

Visibility in smoke

Evacuation lighting



<u>Project</u> Visibility in smoke – evacuation lighting	<u>Report number</u> 2019-002
<u>Project manager</u> <i>Arne Jørgensen, Norwegian road authority</i>	<u>Date</u> 2019-03-15
<u>Members of the project group</u> <i>Pål J Larsen (Norconsult), Arne Jørgensen (Vegdirektoratet) and Petter Hafdell (Trafikverket)</i>	<u>Financial partners</u> <i>Norwegian Road authority Swedish Road authority</i>
<u>Scientific partners</u> <i>Norconsult AS</i>	<u>Report title</u> Visibility in smoke – evacuation lighting
<p>The Norwegian and Swedish road authorities, with financial support from Nord FoU, conducted tests for studying evacuation lighting in tunnels and their visibility in smoke conditions. The purpose was not to test specific products, but to study the general visibility of different lighting solutions and evaluate the appropriate design for evacuation lighting.</p> <p>The test results show that a continuous LED strip mounted on the wall at 1 m above the road surface gives the best illumination for safe evacuation, as measured by contribution to the test subjects' orientation/guidance, feeling of safety and relevant time spent on evacuation (speed of movement). The "spot-luminaires" mounted on the wall at 1 m above the road surface gave almost no contribution to orientation/guidance when placed at 25 m centre-to-centre (cc) intervals. To have any practical relevance this distance must be reduced.</p> <p>Luminaires mounted in the ceiling do not contribute to the illumination of the tunnel room shortly after the start of a car-fire. Long before the smoke layering reaches the eye-height of observers, the light from the ceiling will have completely disappeared.</p> <p>Further investigation on alternative configurations and their influence on movement speed are necessary to make any new specific recommendations.</p>	
<u>Keywords</u> Visibility, smoke, evacuation, lighting, LED strip	
<u>Language</u> English	<u>Number of pages</u> 30

Content

1	Introduction	5
2	Background	6
3	Theory	7
	3.1 Requirements evacuation lighting.....	7
	3.1.1 Current Norwegian requirements.....	7
	3.1.2 Current Swedish requirements	7
	3.1.3 Current European requirements	7
4	Location and Measurement setup.....	8
	4.1 Location	8
	4.2 Measurement setup	8
	4.2.1 Luminaries in experiment.....	9
	4.2.1.1 Linear LED evacuation lighting – L1	9
	4.2.1.2 Spot evacuation lighting – L5 and L8	10
	4.2.1.3 Spot evacuation lighting – L6 and L9	10
	4.2.1.4 Spot evacuation lighting – L7 and L10	11
	4.2.1.5 Normal tunnel lighting underneath cable tray L2-L4.....	11
	4.2.2 Illuminance measuring.....	12
	4.2.3 Video recordings	13
	4.2.3.1 In tunnel recordings	13
	4.2.3.2 Debrief recordings	14
	4.3 Observers	14
5	Results	15
	5.1 Test 1	15
	5.1.1 Setup.....	15
	5.1.2 Illuminance loggings	16
	5.1.3 Debrief experiences	18
	5.2 Test 2	18
	5.2.1 Setup.....	18
	5.2.2 Illuminance loggings	19
	5.2.3 Debrief experiences	20
	5.3 Test 3	21
	5.3.1 Setup.....	21
	5.3.2 Illuminance loggings	22
	5.3.3 Debrief experiences	23
	5.4 Other findings.....	23
	5.4.1 Thermal damage.....	23
	5.4.2 Optical depreciation	24

	5.4.3 Radar	24
6	Discussion	25
	6.1 Test 1	25
	6.2 Test 2	25
	6.3 Test 3	25
	6.4 Outcome	26
7	Conclusions	27
8	Further work	28
	References	29

1 Introduction

The lighting designs of tunnels, in both existing and new installations, are based on previous practical experience combined with some theoretical studies. Evacuation lighting is chosen from products commercially available on the market. Ongoing technological developments in the lighting industry, however, may provide possibilities which designers of new installations should take advantage of. When retrofitting an existing installation, a cost/benefit evaluation will reveal which actions should be taken.

Lighting technology is developing quite rapidly and creating new possibilities. The relevant national regulations may not keep up with these developments and may not necessarily promote best use of commercially available equipment. At the same time, it is not always true that “more is better” in the world of lighting. This study of currently available evacuation lighting is an important input for ongoing and upcoming revisions of road authority guidelines.

The Norwegian and Swedish road authorities have close cooperation in the field of lighting in general and have worked on joint standardisation of technical requirements for the Nordic countries (NMF 2018). For this study a project proposal for “Nord FoU” funding was prepared and approved. Planning and administration of the project were granted to Norconsult AS under the ongoing project “Lysteknisk kompetanse for Vei- og tunnells”.

2 Background

For safe evacuation in smoke, the increased visibility provided by evacuation lighting is very important. Lighting gives guidance, orientation and a general feeling of safety. Historically, evacuation lighting in Norway consisted of single spot luminaires at 1 m height placed at a maximum 67 m individual distance. The European regulation was revised some years ago and the maximum individual distance was set to 25 m, with a national exemption note for Norway allowing 33 m for the rehabilitation of existing tunnels (CEN 2013): this allows for the possibility of adding a luminaire in the spacing between existing luminaires. The EN1838 standard (CEN 2013) referred to in Swedish regulations (Trafikverket 2015) requires a minimum actual lighting level on the floor:

“For escape routes up to 2 m in width, the horizontal illuminances on the floor along the centre line of an escape route shall be not less than 1 lx and the central band consisting of not less than half of the width of the route shall be illuminated to a minimum of 50 % of that value”.

These installations function as orientation lighting during a power outage or under an early smoke development situation. As an additional aid for guidance, continuous LED-strips in a longitudinal orientation along the tunnel are now commercially available. When such new products are introduced, the requirements are determined more by the capacity of the technology and some application of previous best-practice experience. The need for a more evidence-based study of the actual requirements and consequences in a real environment was voiced by the legislative authorities. With this background, an initiative was launched by the Swedish and Norwegian road authorities and Nord FoU funding was granted.

3 Theory

3.1 Requirements evacuation lighting

3.1.1 Current Norwegian requirements

The current requirements are given in the handbook N500 (Statens Vegvesen 2016), which also refers to the handbook V124 (Statens Vegvesen 2014) for details.

Technical requirements for the fixtures refer to EN 60598-2-22 (CEN 2014).

