Locating people in tunnels using Wi-Fi technology

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ABSTRACT

The overall aim of the current project is to investigate the possibility of using people's mobile phones to locate people in a tunnel environment, both during normal operation and during an emergency. As part of the project, a technology for locating people based on Wi-Fi communication between access points in a tunnel and the user's mobile phone is investigated. To examine the precision of the localization system, 39 different trials have been carried out under different conditions during an experiment in a road tunnel in Stockholm, Sweden. In the tests, the Wi-Fi-based predicted location has been compared with the actual location of the people in the tunnel. The conditions investigated include the number of people in a group, the number of available access points in the tunnel, whether the mobile phone distinguishes between an active or passive connection, whether it differs between a person moving or standing still and whether the mobile phone is held in the hand or is stored in the person's pocket. The results indicate that the mean value for the distance between actual and predicted position is in the order of 20 m or less. The variation in distance for a single individual is relatively large and the standard deviation for the mean distance is in the same order of magnitude as the mean value. Despite this, there is a good potential to locate individuals in a tunnel as the distance between emergency exits is often much longer than the uncertainties in the predicted locations of people. These results are promising and indicates the potential of cost-efficient improvement of tunnel safety both for existing and new tunnels. With a refined positioning system, there is potential for further improved ability to locate individuals in a tunnel fire environment with this technology.

KEYWORDS: tunnel safety, evacuation, rescue services, Wi-Fi, indoor localization, indoor mapping, sensor

BACKGROUND

Safety in underground facilities for road and rail traffic, i.e. road and rail tunnels, is largely associated with the technical characteristics of these structures with regard to safety in the event of fire. This applies in particular to the technical characteristics that affect, on the one hand, what possibility people have to self-evacuate or otherwise get to safety, and on the other hand, what possibility the rescue services have to carry out an efficient rescue operation. Mainly, this is because fires in road and rail tunnels can be expected to both develop faster and be larger than in ordinary buildings above ground [1–3]. In the event of a fire in a road or rail tunnel, it is also likely that smoke will quickly spread in large parts of the tunnel system. A consequence of this is that people in road and rail tunnels can be forced to evacuate under very difficult conditions, for example long distances in dense smoke with only a few meters of visibility [4–7]. The unfamiliar road and rail tunnel environment and the long distance to the nearest emergency exit also aggravate the situation. As such, the need for evacuation assistance is often higher compared to normal above-ground buildings.

The need for help during an evacuation of a road or rail tunnel is to some extent met by the recommended tactical approach for rescue efforts in this type of construction [8]. The problem, however, is that also the efforts of the rescue services are associated with great difficulties [9–11].

Apart from the low experience in carrying out interventions in road and rail tunnels, the intervention is usually performed from a limited number of access points. The rescue services will thus lack a complete overview of the accident scene especially in the initial stages of the operation. In this regard, a lack of information about what is burning, where the fire is, whether there are people still in the tunnel, and if so where, has been pointed out as difficulties for a rescue effort [8, 12]. Difficulties that can be crucial when determining for example the appropriate direction for ventilation flow for rescue purposes with tunnel ventilation or mobile fans.

In many cases, the difficulties can be partially managed with the help of various technical systems that can inform about the event that has occurred, for example fire alarm systems, automatic water sprinklers and CCTV systems. However, the majority of these systems are designed in such a way that they mainly contribute with information about the fire, but not the evacuation. Furthermore, systems designed to facilitate evacuation are most useful in the initial stages of a fire and can thereafter provide information only in those parts of a road or rail tunnel that are not affected by fire smoke.

With this background, one of the most prioritized tasks appears to be determining whether people are still inside road or rail tunnels, in which parts of the facility they are located and in which direction they are moving. This information is crucial to determine what strategy and what resources are needed to try to rescue them. A system for locating evacuating people can therefore be a technical installation that can largely contribute to increasing both people's ability to reach a place of safety and the ability of the rescue service to carry out an effective operation.

One such method to locate people could be to exploit the fact that many people already today own a smart phone that has the ability to automatically communicate with a wireless local area network (WLAN). The question is therefore whether this can be a technology that can be used for locating people or whether the technology itself is too imprecise. Seen from a research perspective, there is also an interest in investigating whether the technology can be used to collect data about how people move to be able to predict movement for modelling purposes. There are examples of research that used certain technologies, such as RFID technology, IR technology and Bluetooth technology tested with varying degree of success [13–15]. Still, the technique must be considered in an early stage of development and validations studies are needed.

