EVACUATION LOCUS IN A FULL-SCALE TUNNEL EXPERIMENT

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ABSTRACT

In case of massive fire incidents in tunnels, the ceiling lights are covered by dense smoke and pedestrians must evacuate in the dark tunnel with almost zero visibility. Nonetheless, the walking behavior in a completely darkened tunnel has not been clarified. In the present paper, we experimentally investigated the evacuation loci and responses in a survey questionnaire for a full-scale tunnel. Results indicated few difference in both one-dimensional and two-dimensional walking speed. In terms of stress, the group of subjects that felt stress demonstrated a walking speed that is 0.1 m/s slower than the group that did not feel it. In the questionnaire survey, most of the subjects answered that the wall as the most helpful item, followed by the unevenness (bumps) on the white lines on the road. One of the subjects got lost, stating that she could not find the unevenness (bumps) on the white lines. These two factors can be reasonable guides in a dense-smoke environment or a completely dark-tunnel scenario.

Keywords: tunnel, fire, smoke, evacuation, human behaviour, risk analysis

1. INTRODUCTION

The typically long and enclosed geometry of tunnel spaces contributes to difficulties in the evacuation, rescue, and firefighting operations inside the tunnels, given that even the slightest of incidents produce possible significant losses, i.e., human casualties or economic slowdowns, as demonstrated by tunnel fire incidents in the past. In case of a massive fire, the ceiling lights are covered by dense smoke, thereby reducing the effective visibility for an evacuation. An evacuee's mobility or walking speed in a less visible environment is not only influenced by insufficient lighting, but also by the stratified dense smoke covering the lighting that may induce forced evacuation in the dark. [Togawa, 1955] approximated that the walking speed in a dark architecture is 0.3 m/s, which is within the walking speed of 0.2 to 1.2 m/s [Seike, et al., 2018] that we have reported, whereas the walking behaviour in a dark tunnel has not been clarified. Evacuees during the Sekisho tunnel fire accident in Japan were reported to have used the lights of their mobile phones, but with a dark evacuation environment caused by the dense smoke, but the mobile light function effect was little due to the dense smoke [Tokachi Mainichi newspaper, 2011]. Without regard to the influence of dense smoke and toxic gas on the human body, the walking speed in a dark tunnel may be considered the slowest evacuation speed. Also, evacuees tend to get lost in searching for fire exits. If the evacuees' behaviour and the reason for such a tendency of getting lost in a completely darkened tunnel could be clarified, then we would be able to develop a performance-based design for the emergency facilities.

[Jin 1980] investigated the relationships between psychic unrest levels, walking speed, and smoke density in an architectural space, whereas [Frantzich and Nilsson, 2003 and 2004], [Fridolf et al, 2013 and 2015], and our group [Seike et al., 2016 and 2017] reported the walking speed in a smoke-filled tunnel, but without clarifying the walking speed in a completely darkened tunnel. Therefore, in the present paper, we measure the walking locus, speed, and stress in a darkened full-scale tunnel, to investigate the fundamental characteristics in tunnel fires. The study subjects wore an eye-mask, assuming a middle-to-late evacuation environment. Here we did not use smoke.

2. EXPERIMENTAL SETUP

2.1. Experimental tunnel

We conducted experiments in an obsolete full-scale tunnel, the ex-Tonokuchi tunnel, in Fukui in November of 2018. The horse-shoe-shaped tunnel was 488-m long, 6.6-m wide, and 5.4-m high. The region allocated to the experiment (longitudinal interval and transverse section) is shown in Fig. 1. The longitudinal and wide directions were indicated by x and y, respectively, and the origin was set at the width center point o.