Evacuation-lighting

The requirements in the emergency lighting standard EN 1838 are generally referred to, and reference is also made to EN 16276 for tunnels above 500 m and with AADT above 500. EN 16276 requires 25 m intermediate distances and mounted at maximum 1,5 m height, giving a sustained minimum of 0,1 cd intermediate distance in all directions. The handbook V124 gives further guidance stating:

- A smaller intermediate distance than 25 m gives better visibility in smoke
- A continuous LED-strip gives better guidance
- Dynamic lighting gives the possibility of improved guidance by suggesting a direction of escape
- For bidirectional traffic tunnels longer than 5000 m the requirements are for continuous LED strips.

Evacuation routes and exits shall have 1 lux at the centre of a route. Exit doors shall have continuous green lighting from the centre of tunnel in normal conditions, with emergency green lighting mounted above and, on the sides, shall give light preferably in colour code G in the NCS.

Safety-lighting

Every fourth general luminaire, corresponding to 50 m intermediate distance, shall continue to give light 60 minutes after a power outage.

3.1.2 Current Swedish requirements

The Swedish requirements are listed in TRV publication 2015:086 (Trafikverket 2015). In Sweden EN-16276 is referred to directly for evacuation lighting with the following amendments:

- Guiding evacuation lighting shall be placed 1 m above the road surface
- Evacuation door from tunnel shall be lit at normal conditions and flash at 1-4 Hz during an emergency situation

3.1.3 Current European requirements

EN 16276 and EN 1838 is the most relevant standards for evacuation lighting in road tunnels.

4 Location and Measurement setup

4.1 Location

The test was held at “IF forsikring skadesenter” in Hobøl Østfold county in Norway. A 100 m long tunnel, T 9,5 m profile, was used for testing, without normal traffic. On both sides of the tunnel (seen in the longitudinal direction) there was a heightened concrete boardwalk, approx. 20 cm above the level of the roadway in the tunnel. All measurements of mounting height are referenced to the roadway of the tunnel. Before our test the walls of the tunnel were painted white between 0-3 m height.



Figure 1 Image of test tunnel

4.2 Measurement setup

Visibility as experienced by humans is a subjective matter; everyone has their own experience of how lighting relates to their feeling of safety. Feedback from individuals on visibility, especially in a stressed situation in fire/smoke, will have a subjective component. In this experiment such feedback was recorded as an important part of the result. In addition, the objective measures of visibility were collected through metering of illuminance from all lighting fixtures at 1 m distance throughout the experiment's timeline. Also, each illuminance meter was supplemented with a video camera for continuous feed/documentation on the visibility conditions.

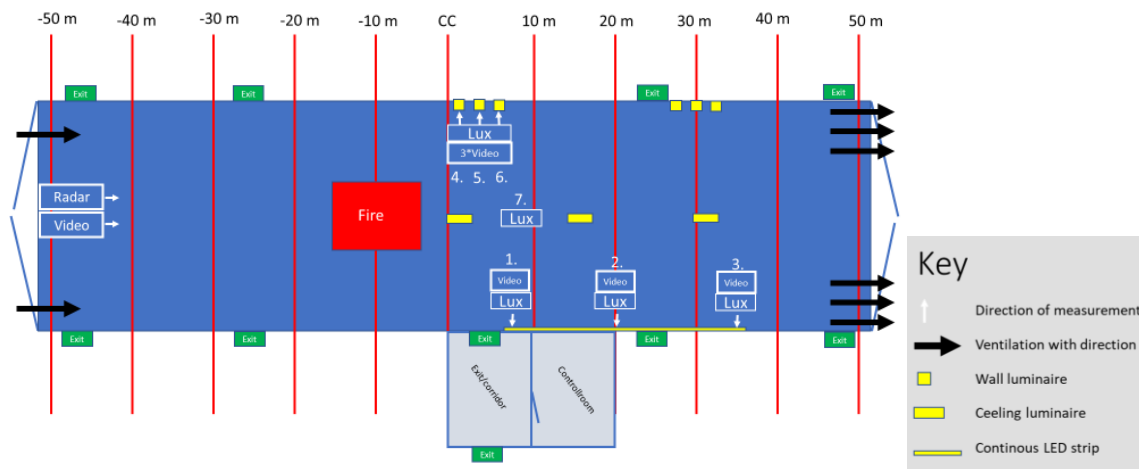


Figure 2 General experiment setup

4.2.1 Luminaires in experiment

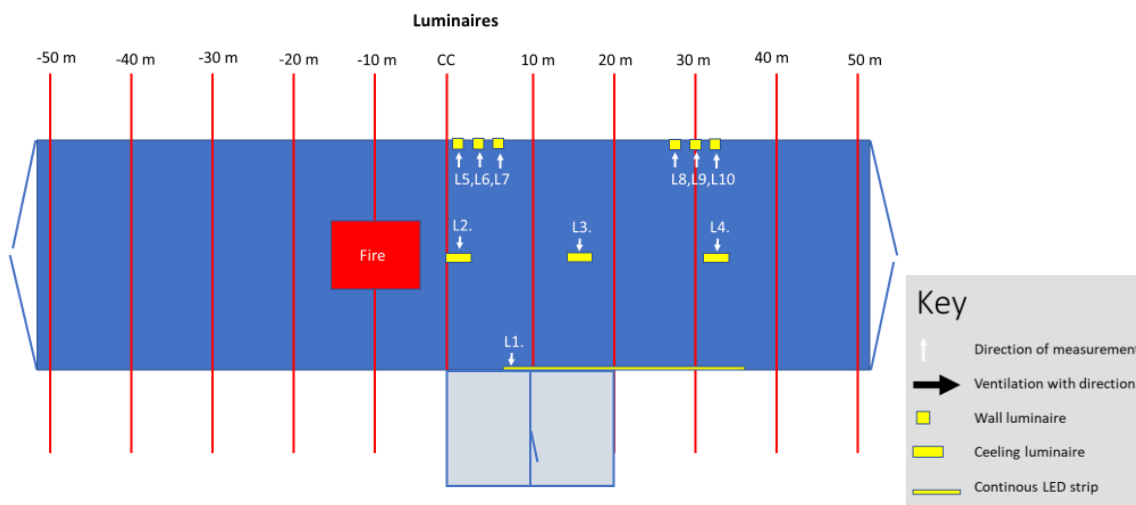


Figure 3 Luminaires in experiment

4.2.1.1 Linear LED evacuation lighting – L1

EnergyOptimal HR Morestrip with integrated self-luminous coating. 10 * 3 m lengths from CC of the tunnel. Mounted at approx. 1,2 m above road surface with metal strips from handrail. Dimmable setup [400-40] lm/m.