Objective

The paper, therefore, aims to investigate the conditions for locating people in a road tunnel using the Wi-Fi function of the person's smart phones during normal conditions, i.e., without any presence of heat or smoke.

The primary goal is to investigate, based on a realistic experiment, the accuracy of a positioning system based on Wi-Fi technology to assess whether the technology can be used for locating people during normal situations and in the case of an emergency.

The goal is also to investigate whether, and if so under what circumstances, the same positioning system can be used as a data collection technique in future research contexts to both facilitate and streamline as well as increase the accuracy of empirical studies of people's movement.

TECHNIQUES FOR LOCATING PEOPLE

Today there are several more or less developed technologies (and related location algorithms) for locating people and their movement outdoors as well as indoors under normal conditions [16]. The GPS technology is the most commonly used in outdoor environments but can only be used to a limited extent when locating people indoors and then it needs to be supplemented with other technologies [17]. However, in road and rail tunnels as well as other types of deep underground facilities, such as mines, with only a limited number of entrances/exits, the GPS technology is not a practical option for locating people, even when supplemented with other technologies.

Bluetooth, RFID and Wi-Fi are, in this context, various examples of technical solutions that can be used indoors for locating people under normal conditions. Which one is most suitable to use in a particular application depends, among other things, on the need for level of detail, precision, range, response time and reliability. The RFID technology has, for example, been applied for a longer time in the mining industry to monitor the location of miners in the many times long and deep networks of tunnels that occur in this type of operations [18]. However, it can primarily (and has historically) been used to identify people within zones rather than their actual position. In other applications, Wi-Fi based technologies have been used to, for example, within a commercial context in detail describe how many visitors make it to a certain part of a shopping center, how long they stay there, and which are the most common walkways [19]. Previous research has shown that the technology can predict the location of a mobile device with a precision of a few meters [20]. This indicate there is a potential for using the technology also for a tunnel environment. More details on this, an overview of other localization technologies as well as techniques for positioning are presented in [21]. As concluded, there seem to be a potential for wireless technologies to track people. However, little research seems to have focused on practical testing, particularly within an emergency application.

METHOD

In this paper, the results from an experiment in which participants (subjects) moved in a tunnel according to predetermined routes is presented. During the experiment, the test subjects wore devices that corresponded to a mobile smart phone, and were located using a Wi-Fi technology. The position was determined through an analysis of the collected material after completed trials. During the experiment, the actual positions of the test subjects in the tunnel were documented using video recording to be able to compare this position with the one obtained from the localisation with the Wi-Fi technology. After the data had been post processed, it was used in analyses with regard to aspects such as precision and accuracy related to the positioning technique. This was done for a variety of set ups, related to the number of people in a certain trial, type of connection condition (e.g. passive and active connection), number of available access points, etc.

EXPERIMENTAL CONDITIONS

The road tunnel

The experiment was carried out in the Sickla tunnel, which is part of the Södra Länken (Southern Link) road tunnel system in Stockholm and at the same time part of national road 75. The tunnel has two unidirectional lanes, and it slopes downwards in the direction of travel (south). The test area is located approximately in the middle of the tunnel, where the tunnel has a straight design. Figure 1 shows a view of the tunnel seen from the north side in the south direction.

Figure 1. Picture showing the tunnel seen from the north side of the tunnel in the direction to the south. The first red-white marking indicates the experimental area's limitation to the north.

At the test site, the tunnel is approximately 10.4 m wide with two lanes of 3.7 m each (measured in the center of the lane markings) and a road shoulder on each side. Along the right side, the shoulder is approximately 2 m wide, while on the left side it is approximately one meter wide. On each side of the tunnel, there are edge elements placed along the tunnel, which provide a smooth surface along the tunnel up to approx. 1.4 m above road level. The experimental area is approximately 110 m long, which is the area between the outermost access points plus 10 m further in each direction. This is illustrated in figure 2, which schematically shows the relevant part of the Sickla Tunnel with the marked trial area and various installations.