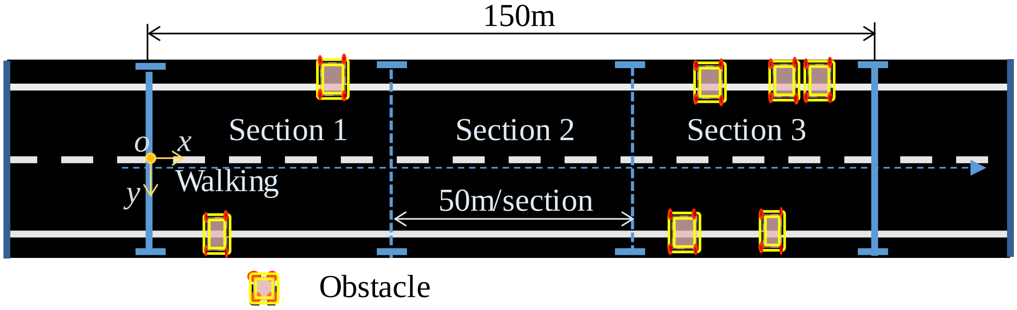


Figure 1: Evacuation route and section.

2.2. Subjects

Table 1 lists the nine subjects (six males, three females; 20.6 years old on average) for this study. The subjects were instructed to wear a safety vest, a mask, and a helmet.

Table. 1: Subjects information

Subjects #	Age	Gender
1	20	Male
2	20	Male
3	22	Female
4	20	Male
5	21	Male
6	21	Male
7	20	Male
8	21	Female
9	20	Female

2.3. Explanation

We investigated the fundamental characteristics for risk analysis in tunnel fires by measurements of the walking speed in a tunnel with no visibility. Subjects wore an eye-mask and were given these instructions:
"Please walk in the tunnel as you would normally walk."
The subjects walked the 150-m-long lanes consisting of several sections with obstacles. Three obstacles were installed on the measuring route (Fig. 1), which were set at random locations to prevent subjects from remembering these locations. Prior to the experiments, subjects were reminded to walk with caution relative to these obstacles.

2.4. Measurement of walking speed

The walking speed of the subjects was derived from their longitudinal and transverse locations, where their experimental attendant left numbered cards every 5 s (see Fig. 2. Note that the subject was blindfolded).
Two walking speed types were addressed herein as follows:
Mean walking speed v_m = one section (50 m)/the passing time in one section (see Fig. 1)

Topical walking speed $$v_t = \frac{\sqrt{\Delta x^2 + \Delta y^2}}{\Delta t}$$

, where Δx and Δy are longitudinal and transverse displacement during Δt (5 s).

Figure 2: A scenario during the evacuation experiment. The subject was blindfolded while his/her locus was traced by the attendant behind.

2.5. Questionnaire survey

Upon completion of the experiments, we asked the subjects to answer a questionnaire. We prepared two sets of questionnaires: one assessing the anxiety factors, and another asking the helpful item for walking by score (Yes: 2 points, Probably yes: 1 points, Neither yes and no: 0 points, Probably no: -1 point, and No: -2 point). The questionnaire is broken down as follows:

A) Anxiety Factors
   (1) Nobody around the subject
   (2) Touching or colliding with the obstacles
   (3) No sound
   (4) Sound (someone collision something)
   (5) Sound (someone’s voice)
   (6) Sound (wind)
   (7) Sound outside the tunnel
   (8) Temperature
   (9) Wall(dirty)
   (10) Unevenness of the road
   (11) Don't know going in the right direction
   (12) Don't know getting to the destination
   (13) Don't know the place where he/she was

B) Helpful item
   (1) Wall
   (2) Obstacle
   (3) Unevenness of the white line*
   (4) Others (written by subjects)

*There is unevenness (bumps) on the white lines to alert the drivers in the tunnel.

