \approx \frac{1}{C_s}\ln\left(\frac{\alpha}{\delta_c k}\right) \tag{14.4}$$

where α is the reflectance of the sign.

Jin also showed that, at the obscuration threshold (for visibilities between 5 and 15 m) the visibility can be expressed as [5]:

$$V_s = \frac{K}{C_s} \tag{14.5}$$

where K is a constant which is 5–10 for a light-emitting sign and 2–4 for a reflecting sign.

If the smoke is an irritant, the visibility is reduced and both the smoke density and the irritation affect the walking speed. There is a linear decrease in visibility as the extinction coefficient increases, in the same way as for nonirritant smoke for $0.1 \leq C_s \leq 0.25$. For $C_s \geq 0.25$ the visibility in irritant smoke can be written as [4, 5]:

$$V_s = (K / C_s)(0.133 - 1.47 \lg C_s) \tag{14.6}$$

The experiments for which the correlation above was developed, showed that a value of $K = 6$ gave best agreement [5]. Note that those tests were performed with a lighted FIRE EXIT sign.

Since

$$C_s = \sigma \cdot \rho_{sm} \tag{14.7}$$

one can write

$$V_s = \frac{K}{\sigma \rho_{sm}} \tag{14.8}$$

where

$$\rho_{sm} = Y_s \frac{\Delta m_f}{V} \text{ or} \tag{14.9}$$

$$\rho_{sm} = Y_s \frac{\dot{m}_f}{\dot{V}} \tag{14.10}$$

depending on whether the object of interest is defined by a volume, V (m^3; for example, a train without openings) or an air flow rate, $\dot{V}$ (m^3/s; for example, a tunnel). Y_s is the soot yield (kg/kg) for the burning material under prevailing conditions. The change in mass of fuel can be given as a mass difference, Δm_f (kg) as in Eq. (14.9) or as a mass flow, $\dot{m}_f$ (kg/s) as in Eq. (14.10). In Table 14.3 the soot yield Y_s is given for some selected materials in kg/kg. In Chap. 7 the soot yield and the effect of the equivalence ratio are discussed further.

The extinction coefficient, C_s, can be obtained either from measurements using Eq. (14.1) or from values of σ and ρ_{sm} using Eq. (14.7).

If one-dimensional smoke flow in a tunnel is assumed, the visibility can be calculated from

$$V_s = \frac{K u A_t}{\sigma Y_s \dot{m}_f} \tag{14.11}$$

where u is the velocity of air in the tunnel (m/s) and A_t is the cross section area of the tunnel (m^2). The heat release rate, $\dot{Q}$ (kW), from a fire can be described as

$$\dot{Q} = \chi \Delta H_c \dot{m}_f \tag{14.12}$$

where χ is the combustion efficiency and ΔH_c is the heat of combustion (kJ/kg). This means that

$$V_s = \frac{KuA_t\chi\Delta H_c}{\sigma Y_s\dot{Q}} \tag{14.13}$$

Note the difference between the optical density (OD), and the extinction coefficient (C_s), where

$$OD = \lg\frac{I_0}{I} = \frac{C_s \cdot L}{\ln 10} \approx \frac{C_s \cdot L}{2.303} \tag{14.14}$$

This is discussed in more detail below, when relating the specific extinction coefficient to the mass optical density, D_{mass} (m^2/kg).

Both the mass-specific extinction coefficient and the soot yield depend on the type of fuel and therefore it is important to have data for different types of fuels. Note that there are different definitions and different ways of presenting this type of data.

Mulholland et al. [6, 7] have studied the specific extinction coefficient and presented an average value of 8700 m^2/kg (wavelength = 632.8 nm) for postflame smoke production from well-ventilated fires. Table 14.1 and 14.2 summarize the mass-specific extinction coefficients for gases/liquids and solids, respectively, with values from different studies. The value 8700 m^2/kg (with an expanded uncertainty of 1100 m^2/kg and 95 % confidence interval) mentioned above is an average of all the included studies. One can note that for some fuels, for example, heptane there is some spread in the specific extinction coefficient between the different studies. This could be an effect of the experimental setup or the scale. However, for some fuels, for example, PS, PVC, and rubber, there are relatively good agreement between the different setups.

Note that the standard SS-ISO 13571:2007 suggests an average value of 10,000 m^2/kg [8].