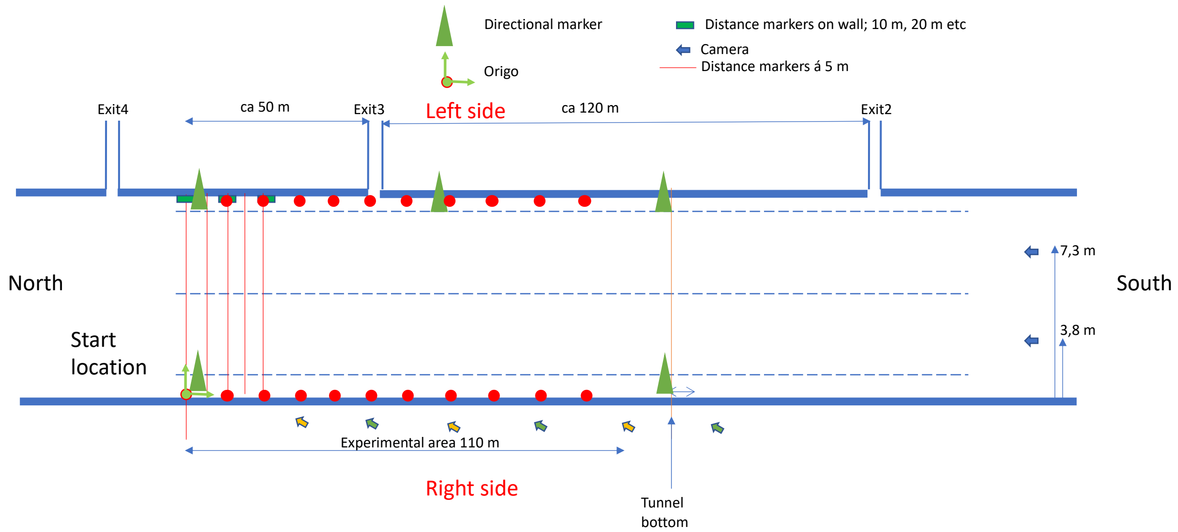

Figure 2. Simplified view of the test area in the Sickla tunnel. Yellow and green bands along the test area indicate the approximate coverage areas of the cameras.

Wi-Fi devices

To avoid a possible conflict with the General Data Protection Regulation (GDPR), which among other things regulates how collected data may be handled, the subjects' own mobile phones were replaced with battery-powered Wi-Fi devices (figure 3), which technically corresponds to the function that mobile smart phones have in terms of communication with surrounding receivers for a Wi-Fi signal. Every Wi-Fi device communicates at least as often as a mobile phone does if it is actively connected (active listening) to a wireless Wi-Fi network. In the current case, a communication between the Wi-Fi devices and the access points took place every second. This is more frequent compared to how a mobile phone usually communicates. However, in this way a controlled connection was obtained and in the following analysis an average value of the data set over each 5 second interval is used for determining each position. The passive listening is represented in the analysis by the fact that only a smaller, randomly chosen sample was included for the positioning. In all trials, each research subject carried two Wi-Fi devices, one held in one hand and the other placed in one of the research subject's pockets.

Figure 3. Wi-Fi device with battery used during the experiments to represent a mobile phone.

Access points

To locate the subjects, 20 access points were set up along the experimental area, see figure 2. The access point is the device that can communicate with the Wi-Fi devices that the subjects carried with them during the experiments. The access points were of the Teltonika RUT955 type, which is also a 4G router with built-in GPS, and thus makes it a suitable access point for mobile measurements. Each access point was placed on the ground along the long sides of the experimental area at 10-meter intervals.

Video cameras, markers and obstacles

In order to document the real position of the subjects during the tests, six video cameras on tripods were used and placed on the edge elements along the right side of the tunnel with a c/c approximately corresponding to 20 m. The location of each camera is shown in figure 2 where they are illustrated as small arrows in the lower part. Each camera recorded approximately 20 m of the length of the tunnel and basically the entire width of the tunnel.

To facilitate the analysis, there were distance markings along the tunnel and markings across the tunnel at 5-meter intervals. In this way, each research subject could be located on the videos. The tunnel was also equipped with directional markers (road cones) that the research subjects used to be able to keep a straight walking direction.

A vehicle was placed in the tunnel during some of the trials to investigate the effect of shadowing the radio signal. The vehicle was of the minibus type and, when it was used, was located approximately 80 m from the starting point.

Participants

A total of 16 people participated in the trials. These were recruited from fire engineering consultancy firms in the Stockholm region as well as from Brandforsk, LTH Fire Safety Engineering, Region Stockholm and the Swedish Transport Administration. The recruitment was carried out via personal contacts with the respective organization and the criterion for being allowed to participate was that each person had a self-assessed physical ability to move freely within the trial area. Due to the recruitment procedure, all research subjects were known to the researchers.