3. RESULTS AND DISCUSSION

3.1. Walking speed

Figure 3 shows the walking speed v_m in each 50-m section. The blue-coloured columns represent Section 1 in Fig. 1, the orange ones as Section 2, and the grey ones are Section 3. The dotted bars are the averaged value of each subject. The dotted line in Fig. 3 shows the total average value. Subject #3 returned to the starting point by touching the wall or obstacles after getting lost in the direction, and after re-conducting for 3 times. Thus, we decided to assign her a speed of 0 m/s, which indicates that she gave up. The walking speed v_m was from 0.47 m/s (subject #8) to 1.27 m/s (subject #1), while the average value of all subject walking speeds was 0.78 m/s. The fastest average walking speed was 1.08 m/s, whereas the slowest was 0.56 m/s, excluding that of subject #3. The walking speed v_m in Section 2 had the fastest mean value of 0.87 m/s, while those of Sections 1 and 3 were 0.75 and 0.74 m/s, respectively, as there was no obstacle in section 2.

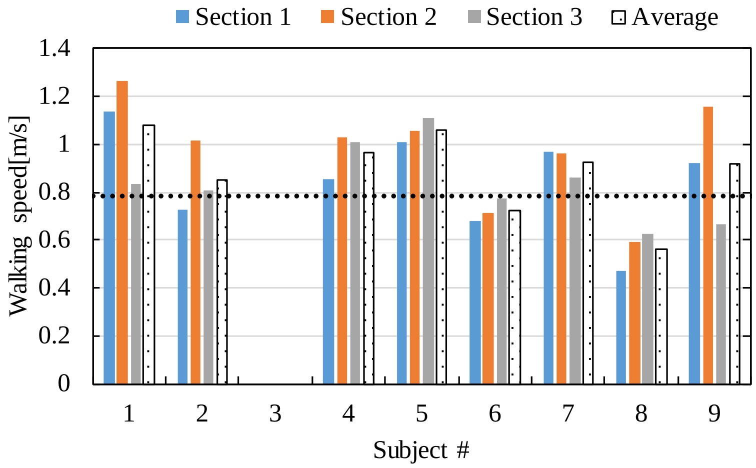


Figure 3: The walking speed v_m in each 50-m section.

3.2. Locus

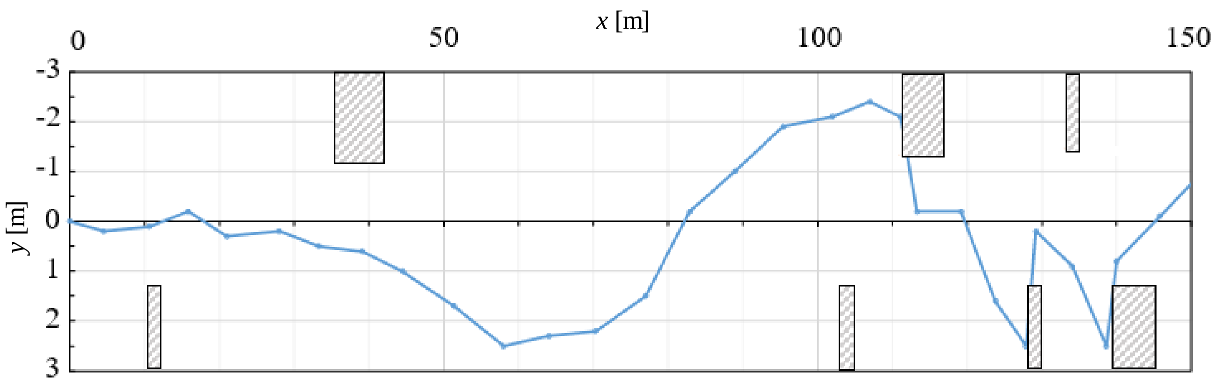
Under this section, we investigated the evacuation behaviour of the subjects by their locus, including subjects who gave up. Figures 4(i) through (iv) show the maximum walking speed subject locus (subject #1) closing in to the mean walking speed subject locus (#9), the minimum walking speed subject locus excluding giving up (#8), and the giving up subject locus (#3), respectively. All loci were measured individually every 5 s.