Tewarson [9] presented data for many different types of fuels. There the information is given as

$$D_{mass} = \frac{OD \cdot Y_s}{L \cdot \rho_s} \tag{14.15}$$

Using Eqs. (14.7), (14.14) and (14.15), a relationship between the specific extinction coefficient and D_{mass} can be found:

$$\sigma = \frac{\ln 10 \cdot D_{mass}}{Y_s} \tag{14.16}$$

In Table 14.3 and 14.4 Y_s and D_{mass} for a number of fuels and building materials are listed. Equation (14.16) is then used to calculate the mass-specific extinction coefficient. In the table, there are two columns with soot yield. The reason for this is that, the more recent version of the SFPE handbook has somewhat different values

Table 14.1 Examples of mass-specific extinction coefficients (at 632.8 nm) for burning gases and liquids [6]

Fuel	σ [m^2/g]	Description
Gases		
Propane	8000	170–350 kW
Ethene	7800	Turbulent diffusion burner, 5–10 kW
Ethene	8800	5 cm diameter burner, 2.0 kW
Propene	7000	Turbulent diffusion burner, 5–10 kW
Butadiene	7500	Turbulent diffusion burner, 5–10 kW
Acetylene	5300	Turbulent diffusion burner, 5–10 kW
Acetylene	7800	Premixed burner at equivalence ratio of 2.5
Acetylene	7800	5 cm diameter burner, 2.6 kW
Liquids		
Heptane	10,300	Small-scale to large-scale
Heptane	7800	30 cm (60 kW) and 50 cm (250 kW) pools
Heptane	6400	Turbulent diffusion burner, 5–10 kW
Benzene	7800	Turbulent diffusion burner, 5–10 kW
Styrene	9700	2 cm diameter pool
Cyclohexane	7500	Turbulent diffusion burner, 5–10 kW
Toluene	7000	Turbulent diffusion burner, 5–10 kW
Kerosene	10,100	Small-scale to large-scale
Kerosene	9200	Small-scale, 1–5 kW
Petrol	11,200	5 mL of fuel
Diesel	10,300	5 mL of fuel
Fuel oil	11,600	5 mL of fuel
Fuel oil	7200	Small-scale, 1–5 kW
Fuel oil	9400	Small-scale, 1–5 kW
Paraffin oil	9100	5 mL of fuel
Butane	9900	5 mL of fuel
Crude oil	8800	40 cm (60 kW) and 60 cm (180 kW) pools

compared to the 1st edition. The 1st edition version is included since those values correspond to the reported values of D_{mass}.

For some materials there is a large variation in the values of the specific extinction coefficient calculated from D_{mass} in Table 14.3 and 14.4 compared to the measured values listed in Table 14.1 and 14.2. The specific extinction coefficient depends on the experimental setup and the size of the fire as shown by the values in Table 14.1 and 14.2. In some cases there is a good correlation between the values in Table 14.1 and 14.2 and Table 14.3 and 14.4.

Table 14.5 shows the difference in soot yield for some fuels at different fire sizes. It can be seen that the mass-specific extinction coefficient depends on the fuel type, but does not seem to depend on the flame conditions (laminar or turbulent) [3].

Table 14.2 Examples of mass-specific extinction coefficients (at 632.8 nm) for burning solids [6]

Fuel	σ [m^2/g]	Description
Solids		
Douglas fir	10,300	Small-scale to large-scale
Oak	7600	Small-scale, 1–5 kW
Wood crib	8500	1 crib (50 kW), 3 cribs (250 kW)
HDPE	8800	Small-scale, 1–5 kW
PP	7400	Small-scale, 1–5 kW
PMMA	10,500	Small-scale to large-scale
PMMA	7900	Small-scale, 1–5 kW
Polycarbonate	10,200	Small-scale to large-scale
Polycarbonate	7600	Small-scale, 1–5 kW
PVC	9900	Small-scale to large-scale
PVC	9000	Small-scale, 1–5 kW
PS	10,000	Small-scale to large-scale
PS	9600	Small-scale, 1–5 kW
Styrene-butadiene rubber	10,400	Small-scale to large-scale
Rubber	10,100	Small-scale, 1–5 kW
Polyurethane crib	8100	1 crib (100 kW), 3 cribs (300 kW)

PE polyethene, *PP* polypropene, *PS* polystyrene, *PUR* polyurethane

Using Eqs. (14.13) and (14.16) one can derive an equation for visibility based on D_{mass}:

$$V_s = \frac{K \cdot \chi}{\ln 10} \frac{uA\Delta H_c}{D_{mass}\dot{Q}} \tag{14.17}$$

If a combustion efficiency of unity is assumed, Eq. (14.17) reduces to:

$$V_s = \frac{K}{2.3} \frac{uA\Delta H_c}{D_{mass}\dot{Q}} \tag{14.18}$$

and if a value of $K=2$ is assumed, one obtains the following expression:

$$V_s = 0.87 \frac{uA\Delta H_c}{D_{mass}\dot{Q}} \tag{14.19}$$

which is the same equation presented by Ingason [11]. Ingason also summarized mass optical densities for different vehicles. These are given in Table 14.6.