The recruitment was carried out in such a way that the person received complete information about what the experiment was about. This was done in order to allow for the test subject to assess whether he or she wanted to sign up and participate. An internal ethics assessment was carried out prior to the trials to ensure that the research subjects would not be exposed to any unnecessary risks or intrusions into their personal integrity. As part of risk minimization, all research subjects were provided with a safety west and a protective helmet. Each subject had to sign a consent form prior to his/her participation, and was compensated with 500 SEK (approx. € 50) afterwards. All research subjects were insured in a so-called special personal injury protection insurance from the Legal, Financial and Administrative Services Agency (Kammarkollegiet) in Sweden.

Trial scenarios and implementation

The experiment included four different main scenarios. Each scenario included a number of different trials. Within one scenario, there is mainly a variation in the number of research subjects who move in the tunnel and several trials are repetitive. This means that a scenario is characterized by:

- walkways for the research subject or group of research subjects,
- if the subject, for a while, stands still at a certain position in the tunnel, and
- if there is an obstacle in the form of a vehicle in the tunnel.

In each trial, data was collected from both Wi-Fi devices of the research subjects (representing a smart phone). A total of 39 trials were conducted. The number of research subjects who carried out a single experiment varied from a single individual to the entire group of 16 people.

Walking routes

There was a total of five different walkways or routes along which the research subjects could move, see Figure 4. Route A and B (used in scenarios 1 and 3) were near the middle of the two lanes of the tunnel. Route E (used in scenario 4) followed the lane line marking on the right side. Route C and D (used in scenario 2) only partially followed the tunnel's natural route. The participants were asked to walk as straight as possible along the designated paths, which were highlighted with road cones.

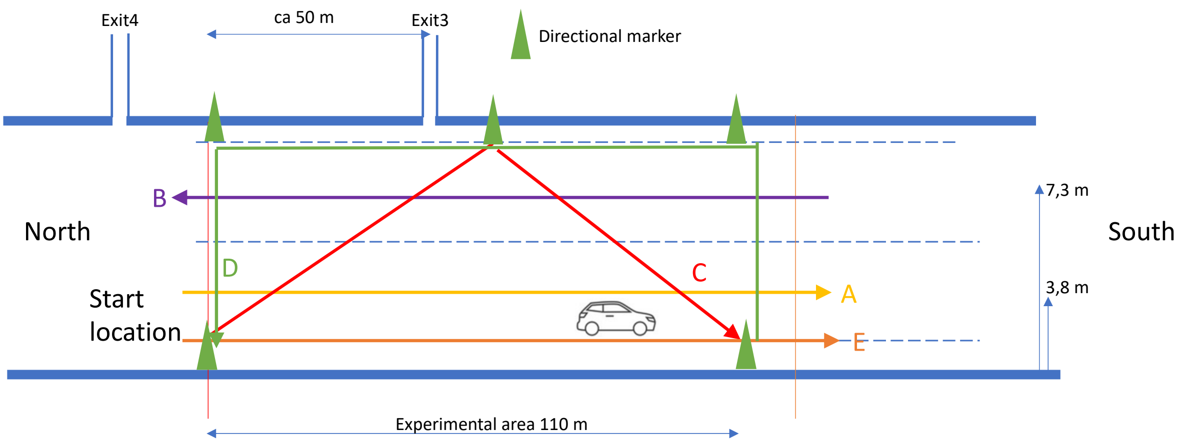

Figure 4. Walkways for the different scenarios.

Stop in the tunnel

Scenario 3 is characterized by the research subject first walking a distance, approximately 50–60 m and then stopped in the tunnel. The person stood still for one minute and then walked the final part of the route. In these cases, the movement took place along routes A and B.

Obstacles

In scenario 4, there was a vehicle deployed in the tunnel, see Figure 4, and in that scenario the research subjects walked along section E in the tunnel.

Procedure

The experiment was carried out on the night between 27 and 28 October 2021. All the people involved gathered for a joint briefing at 22:00 on 27 October. Research subjects signed the consent form, and was then given the two Wi-Fi devices that would represent mobile phones as well as number pads to be put on the clothes. Thereafter, everyone was transported to the trial site and the trials were prepared.

At the start of the experiment, the video cameras were synchronized with an audio signal at exactly 23:45:00. Based on that signal, the video films were later prepared so that they could be viewed synchronized with the same start time and with the Wi-Fi-based locations. Before each trial, the research subjects who participated in each experiment were informed about the conditions that applied. Research subjects who did not participate in an ongoing trial were approximately 10 m outside the experimental area.