In Fig. 4(i), subject #1 walked by not touching the wall till x = 58 m but touching the wall first (x = 58 m, y = 2.5 m) went to the opposite side and touched the obstacle (x = 111 m, y = −2.1 m), went to opposite side (x = 127.9 m and y = 2.5 m), avoiding the obstacle and touching the wall (x = 138.6 m, y = 2.5 m), before finally arriving to the goal. Accordingly, he was to walk straight confidentially but he had surprised touching or colliding the wall and obstacles. Even his walking speed was the fastest speed in the present results.

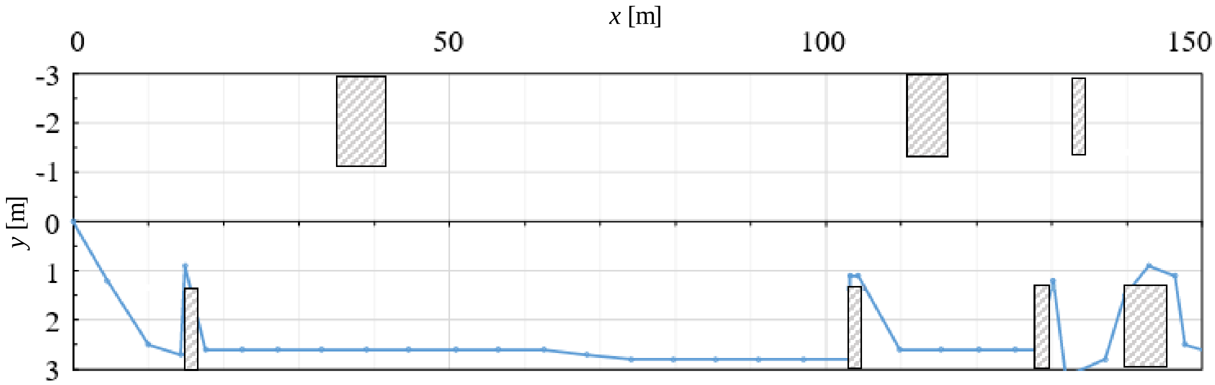
In Fig. 4(ii), subject #9 walked toward the obstacle, followed to the obstacle, after that she walked with touching the wall.

In Fig. 4(iii), subject #8 walked, touching the wall and following the obstacles, but she walked without touching anything from around x = 80 m and y =2 m. During this time, the walking distance was longer than that of touching the wall, but she touched the obstacle, went to the wall, and walked touching the wall and following the obstacle finally. In these subjects' locus, the wall could be one of the functions of the guide, but the walking speed might decrease from that of not touching the wall.

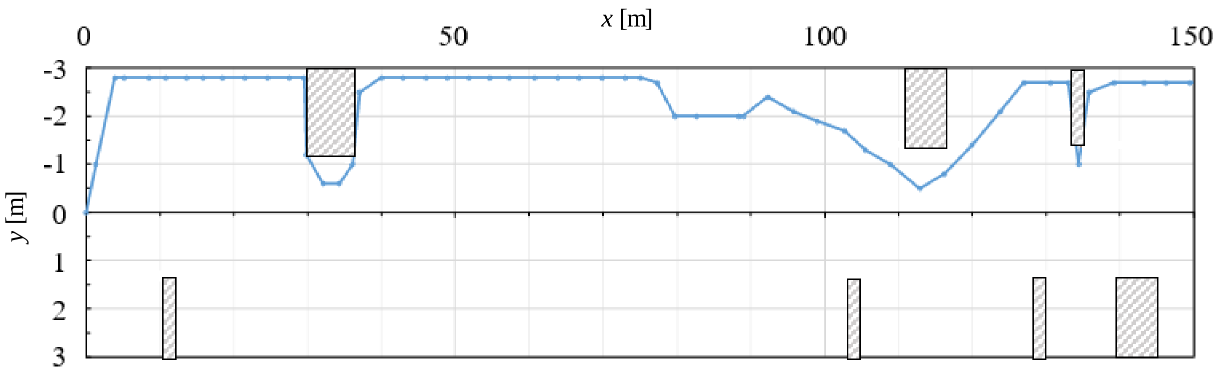
Finally, in Fig. 4(iv), subject #3 walked and collided to the wall at around x = 5.3 m and y = −2.8 m. After the collision, she went to the width centre point around x = 5.1 m and y = −0.9 m, and then went back to the wall at x = −3.8 m and y = −2.8 m. Alternatively, she went to the opposite wall at x = 6.2 m and y =2.8 m, but returned to the starting point and went through the origin, then went to the x = −1 m and y = −2.1 m, and returned to the correct direction. She walked at x = 5 m and y = 2.8 m, touched the wall, and then returned to the starting point. She repeated the experiments three times, but with all not satisfying the goal. We could clarify that she got lost after touching something (wall or obstacles). The discussion of the reason why is with questionnaire survey.