In a test series in the Runehamar tunnel in Norway, Ingason et al. [13] performed tests simulating fires in heavy goods vehicle (HGV) cargos. Except for a pool fire test using diesel, different mixtures of cellulosic materials and plastics (18–19 % plastics in each test) were used as fuel to simulate the cargo. During these tests the extinction coefficient was measured. The mass optical density estimated from the

Table 14.3 Soot yield, D_{mass} and specific extinction coefficient for selected materials

Material	Y_s (kg/kg)	Y_s (kg/kg)	D_{mass} (m^2/kg)	σ (m^2/kg)
Reference	[9]	[10]	[9]	Calculated, Eq. (14.16)
Ethane	0.008	0.013	24	6900
Propane	0.025	0.024	81	7500
Butane	0.026	0.029	155	13,700
Ethene	0.045	0.043	201	10,300
Propene	0.103	0.095	229	5100
1,3-Butadiene	0.134	0.125	319	5500
Acetylene	0.129	0.096	315	5600
Heptane	0.037	0.037	190	11,800
Octane	0.039	0.038	196	11,600
Benzene	0.175	0.181	361	4700
Styrene	0.184	0.177	351	4400
Kerosene	NA	0.042	NA	NA
Isopropylalcohol	0.014	0.015	NA	NA
Wood (red oak)	0.015	0.015	37	5700
Wood (hemlock)	NA	0.015	NA	NA
Toluene	NA	0.178	NA	NA
ABS	NA	0.105	NA	NA
PE	0.060	0.06	230	8800
PP	0.059	0.059	240	9400
PS	0.164	0.164	335	4700
Nylon	0.075	0.075	230	7100

NA not available

measurements for different types of materials (cargo) is presented in Table 14.7. The values correlate well with the values given for "truck" in Table 14.6. The values for diesel are similar to those given for benzene and styrene in Table 14.3.

For the estimation of the visibility in a tunnel either Eq. (14.13) or Eq. (14.17) can be used depending on which information is available on the involved parameters. If the visibility is to be determined for a line of sight having a distance x m downstream of a fire with a nonconstant HRR, it is important to take the transport time into account and relate the transient visibility to the relevant HRR. This was discussed also in Chap. 8 on gas temperatures, where a relation for the actual time and its dependency on a nonconstant velocity was presented. If for simplicity, a constant velocity, u, is assumed, the actual time τ (s) for the fire development at the distance x from the fire can be calculated as

$$\tau = t - \frac{x}{u} \tag{14.20}$$

where t (s) is the measured time from the ignition of the fire.

Table 14.4 Soot yield, D_{mass} and specific extinction coefficient for selected building materials

Material	Y_s (kg/kg)	Y_s (kg/kg)	D_{mass} (m^2/kg)	σ (m^2/kg)
Reference	[9]	[10]	[9]	Calculated, Eq. (14.16)
PUR foam, flexible, GM21	0.131	0.131	NA	NA
PUR foam, flexible, GM23	0.227	0.227	326	3300
PUR foam, flexible, GM25	0.194	0.194	286	3400
PUR foam, flexible, GM27	0.198	0.198	346	4000
PUR foam, rigid, GM29	0.130	0.13	304	5400
PUR foam, rigid, GM31	0.125	0.125	278	5100
PUR foam, rigid, GM35	0.104	0.104	260	5800
PUR foam, rigid, GM37	0.113	0.113	290	5900
Polystyrene foam, GM47	0.180	0.18	342	4400
Polystyrene foam, GM49	0.210	0.21	372	4100
Polystyrene foam, GM51	0.185	0.185	340	4200
Polystyrene foam, GM53	0.200	0.2	360	4100
PVC-1 (LOI=0.50)	NA	0.098	NA	NA
PVC-2 (LOI=0.50)	NA	0.076	NA	NA
PVC (LOI=0.35)	NA	0.088	NA	NA
PVC (LOI=0.30)	NA	0.098	NA	NA
PVC (LOI=0.25)	NA	0.078	NA	NA
Cable, PE/PVC 1	0.076	0.076	242	7300
Cable, PE/PVC 2	0.115	0.115	NA	NA
Cable, PE/PVC 5	0.136	0.136	NA	NA

NA not available

For estimation of the soot yield, the $\dot{Q}(\tau)$ is used in Eq. (14.13) or Eq. (14.17), that is, the transportation time should be accounted for in this case.