RESULTS

The main results from the trials are the difference in location between the two measurement methods, Wi-Fi and video-based locations respectively. The data collected has been processed in different ways to represent the possible methods of Wi-Fi communication to investigate the effect of the number of access points available in the tunnel. In all cases, the Wi-Fi position is based on an analysis of the three strongest signals from the mobile device at any given time (trilateration). Prior to the analysis, a number of different ways of processing the collected material were investigated and the method with the three strongest signals was shown to provide reasonably good precision on a test data. It should be mentioned that the experiment included a variety of alternative conditions manifested in the trials. In this paper only a few of the experimental conditions are presented due to space restrictions.

The analysis of the positioning takes place as a comparison between a Wi-Fi-based position and the corresponding real position as documented by the video cameras. The amount of data is extremely large, and therefore only part of the material from the trials will be reported in this paper. The remaining data material will be published in later papers, but a good idea of the capabilities of the technology can still be obtained through the results now presented.

Most of the results presented are based on analysis with data where every other access point is available for communication (called base case), figure 5. A comparison is also made against the cases where all access points are available for positioning. Furthermore, the results are mainly based on experiments where a single research subject or a small group participates in the experiment. The diagrams in the paper reporting the results show the same view as the illustration below but with the research subjects' locations inserted.

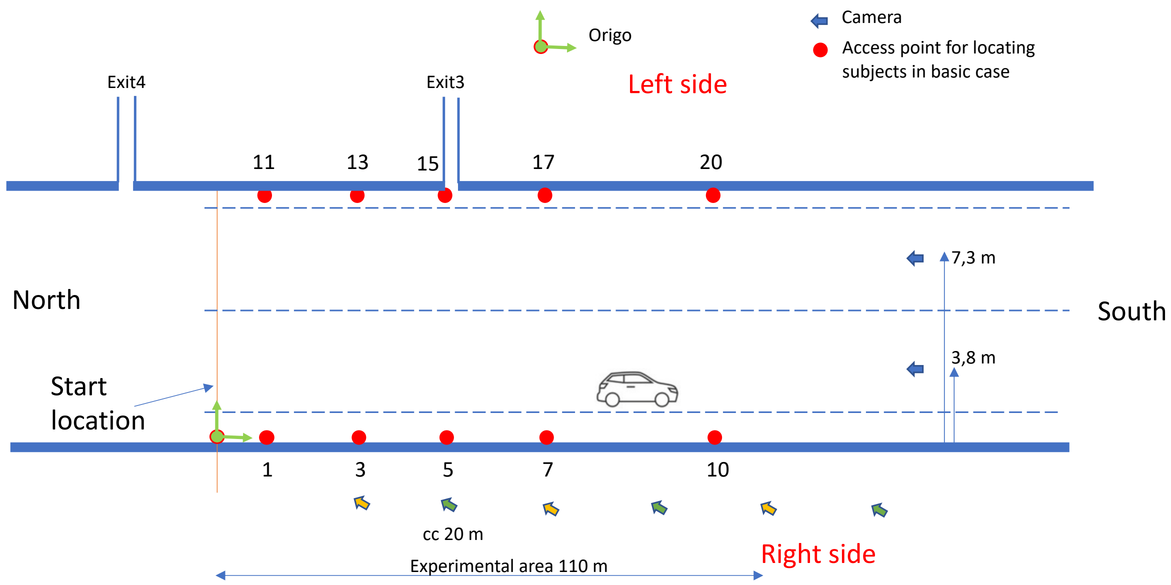

Figure 5. Available access points for the base case of the results.

Location in the base case with single individuals and with a hand held mobile phone device
In trials 1–3 and 7–9, the research subject moves along the middle of the lanes in the tunnel, i.e. along walkways A and B respectively, see figure 4. In all experiments reported in this section, the research

subject holds his mobile phone device in his hand. Figure 6 and figure 7 report the position of the six research subjects who participated in the six trials. The diagrams indicate whether it is real position, marked with R for the research subject's number (e.g. R170) or W for the Wi-Fi position. In trials 1–3, all subjects walked about 4.1 m from the side of the tunnel.

In trials 7–9, the research subjects walk back to the starting point of the experiment along route B, which in this case is 7.1 m from the side of the tunnel. The tunnel's lanes are in the diagrams between 2.0 m and 9.4 m. The total width of the tunnel is 10.4 m.