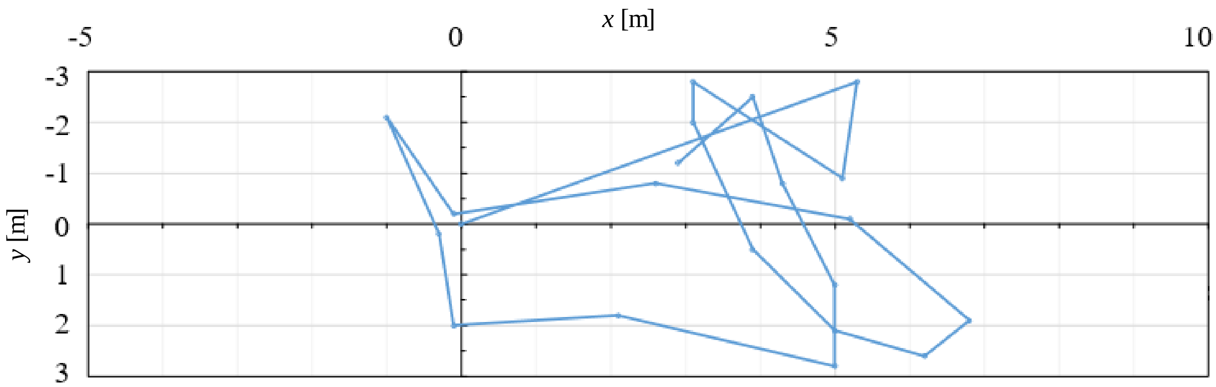
(i) Maximum walking speed subject locus (#1).



(ii) Closing-in to the mean walking speed subject locus (#9).



(iii) Minimum walking speed subject locus excluding giving up (#8)



(iv) Giving up subject locus (#3).

Figure 4: A representative subject locus

(max, mean, min excluding giving up and subjects who give up)

Table 2 shows the topical walking speed v_t from a certain distance in each 5 s. The topical average value was calculated by the first location (origin point in Fig. 5) to the final location in Fig. 5 with time. It can be seen that the #1 subject's walking speed was the fastest. Also, the minimum walking speed of subject #1 at 0.44 m/s was close to subject #3's averaged walking speed. Subjects #9 and #8s' maximum and minimum walking speed differences were 0.1 m/s; however, these differences were integrated so that the averaged walking speed was 0.3 m/s differences. Moreover, #3's walking speed was almost the slowest except the minimum walking speed, and she moved with slowing speed of 0.45 m/s, but she went around the starting point and got lost.