Figure 3 Images of continuous LED strip

4.2.1.2 Spot evacuation lighting – L5 and L8

EnergyOptimal Morrem guidance light with integrated projected green laser strip to the road surface. Mounted below the handrail approximately. 85 cm above road surface. Dimmable setup [2700-270] lm.



Figure 4 Images of spot evacuation lighting, position L5 and L8

4.2.1.3 Spot evacuation lighting – L6 and L9

Gifas Markled 5600 K 50 cd mounted at approximately. 1 m hanging flat against the wall below the handrail. Dimmable setup (not used in the test).



Figure 5 Images of spot evacuation lighting, position L6 and L9

4.2.1.4 Spot evacuation lighting – L7 and L10

Gifas Traficled 5600 K 30 cd mounted at approximately. 1 m hanging flat against the wall below the handrail. Dimmable setup (not used in the test).



Figure 6 Images of spot evacuation lighting, position L7 and L10

4.2.1.5 Normal tunnel lighting underneath cable tray L2-L4

Thorn GTLED standard tunnel luminaire. 4100 K, 54 W, Ra 70.



Figure 7 Images of ceiling luminaire

4.2.2 Illuminance measuring

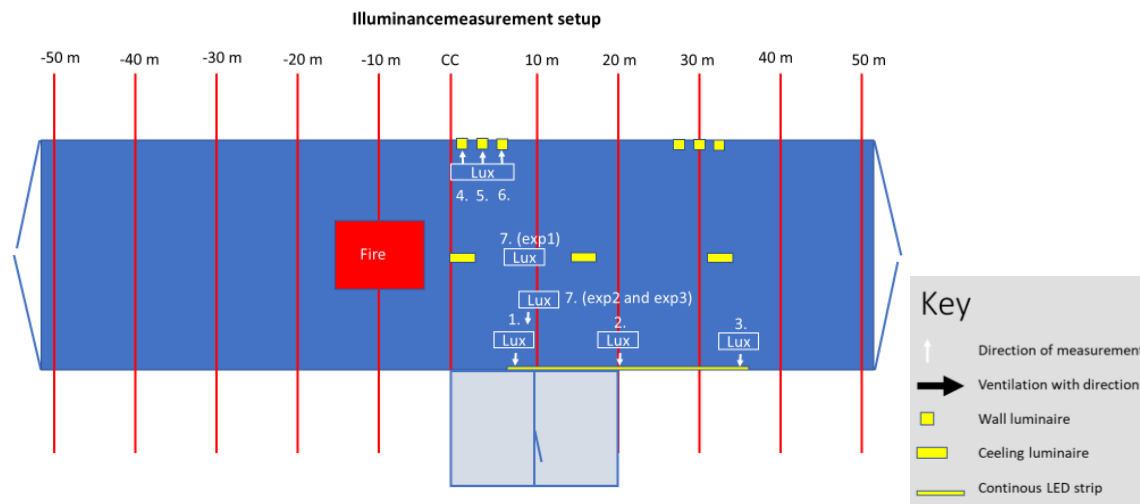


Figure 8 Illuminance meters in experiment

7 Hagner ELV-841 tunnel illuminance meters were placed in the marked positions shown in figure 2. All meters were placed perpendicular to the lighting fixtures at approximately 1 m distance. In experiment number 1 meter number 7 was placed on the floor facing the roof to register illuminance from luminaires L2 and L3. In experiment no. 2 and 3 it was placed facing L1 at an approximate 2 m distance.



Figure 9 Images of illuminance logger

4.2.3 Video recordings

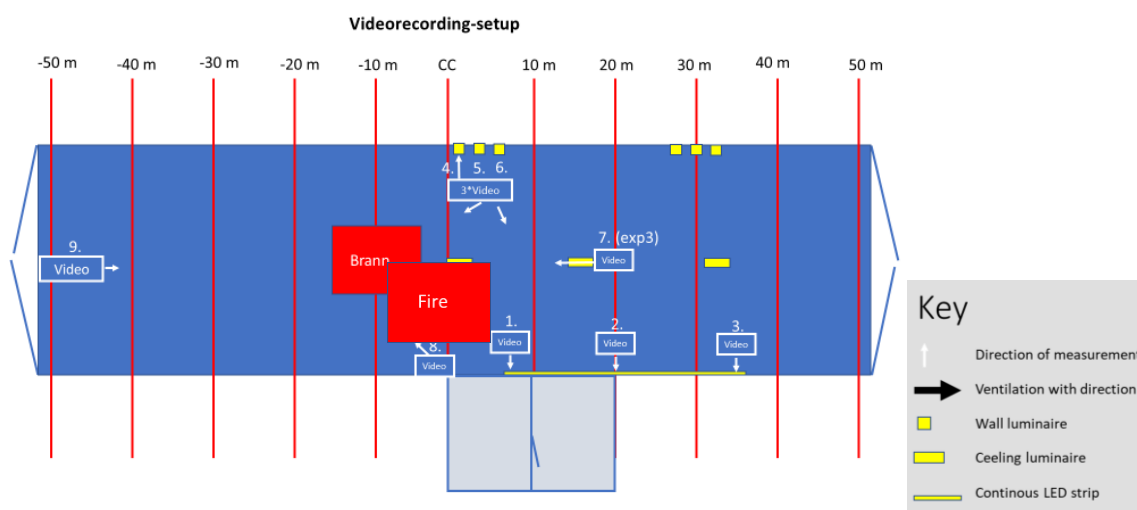


Figure 10 Video recordings in experiment

4.2.3.1 In tunnel recordings

8 * Kit Vision smart escape small video cameras mounted on tripods. Not used in analysis only as supplementary to the subjective observers.



Figure 11 Images of video recording setup in tunnel

4.2.3.2 Debrief recordings

Windows video recorded on a laptop.

4.3 Observers

It was not possible to select a set observers to be statistically representative of the visual performance of the general population in advance of the test. There were 7 observers present at each experiment in addition to 2 firemen. The observers were 6 men and 1 woman, ranging from 27-60 years old. Observers were equipped with helmet, protective glasses, gloves, protective suit and oxygen masks.