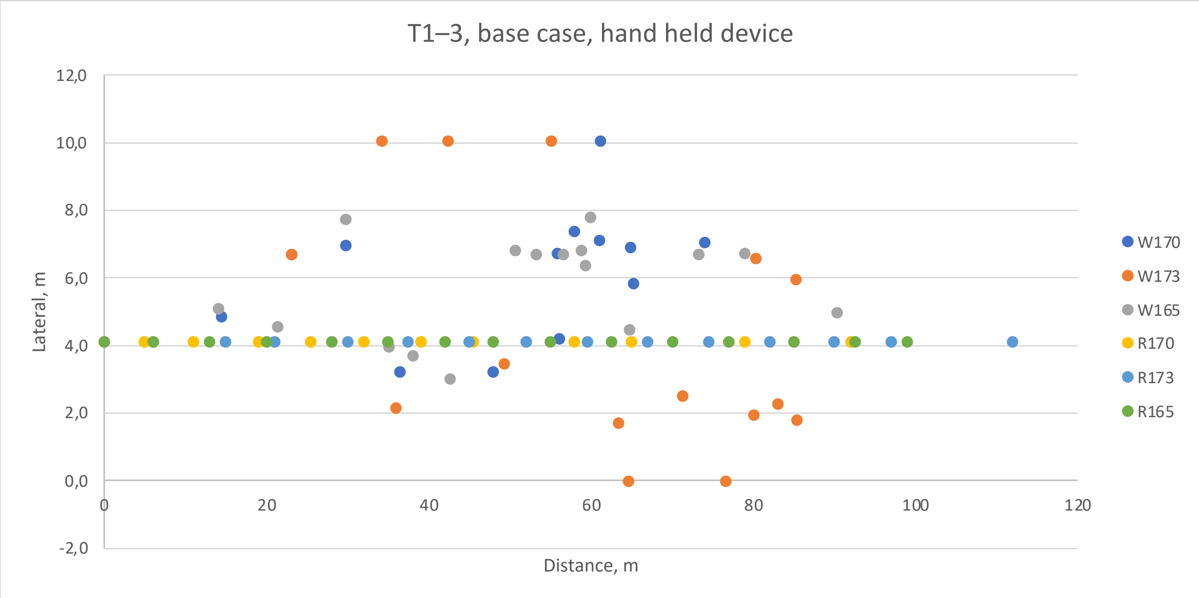

Figure 6. Trial 1–3 in the base case with a hand-held device. W indicates Wi-Fi position and R indicates real position.

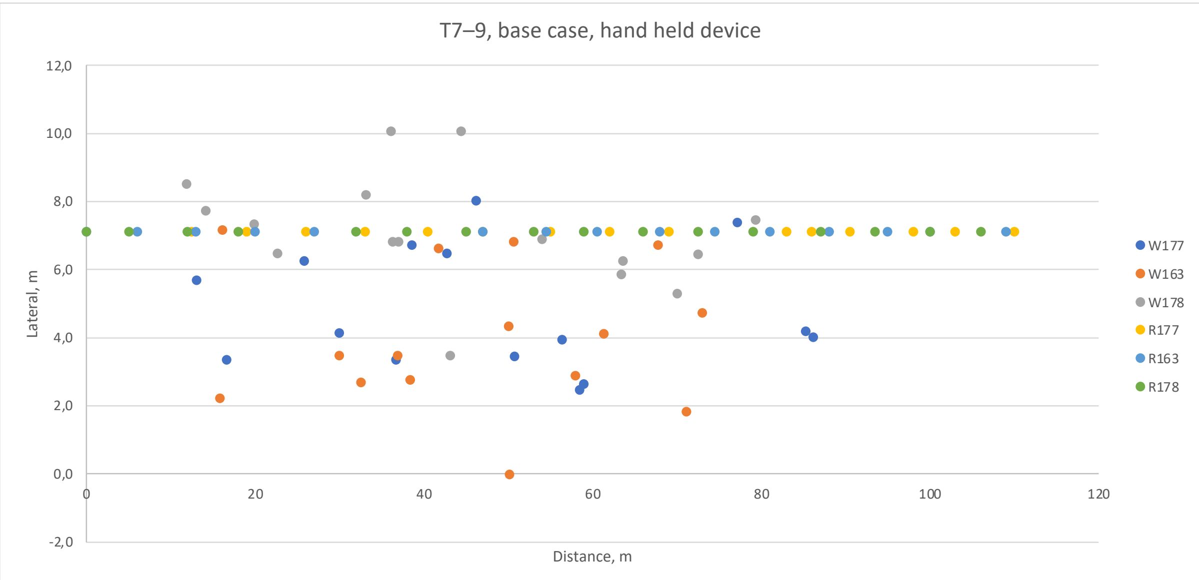

Figure 7. Trials 7–9 in the base case with a hand-held device. W indicates Wi-Fi position and R indicates real position.