Table. 2: Topical walking speed v_t (#1, #9, #8, and #3)

Subjects #	1	9	8	3
Max $v_{t,max}$	1.40	1.26	1.14	1.04
Min $v_{t,min}$	0.44	0.22	0.12	0.18
Average v_{ta}	1.07	0.91	0.58	0.45

The topical mean walking speeds v_{tm} of subjects #1, #9, and #8 were shown on the linear regression line with distance as the dependent variable using the least square method (see Fig. 5). The topical mean walking speed v_{tm} (inclination of the linear regression line) of subject #1 was 1.12 m/s (R^2 = 0.99, blue). The topical mean walking speed (inclination of the linear regression line) v_{tm} of subject #9 was 0.96 m/s (R^2 = 0.99, orange). Accordingly, the topical mean walking speed (inclination of the linear regression line) v_{tm} of subject #8 was 0.56 m/s (R^2 = 0.99, grey). The moving distance to the width was 5.8 m (#1), 8.6 m (#9), and 6.1 m (#8), or approximately less than 4%–6% as compared with the longitudinal distance, which was completely shorter than that of length (150 m).

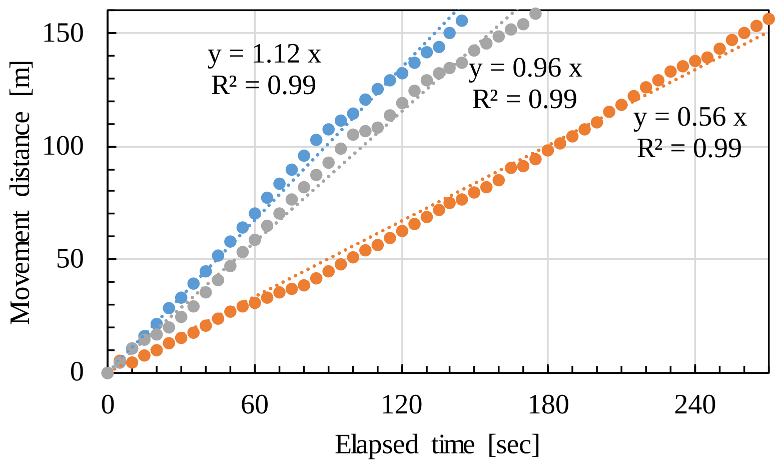
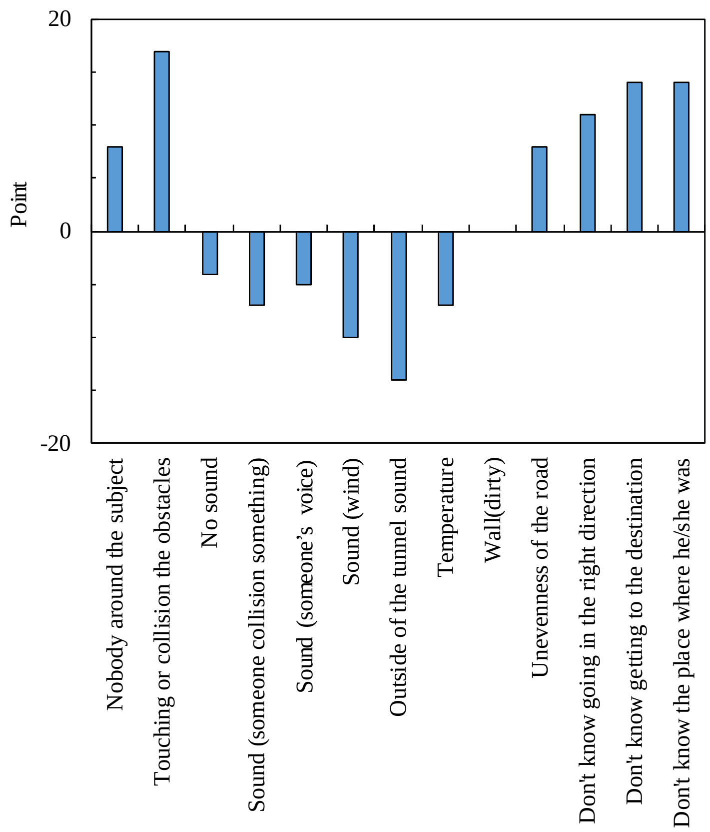