5 Results

By mistake all illuminance sensors were delivered calibrated for [0-20.000] instead of [0-2000] lux. Therefore, the loggings presented here must be interpreted only as relative indications. Small interference and noise levels of the transmitting cable will also have a large influence on the measurements. It is also worth noticing that the sudden drops to 0 in the loggings may be caused by the test persons standing/walking between instrument and light source

5.1 Test 1



Figure 12 Car for test 1, before and after

5.1.1 Setup

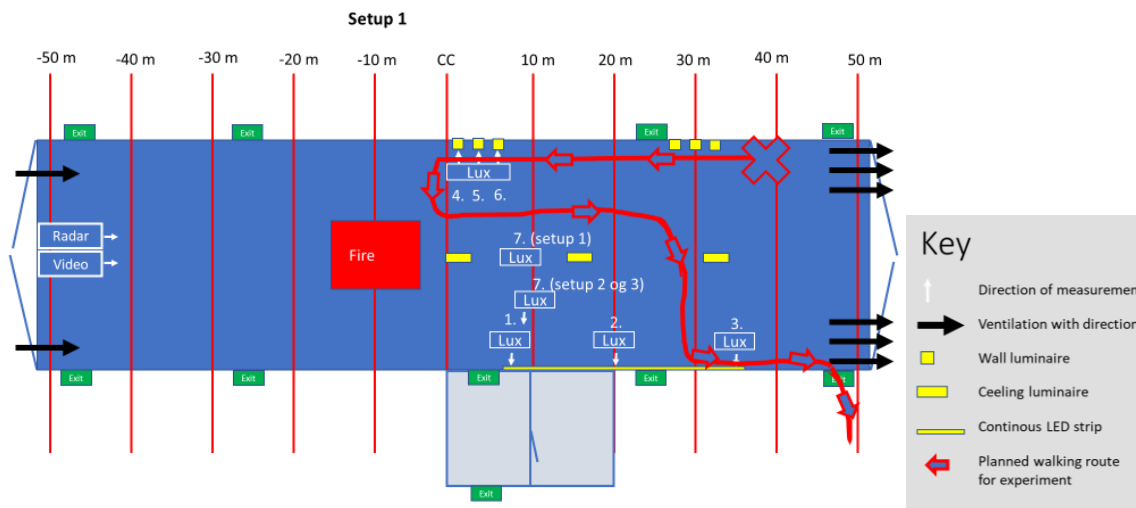


Figure 13 Setup test 1

The intent of the setup was to achieve “worst conditions” with a dense dark smoke, simulating no ventilation. LED strip was set to 50 % setting, giving approximate 200 lumen per meter, and the EnergyOptimal point source was also set to 50 %.

5.1.2 Illuminance loggings

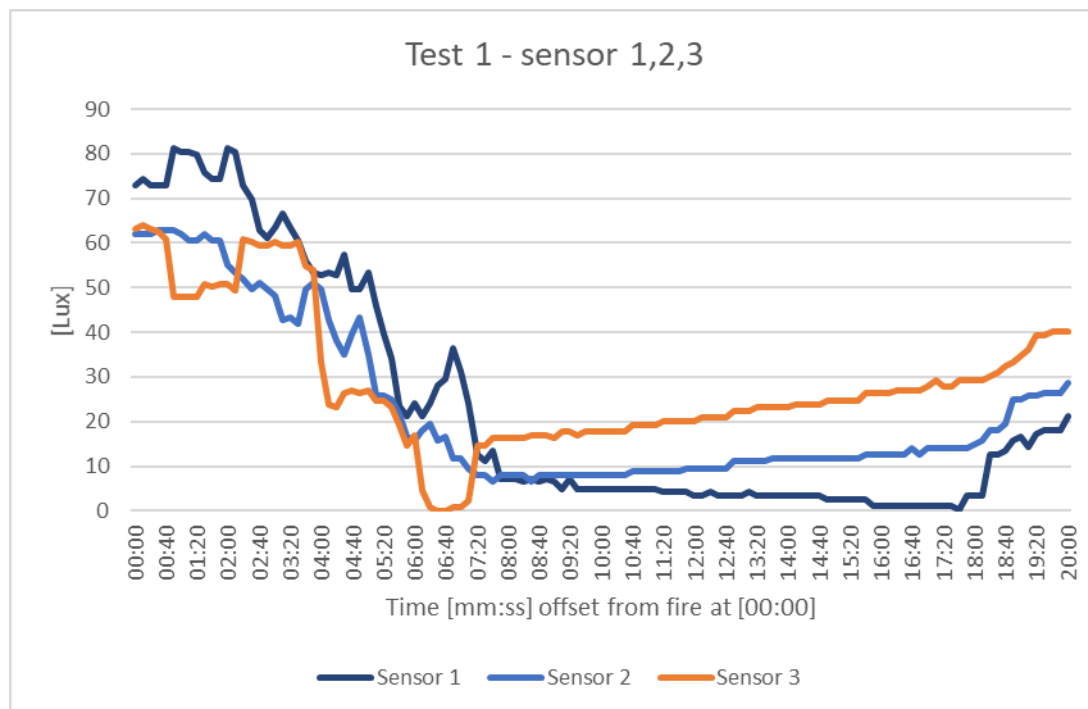


Figure 14 Test 1 illuminance logging, sensor 1, 2 and 3

Logs of data from sensors 1, 2 and 3 show LED strip performance at different distances from fire. All show a similar development from the start of fire and increasing smoke. After the fire was put out, and the test was over at approximately. 12 minutes, ventilation was turned on and it is observed that the visibility increases most rapidly farthest from the fire.