It can be observed that there is a relatively clear deviation between the actual (R) position in the tunnel and the one predicted by the Wi-Fi system (W) and the deviation between individual comparisons is difficult to follow (a single R vs. W location). Figure 8 shows the results for trial 1 where the subject's actual locations have been linked to the corresponding Wi-Fi-based locations.

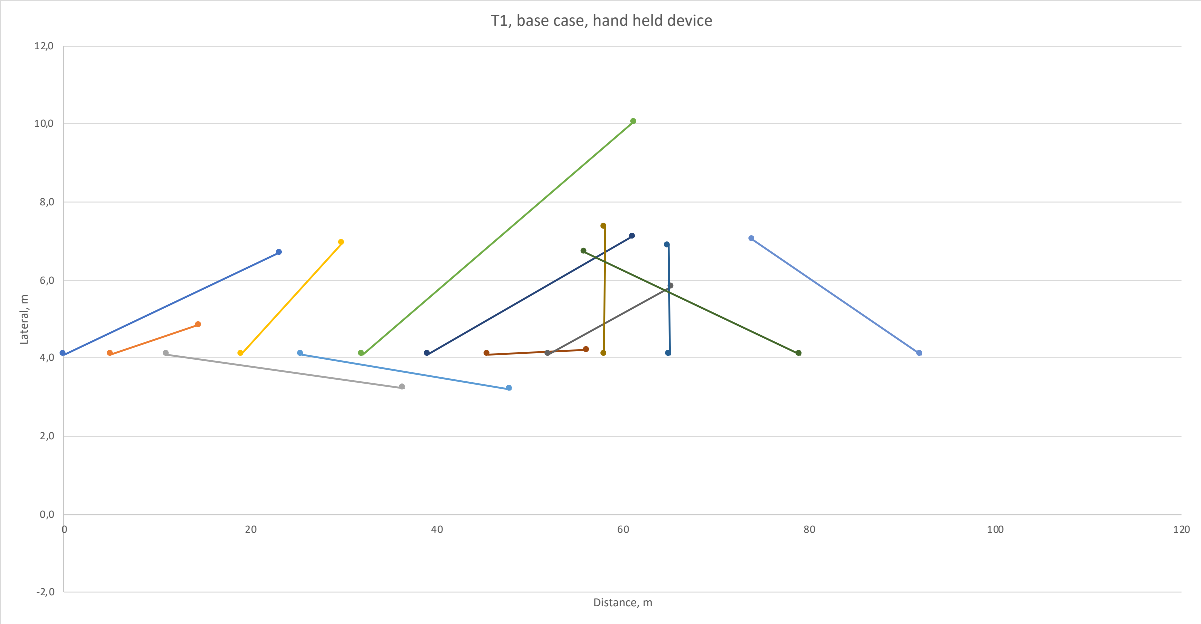

Figure 8. Real and Wi-Fi-based position for trial 1 (subject No. 170).

In principle, it never occurs that the real and the Wi-Fi-based position correspond precisely, but there is a certain pattern in the deviation between the two locations during the course of the experiment. At the beginning and at the end of the experimental area, the Wi-Fi positions tend to lean towards the middle of the tunnel. This tendency is also visible in other trials and for other conditions. The first access point for trials 1–3 is located 10 m from the starting point, which means that the Wi-Fi equivalents of the first real positions are based on access points 10, 30 or even 50 m from the starting point, as three signals are used for locating the device.

Considering the tendency in the direction of the deviation illustrated in Figure 8, the mean distance and the associated standard deviation are calculated for the positions that are between the access points used, i.e., between 10 m and 100 m. Mean value and standard deviation (for a sample) were determined for the results of all investigated research subjects and for the entire experimental group in question. Trial group refers to trials that are designed in the same way, e.g. T1–3. Table 1 below reports calculated distances for trials T1–3 and T7–9.

Table 1. Calculated mean distances between real and Wi-Fi-based position for the base case and handheld mobile device.

Trial No./Subject No.	**Locations between 10m and 100 m**	
	Mean value, m	**Std. deviation, m**
T1/170	16,6	9,0
T2/173	25,5	18,2
T3/165	16,2	14,6
T1–3	**19,4**	**14,8**
T7/177	19,9	18,5
T8/163	18,6	10,7
T9/178	12,2	7,7
T7–9	**16,8**	**13,2**

In a comparison when all positions are used for calculating the average value and when only those between 10 m and 100 m are used, it is found that there is a fringe effect at the edge of the test area that affects the precision of the Wi-Fi technology. However, in most cases the difference is not that great and for the case above with the average value for all positions 20.3 m for tests 1–3 and 19.3 m for tests 7–9, with should be compared with 19,4 m and 16,8 m.