Example 14.1 An HGV loaded with polypropene (ΔH_c=38.6 MJ/kg) is burning in a tunnel with the cross section W=9 m and H=6 m. The air velocity in the tunnel is 2 m/s. The HRR of the fire increases linearly at 210 kW/s for 12 min. What is the visibility after 6 min at a distance of 500 m downstream of the fire? Assume nonirritant smoke.

Solution: Start with calculating the actual time using (14.20): $\tau = 360 - 500/2 = 110$ s. This gives $\dot{Q}(\tau) = 210 \times 110 = 23100$ kW. From Table 14.3 the $D_{mass} = 240$ m^2/kg for polypropene can be found. Using Eq. (14.18) and assuming $K=2$ gives

$$V_s = \frac{2}{2.303}\frac{2\cdot 9\cdot 6\cdot 38600}{240\cdot 23100} = 0.65 \text{ m}.$$

In this solution we used K=2 (lower end of the interval for reflecting signs), which often is used, but note that in many cases other values are used, for example, K=3, that is, the centre of the interval for reflecting signs.

Table 14.5 Yield of soot for different fuels and different HRR [7]

Material	Y_s (kg/kg)
Propane, 50 kW	0.0106
Propane, 200 kW	0.0063
Propane, 450 kW	0.0052
Heptane, 300 kW	0.0129
Toluene, 250 kW	0.100
Heptane/Toluene, 320 kW	0.082

Table 14.6 Mass optical densities (D_{mass}) for different types of vehicles [11, 12]

Type of vehicle	D_{mass} (m^2/kg)
Road	
Car (steel)	381
Car (plastic)	330
Bus	203
Truck	76–102
Rail	
Subway (speed)	407
Subway (aluminium)	331
IC type (steel)	153
ICE type (steel)	127–229
Two joined half-vehicles (steel)	127–178

Table 14.7 Mass optical densities (D_{mass}) for different types of HGV cargo materials [13]

Type of cargo/material	D_{mass} (m^2/kg)
Diesel	360–450
Wood/PE	13–82
Wood/PUR	47–138
Furniture/rubber	10–87
Cartons/PS cups	30–120

14.3 The Influence of Visibility on Egress

One of the most well-known and used relationships between visibility (extinction coefficient) and walking speed is presented by Jin [4]. The values are presented in Fig. 14.1 and also included in Fig. 14.2. These tests were performed with a limited number of participants.

Frantzich and Nilsson [14] performed tests in a tunnel with these dimensions: 36.75 m long, 5.0 m wide and 2.55–2.70 m high. In total 46 persons participated in the study, with an average age of approximately 22 years. The extinction coefficient was measured using a 5 mW diode laser with a wavelength of 670 nm. The measurements were performed at a height of 2 m in the tunnel with a sight distance of 1 m.

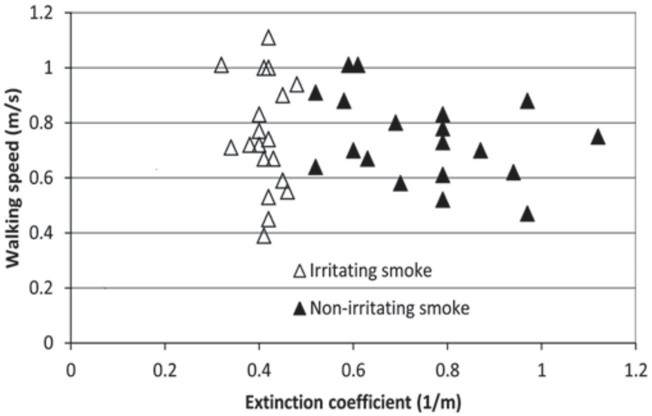

Fig. 14.1 Relationship between the walking speed and the extinction coefficient for irritant and nonirritant smoke after Jin [4]