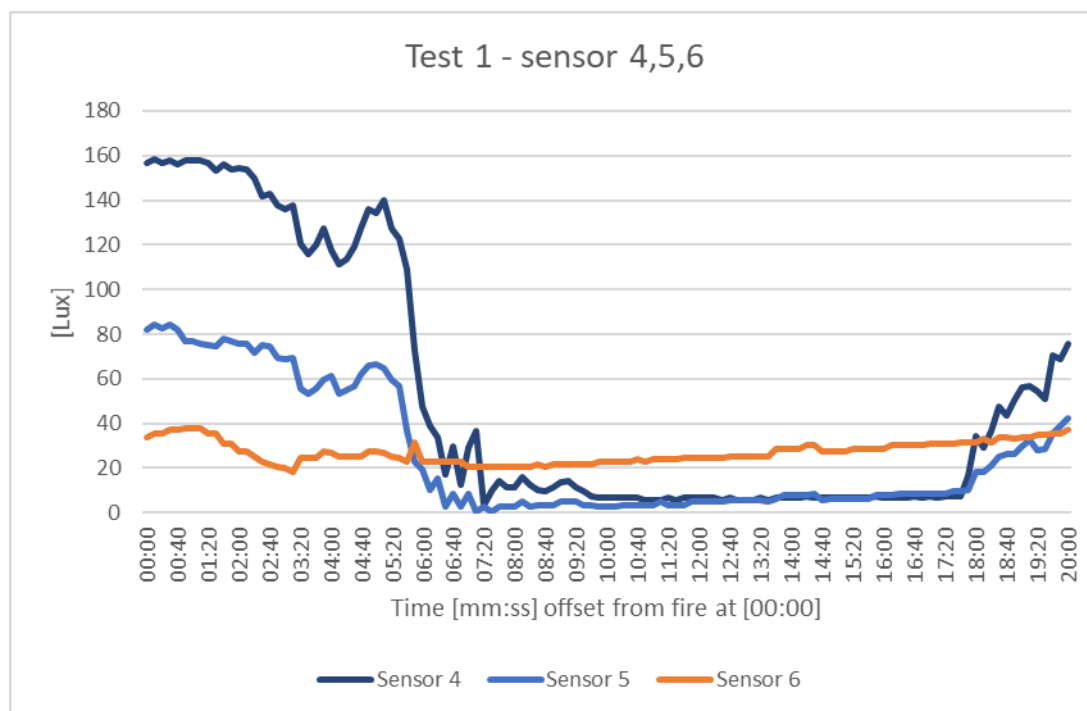


Figure 15 Test 1 illuminance logging, sensor 4, 5 and 6

Logging of sensor 4 shows a higher installed flux for luminaire 4 then 5 and 6. For the point source there can be observed a clear lowering when the layering of the smoke reaches the mounting height and a quick increase in the level when the height of smoke layering increases, after which it stays dark until ventilated.

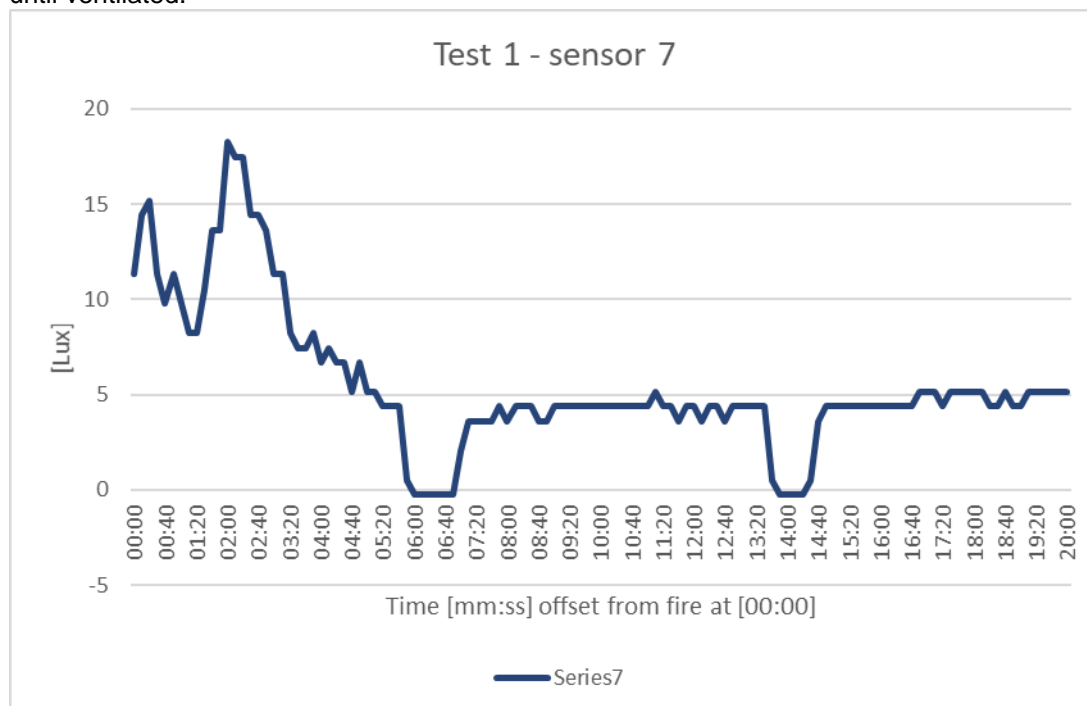


Figure 16 Test 1 illuminance logging, sensor 7

Sensor 7 shows that light from the ceiling disappears at a time when the luminaries at 1 m height have not been influenced yet. Also, the later period of ventilation has no influence on the sensor.

5.1.3 Debrief experiences

Observers:

Worst conditions were achieved in the test tunnel. This was the first time in real smoke for most of the test persons and the experience of complete darkness may have had a psychological influence on the evaluation results. Test persons reported a maximum of 1 m visibility distance to every evacuation light source included. This was the same for the LED-strip, but 1 m visibility was sufficient for good orientation and guidance to allow quick evacuation. Previous experiments with artificial smoke show that light illuminate the smoke, thus contributing to both visibility and orientation. Real smoke, on the other hand, gives a near total blackout. The ceiling luminaries were quickly completely darkened from the start of the experiment, before the smoke lowered towards eye height, the smoke in the top layer, causing a complete blockage of light from the luminaries mounted at 4 m.

Firemen:

Conditions with closed tunnel end-doors caused an under-ventilated fire with limited available oxygen content in the air (Norwegian: “sur brann”). These conditions simulate a long tunnel with high gradient and a cloud where the smoke meets cold air. The layering of the smoke was below approximately. 0,5 m, representing worst possible conditions.

5.2 Test 2



Figure 17 Car for test 2, before and after

5.2.1 Setup

Fire and smoke conditions were similar to the first setup, but ventilation was not activated after the fire was out; only the doors at the end were opened. Different levels of light output and its influence on visibility distance and contribution to orientation/guidance were noted/registered.