Figure 5: Topical mean walking speed v_{tm} time profile

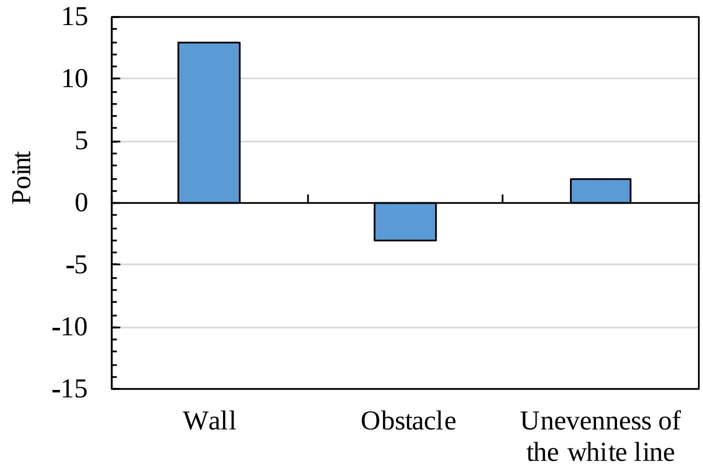
3.3. Questionnaire survey

Figure 6 shows the results of the survey questionnaire. The horizontal axis representing the ratio of the answered score to the total point. Figure 6(i) depicts that touching or colliding with obstacles was the most anxious feeling, with a reply of 17 pt. The most helpful item for walking was the wall 13 pt, and next was unevenness (bumps) of the white lines (2 pt). An interesting point was subject #3 getting lost and she told us that she could not find the unevenness (bumps) of the road. Thus, she moved by touching the walls or obstacles but got lost in her direction. The walls and obstacles did not guide her well, which was a totally different scenario with the other subjects who moved to the walls and were aided by the unevenness (bumps) of the white lines.

Five of the subjects pointed out that the obstacles were not helpful for walking, and that they could have got lost by walking with the obstacles. We could see in the experiments that the subjects who got lost (including those who gave up), determined the appropriate direction by touching with two hands. By contrast, the subjects who found the right direction used a single hand to touch the wall or obstacles first and then walked to the direction with one hand touching the wall and raising another hand toward the correct direction, in addition to feeling the unevenness (bumps) of the white line. These two factors may be acceptable guides in finding the right direction within a dense-smoke environment or a completely dark-tunnel situation.



(i) Anxiety factors



(ii) Helpful items

Figure 6: Questionnaire survey results

4. CONCLUSIONS

We experimentally investigated the evacuation loci of subjects and results of a survey questionnaire for a full-scale tunnel scenario. These are the generalized results:

- The mean walking speed v_m was 0.47 m/s (Subject#8) to 1.27 m/s (Subject#1), with an average value of 0.78 m/s for all subjects. The mean walking speed in Section 2 was the fastest average value of 0.87 m/s, and those in Sections 1 and 3 were 0.75 and 0.74 m/s, respectively. This was because there was no obstacle in Section 2.
- One subject got lost and gave up the experiments for the three trials. She went and returned many times, and it was clarified that she got lost after touching something (wall or obstacles).

- The moving distance of the subjects to the width was around less than 4% to 6% comparing with longitudinal distance, so that completely shorter than that of length (150 m). Hence, the evacuation speed was substantially the one-dimensional, i.e. longitudinal, speed in the tunnel space.
- Of the survey questionnaire, the subjects answered the tunnel wall as the most helpful item, followed by unevenness(bumps) on the white lines on the road. One of the subjects got lost, saying she could not find the unevenness (bumps) on the white lines on the road. These two factors can be acceptable guides in a dense-smoke environment or completely dark-tunnel scenario.

5. ACKNOWLEDGMENTS

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