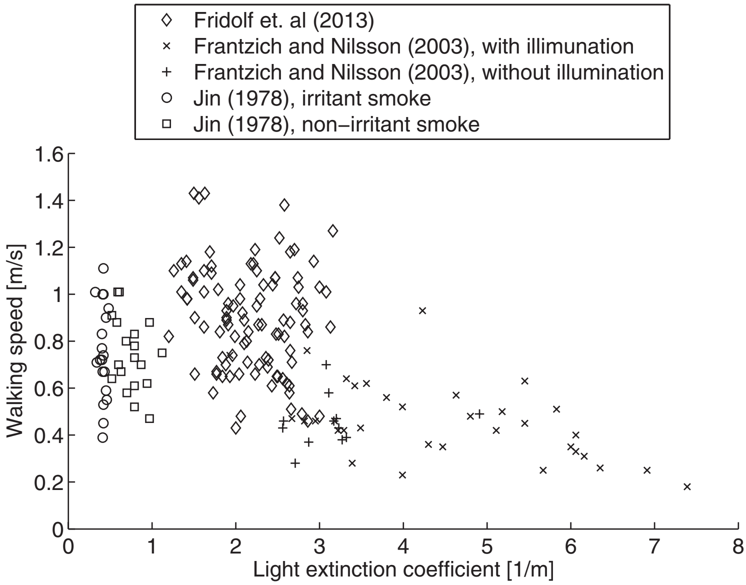

Fig. 14.2 Relationship between the walking speed and the extinction coefficient for irritant and nonirritant smoke [15]. The graph is based on several different sources [16, 14, 17]

In their tests, Frantzich and Nilsson used the value $K = 2$ in Eq. (14.5) for calculating the visibility, that is, at the lower end of the interval reported to be valid for reflecting signs. One aim of the study was to verify the results by Jin. However, the extinction coefficient in the tests by Frantzich and Nilsson was found to be between 2 m^{-1} and 8 m^{-1}, while in the tests by Jin it was below 1.2 m^{-1}. Another difference between the tests was that Jin used black fire smoke while Frantzich and Nilsson used white artificial smoke with addition of acetic acid. It is difficult to say what these differences mean for the results. Frantzich and Nilsson have, however, shown that the equation for visibility is valid both for black fire smoke and for white artificial smoke [14]. The results from the walking speed tests are included in Fig. 14.2.

Based on the tests, Frantzich and Nilsson found the following relation [14]:

$$u_w = -0.057 \cdot C_s + 0.706 \tag{14.21}$$

when the general lighting (normal lighting inside the tunnel) was used, where u_w is the walking speed. When the general lighting was not used, there was no statistically significant influence of the extinction coefficient on the walking speed. Furthermore, Frantzich and Nilsson showed that there was an influence on the walking speed of the choice of walking along a wall or not [14].

The walking speeds registered by Frantzich and Nilsson were lower (varied between 0.2 and 0.8 m/s) than those measured by Jin. This is expected since the visibility was higher in Jin's test series. Frantzich and Nilsson also argued that the measured walking speed should be multiplied by a factor lower than 1 to get an effective walking speed, taking into account both stops on the way and the fact that the persons did not take the closest way to the escape route. There was a large variation in this factor between the people participating in the tests with an average value of approximately 0.9. Also, the dependency of the extinction coefficient has a high uncertainty. Furthermore, it was concluded that the walking speed was in general higher for those walking along the tunnel wall for at least two thirds of the walking distance studied in the tests. The dependency on the extinction coefficient was also more evident in the cases where the test participants walked along the wall. The choice of route, therefore, seems important for determining the effective walking speed and there might also be other properties or conditions affecting the walking speed such as a person's height and gender.

To increase the number of data points, Fridolf et al. performed tests similar to Frantzich and Nilsson with a span in extinction coefficients between 1.2 m^{-1} and 7.5 m^{-1}. The results are included in Fig. 14.2. They then combined their results with those of Frantzich and Nilsson and derived a new relationship for walking speed:

$$u_w = -0.1423 \cdot C_s + 1.177 \tag{14.22}$$

or if visibility is used as the independent parameter:

$$u_w = 0.5678 \cdot V_s + 0.3033 \tag{14.23}$$

where $K=2$ was used when calculating the visibility. The correlation with the extinction coefficient is statistically somewhat better ($R^2=0.4132$) than the correlation with the visibility ($R^2=0.3612$). Using the extinction coefficient directly also avoids the use of the constant K. In Fig. 14.3 the walking speed is shown as a function of visibility for the test series mentioned above [15]. Note that $K=3$ was used when producing Fig. 14.3.