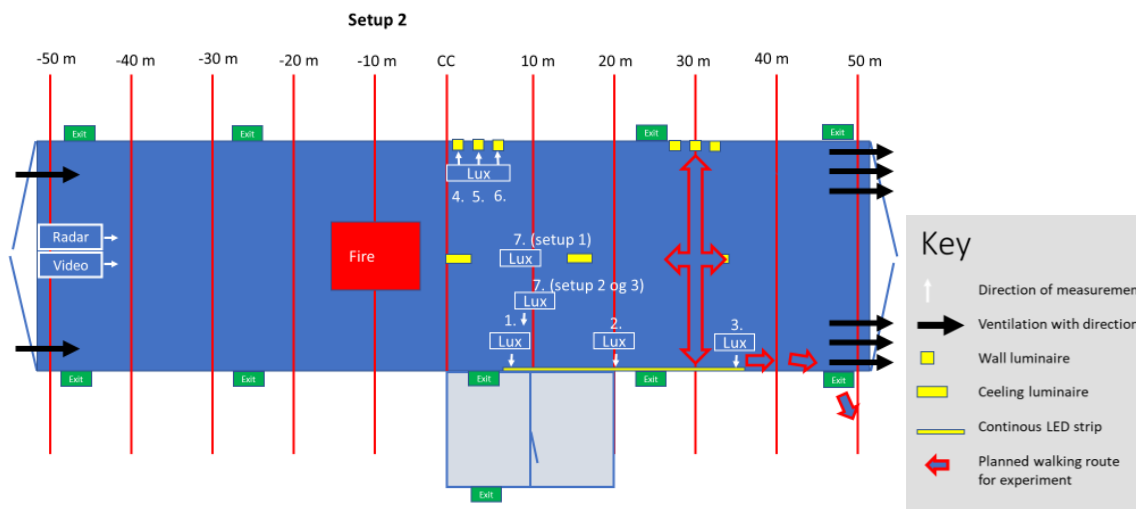


Figure 18 Setup test 2

5.2.2 Illuminance loggings

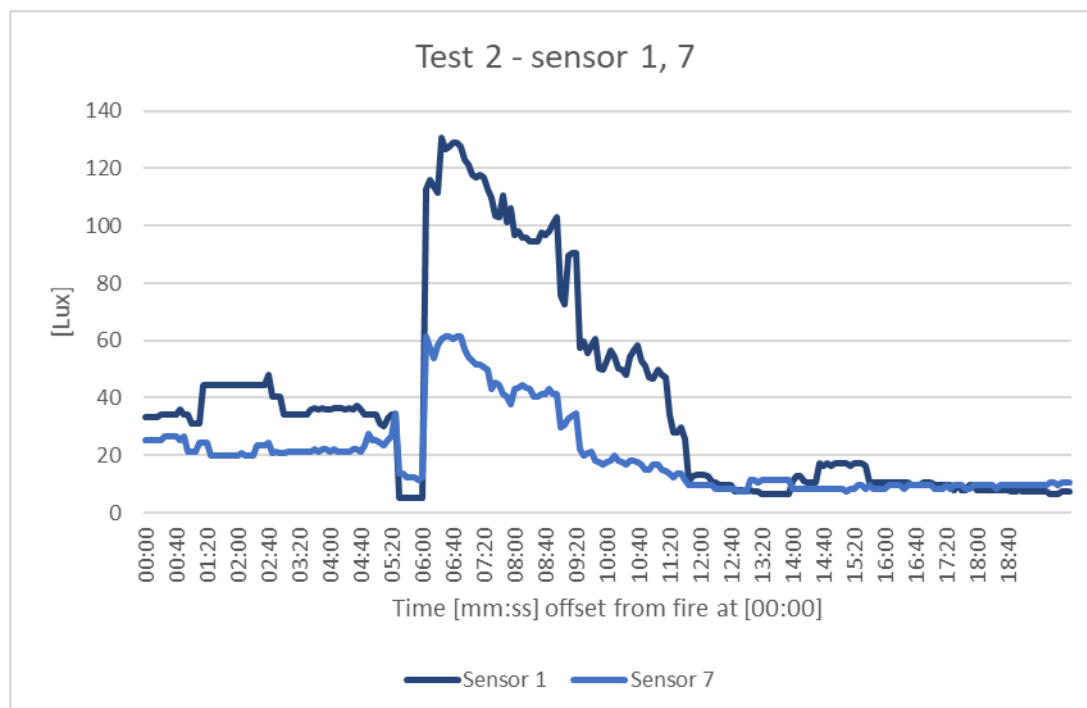


Figure 19 Test 2 illuminance logging, sensor 1, and 7

Sensor 1 and 7 were placed at the end of the continuous LED strip (the end facing the fire), the sensor was aimed towards the strip, sensor 1 at 1 m and sensor 7 at 2 m distance. One can observe an approximate linear relation between distance and measured illuminance at the start, this relation disappears after dense smoke develops. From 0 minutes the luminaries were operated at 10 % output, at 5:30 they were switched off, and 30 seconds later they were switched to 100 %. The increase in level can be seen clearly, but one can observe that after approximately 12 minutes the difference in illuminance between 1m and 2 m distance is not significant.

5.2.3 Debrief experiences

Observers:

Trials at different levels were performed. The observers experience showed that going from approximate 10-50–100 % level gave little difference to what distance the lights were visible. Some test persons reported slightly longer visibility distance with more output, while some reported no difference at all. Regarding situational comfort, the 10 % level was reported to give sufficient guidance (when first seen), while the increase to 50 % and 100 % levels did not give any practical increase in evacuation speed.

Fireman:

Lower level gave better visibility as the smoke is less lit up, making it easier to see a leading line at the lower lighting level. The higher light levels create an increased capsular effect in the smoke, and more glare.

5.3 Test 3



Figure 20 Car for test 3, before and after

5.3.1 Setup

Dense smoke developed approximately 5 minutes before ventilation was turned on (2 fans blowing in and 2 blowing out). The LED strip and Morrem guidance light were set to 50 % dimmed, Markled and Trafficked were set to 100 % output. At the end of the experiment the firemen start to extinguish the fire with water, and observe the impact on visibility.

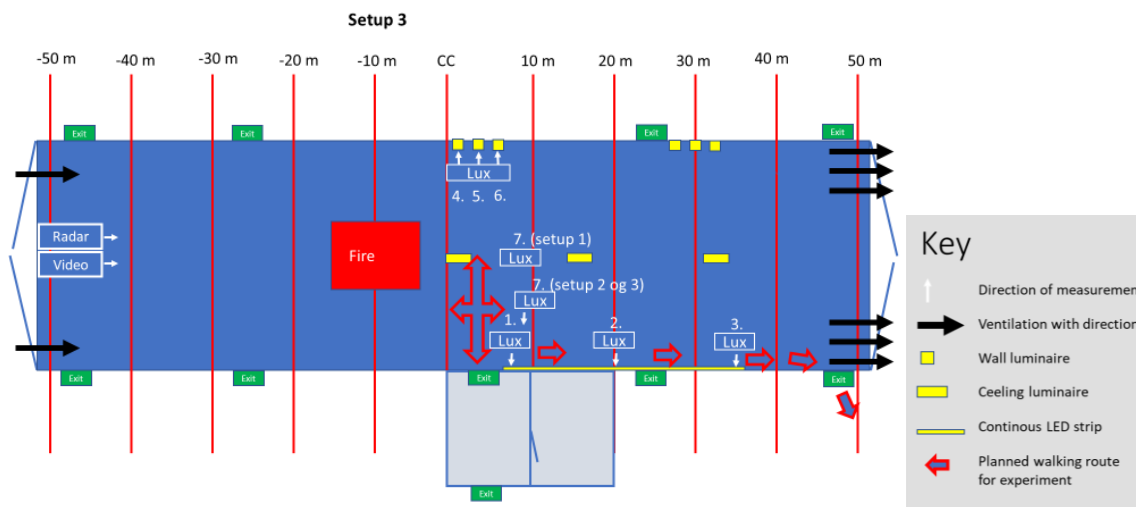


Figure 21 Setup test 3

5.3.2 Illuminance loggings

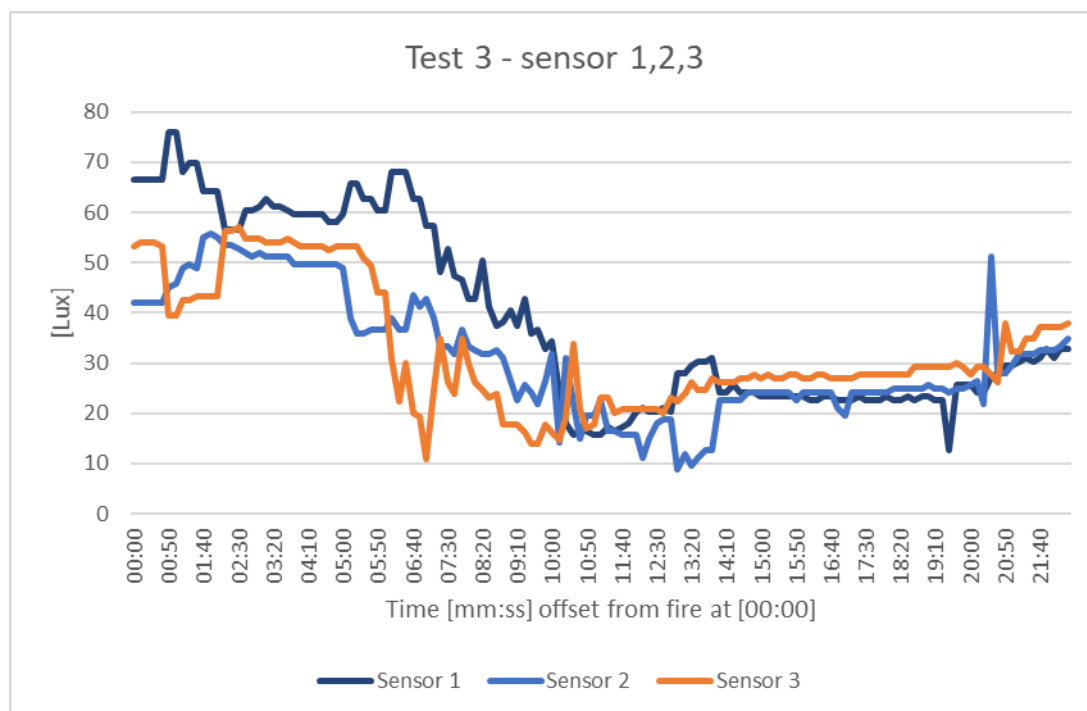


Figure 22 Test 3 illuminance logging, sensor 1, 2 and 3

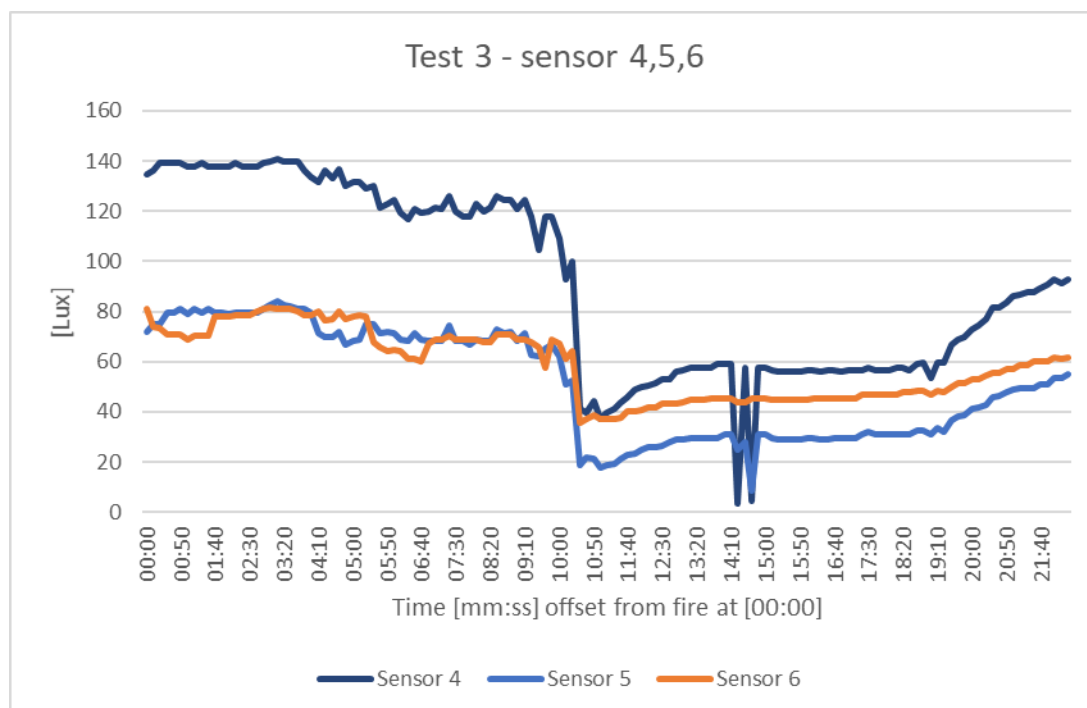


Figure 23 Test 3 illuminance logging, sensor 4, 5 and 6

After switching on the ventilation, an increase in detecting illuminance can be observed. After water was added a quick response with increasing illuminance levels can also be observed.

5.3.3 Debrief experiences

In ventilated smoke the experience was approximately 15 m visibility distance, giving good orientation from opposite sides of the tunnel (wall to wall). In these conditions the evacuation lights were almost too bright. But experience from the opposite side, looking backwards to the far end while walking towards the exit, still showed complete darkness with no visibility.

When water was added the “lit smoke” experience was more visible. The luminaries whose optics send light downward were experienced as being more comfortable than the optics sending light in every direction. The single luminaire evacuation light, giving a continuous high light level with some glare might have the effect of slowing down when passing the luminaries giving a longer evacuation time.