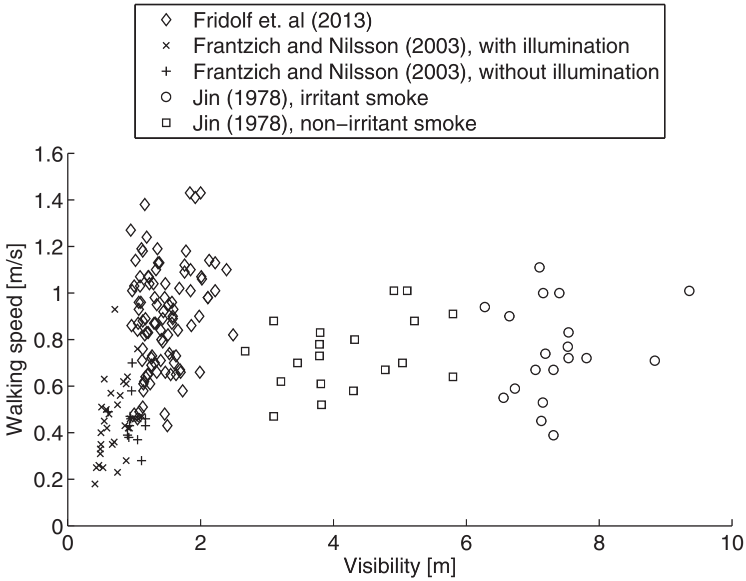

Fig. 14.3 Walking speed as function of visibility [15]. The graph is based on several different sources [16, 14, 17]. Note that a value $K=3$ was used to produce these results

In the guidelines to the Swedish building code there are suggestions for walking speeds to be used in performance based design of means for evacuation [18]. Note that these guidelines are for buildings rather than tunnels. However, the basic unhindered walking speed is set to 1.5 m/s. Note also that the influence of visibility is not discussed in these guidelines, probably since high visibility (10 m for areas >100 m^2) is one of the design criteria. For children or people with disabilities (in mobility or orientation) the walking speed is set to 0.7 m/s. There is also a decrease in walking speed in stairways (0.6 m/s up and 0.75 m/s down) in relation to the basic unhindered walking speed.

Frantzich [19] has also shown an effect of people getting used to the surface and the conditions. In tests with evacuation of metro trains the walking speed near the train was 1.0–1.4 m/s while further away (130 m from the train) it was 1.0–1.8 m/s. The tests were run without smoke and with emergency lighting, but Frantzich argues that this adaption effect should exist also during evacuation in fire smoke or darkness. When the tests were performed in darkness (without smoke) the walking speed varied between 0.5 and 1.0 m/s.

Example 14.2 What is the walking speed in Example 14.1?

Solution: Using the equation proposed by Fridolf et al., Eq. (14.23) gives $u_w = 0.568 \cdot V_s + 0.3 = 0.568 \cdot 0.65 + 0.3 = 0.47$ m/s. *One should here again note that this is based on $K=2$ and that a value $K=3$ is used to derive the graph in Fig. 14.3. One can still see that the visibility in this case is in the lower end of the graph and that the resulting walking speed is not very much higher than the constant value given by Eq. (14.23).*

Example 14.3 At what time has the fire in Example 14.1 reached a point where the walking speed is 0.9 m/s at a position 150 m downstream of the fire?

Solution: The heat release rate $\dot{Q}(\tau) = 210 \cdot \tau$ *and* $\tau = t - 150/2$*. Using this together with Eq. (14.18) give after some algebraic steps:*

$$t = \frac{1}{210} \cdot \frac{K}{2.3} \frac{uA\Delta H_c}{D_{mass} V_s} + \frac{150}{2} = \frac{1}{210} \cdot \frac{2}{2.303} \frac{2 \cdot 9 \cdot 6 \cdot 38600}{240 \cdot 0.9} + \frac{150}{2} = 155 \text{ s}$$

14.4 Summary

Visibility is very important for evacuation during a fire and, therefore, a very important parameter for fire safety in a tunnel. In this chapter different methods to define and describe visibility have been presented and discussed. The main methods for estimating the visibility in smoke-filled spaces are to use either the mass-specific extinction coefficient or the mass optical density. For both methodologies there are experimental values available for some materials of interest. The focus has been on the mass extinction coefficient methodology, but at the end this method was compared and correlated to the mass optical density methodology. Values of these parameters for selected materials were presented and conversion of values for one of the parameters into the other was discussed. Finally, the effect on walking speed during egress was discussed and some methods for estimating walking speed were presented.

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