5.4 Other findings

5.4.1 Thermal damage



Figure 24 Images of thermal damaged equipment

The luminaire in position 2 suffered severe damage to the fixtures and electrical equipment. It was noted that this was the case for position 2 only, while position 1 (closest to the fire) was not damaged.

5.4.2 Optical depreciation



Figure Error! Bookmark not defined. Images of luminaries reciation of luminaires

The figures above show how soot accumulation decreased illuminance from the ceiling luminaires.

5.4.3 Radar

A supplier of radar equipment was present doing their own separate test. No results available for this report.

6 Discussion

6.1 Test 1

The worst conditions with a “total blackout” confirmed the hypothesis that normal lighting located on the ceiling disappears a long time before the smoke becomes a problem at ground level. Also, the visible distance to all lighting was observed to be below 1 m. The design requirements stating “1 lux on the floor” or a maximum separation distance of 25 m experience would, in our tests, have provided little to no practical guidance. Luminaries were visible just as the observers passed them, but provided no overall direction, orientation or visible effect on the escape route. On the other hand, the LED strip, after first being seen, gave people a clear orientation and direction of escape. It also gave a subjective feeling of safety as it indicated a “feeling of room”, not just a single disconnected spot of light.

6.2 Test 2

By creating worst-case conditions, this experiment gave a good test of measured and experienced lighting levels. Moving from 10 % - 50 % - 100 % level showed that in a totally smoke blackout an increase of luminous flux not necessarily lead to an improved practical effect. Results showed that the visible distance did not increase linearly as output was increased. Rather, the results showed a tendency toward increased output from luminaries causing only more glare. For the LED-strip this result might be a relevant issue. The 50 % level, representing 200 lm/m seems like a good design solution. Higher flux did not increase the visible distance, the effect resulted just in more lighted smoke. This lighted smoke made it more difficult to see the line along the wall, which was the feature which had the most positive contribution towards orientation/guidance.

For the single luminaire, this linear guidance effect is not present regardless of the lighting level, so the motivation for keeping the flux low might not be as relevant. The experience of the observers indicated that levels above 50 % (approximate 200 lm/m for continuous LED strip) gave no significant positive increase on the visibility or orientation.

6.3 Test 3

Test conditions simulating a more “normal fire” with tunnel ventilation showed a longer visibility distance for the evacuation lighting. And yet, the 6-10 m visibility distance shows that single luminaries placed at 25 m interval distance give poor orientation and guidance for the persons evacuating. To have an effect this distance should be decreased to maximum 10 m. At the same time, one must consider our test used a 5 MW fire; in the case of a larger fire the ventilation might not give the same effect and our “worst case” scenario might be more representative. Under worst-case conditions, even at 2 m cc distance would give poor guidance.

In addition, a single luminaire does not provide any information about orientation relative to the room. The experience of the continuous LED-strip, however, provides a good experience of the tunnel room so that the time spent on evacuation decreases. A compromise solution would be single luminaries which are physically extended in the longitudinal direction (not only by optical illusion) of the tunnel by a length of 1 m. A requirement for 1 m-long LED strips every 5 m for increased orientation might improve the effect. A luminaire with increased physical size in longitudinal direction would be more easily detected.

Further investigation of real-time escape performance under realistic smoke from a larger potential fire source, such as simulating a truck fire, should be done to give more accurate advice. Different

mounting heights, lower than 1 m, were not investigated and might have an impact. Mounting lights at such a low height may, however, cause increased maintenance issues.

6.4 Outcome

The main purpose of our testing was to investigate different types of evacuation lighting and evaluate their contribution to guidance, orientation and a general feeling of safety. One finding that is obvious is that the type and density of smoke have a direct influence on all these factors. An interesting observation is that increased lighting, which might have given a better feeling of safety under normal conditions, was not helpful to either guidance, orientation or the feeling of safety in our setup. Single luminaires give no orientation or guidance if one cannot see the next luminaire, and the wall surface cannot be used for direction either as it is hidden behind thick smoke. If the single luminaires could be physically stretched out in the longitudinal direction, then they would give more contribution to guidance/orientation, even if only a single luminaire is seen.

As the layers of smoke rose and accumulated under the ceiling, the high-mounted luminaires for general lighting quickly lost their function and gave no light towards the floor, becoming useless in this setting.

The tests were only with cars and all 3 experimental setups had similar fire-effect, approximate 5 MW. There is a chance that a larger fire-effect and/or longer tunnel would create a different layering of the smoke and thereby different outcomes.

The subjects in these tests were not a random selection from the general population. All persons were either firemen or had knowledge of evacuation lighting and were instructed beforehand on the hypothesis and plan for the experiment. Using test subjects without previous knowledge or instructions might have given other feedback.

7 Conclusions

Contribution from luminaries in the ceiling can be neglected in an escape situation.

Single luminaries at 1 m height with a 25 m cc distance give no help in smoke conditions. In the case of a ventilated car fire a decrease to 10 m cc distance is necessary to give any practical guidance effect. Under worst-case conditions the single luminaries give little to no contribution at all.

Continuous LED strips provide good orientation and guidance along the wall. 200 lm/m is sufficient for the visible effects needed in an escape situation in smoke. In thick smoke, no light will reach the floor, no matter how high the installed lumen intensity (lm/m).

Further investigation of the different effects induced by a large fire, for example, of a truck fire, will enrich the present findings.

8 Further work

Investigate if physically long luminaires along the tunnel wall, for example 1 m long, provide additional guidance/orientation compared to single point luminaires lighting placed in the longitudinal direction. Investigate relevant time spent on escape under real smoke conditions with different evacuation lighting installations.

References

- CEN. 2013. *EN 16276 Evacuation lighting in road tunnels*. Stanard, CEN.
- CEN. 2013. *EN 1838 Lighting applications - Emergency lighting*. CEN.
- CEN. 2014. *EN 60598-2-22 Particular requirements - Luminaires for emergency lighting*. CEN.
- NMF. 2018. *NMF01:2018 Led luminaires - requirements*. NMF.
- Statens Vegvesen. 2016. *N500 Vegtunneler*. Statens Vegvesen.
- Statens Vegvesen. 2014. *V124 Teknisk planlegging avveg- og tunnelbelysning*. Statens Vegvesen.
- Trafikverket. 2015. *TRV 2015:086 Vägars och gators utforming*. Trafikverket.

NordFoU

CVR nr.: 35272704

Nordfou.org

Havnegade 27

1058 København K