Location in the base case with single individuals and a mobile phone device in the pocket
To investigate the effect of how the mobile phone is stored during locating the device, each research subject carried two devices, one of which was kept in the pocket. The analysis for this has been carried out for trials T1–F3 and T7–F9. Distance between real position and Wi-Fi-based position is reported in table 2. The variation is also reported in the form of the standard deviation. In the column to the right the corresponding results from experiments with handheld devices are presented for a comparison.

Table 2. Calculated mean distances between real and Wi-Fi-based position for the base case and mobile phone device carried in the pocket.

Trial No./Subject No.	**Locations between 10m and 100 m. Device located in the pocket**		**Locations between 10m and 100 m. Handheld device.**
	Mean value, m	**Std. deviation, m**	**Mean value, m**
T1/170	15,8	13,6	16,6
T2/173	20,0	20,4	25,5
T3/165	14,8	8,9	16,2
T1–3	**16,8**	**14,6**	**19,4**
T7/177	16,6	11,1	19,9
T8/163	16,2	11,2	18,6
T9/178	12,4	7,7	12,2
T7–9	**15,0**	**10,0**	**16,8**

It seems that the handheld device results in a larger deviation between real location and Wi-Fi-based location. The two devices did also not predict the same location as indicated in figure 9 (for trial 2). In this figure the lines connect locations predicted by the two devises (having the same time stamp) as the subject went along the experimental route. This large deviation is also found for the other investigated trials.

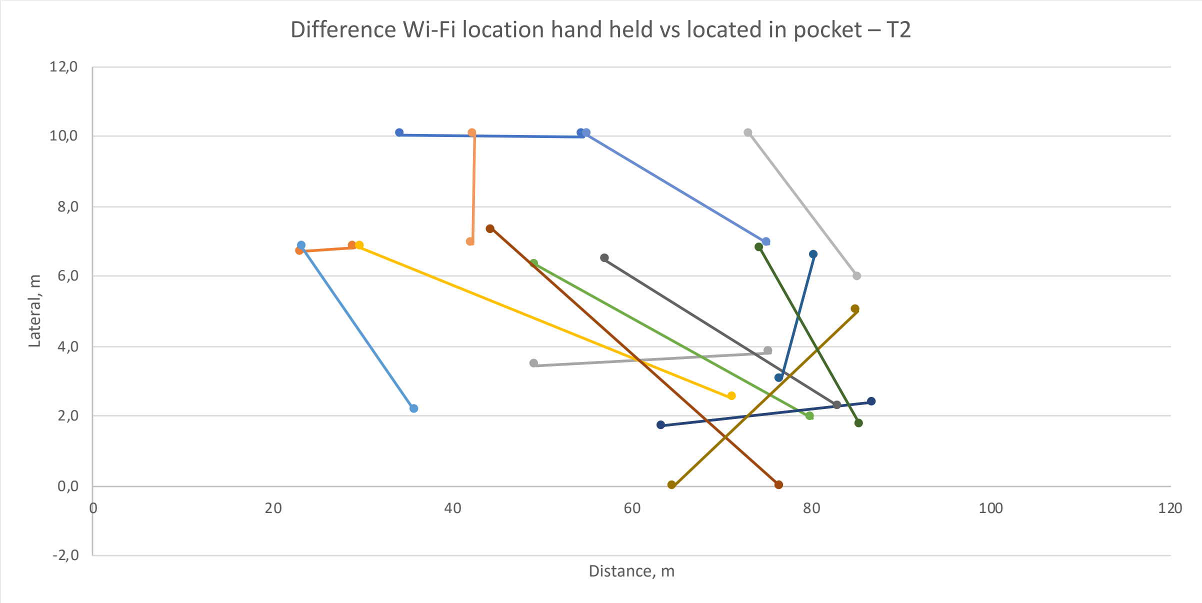

Figure 9. Wi-Fi-based positions for trial 2 in the base case but with a differently held mobile phone device, in the hand or in the pocket, for all time steps in the trial.

Location in the base case with a small group and hand held mobile phone device
The number of people moving in a group can affect the accuracy of Wi-Fi location. In the problem identification before the trials, this variable was noted as one to be included. Several different group constellations were examined during the trials, but only one trial is presented in this paper.

In trial 4, it is investigated when five people in a group move along route A. The positions of the five research subjects are reported in Figure 10. In this case, the people move more laterally while walking along the experimental route compared to the previous cases when basically all walks an identical path.

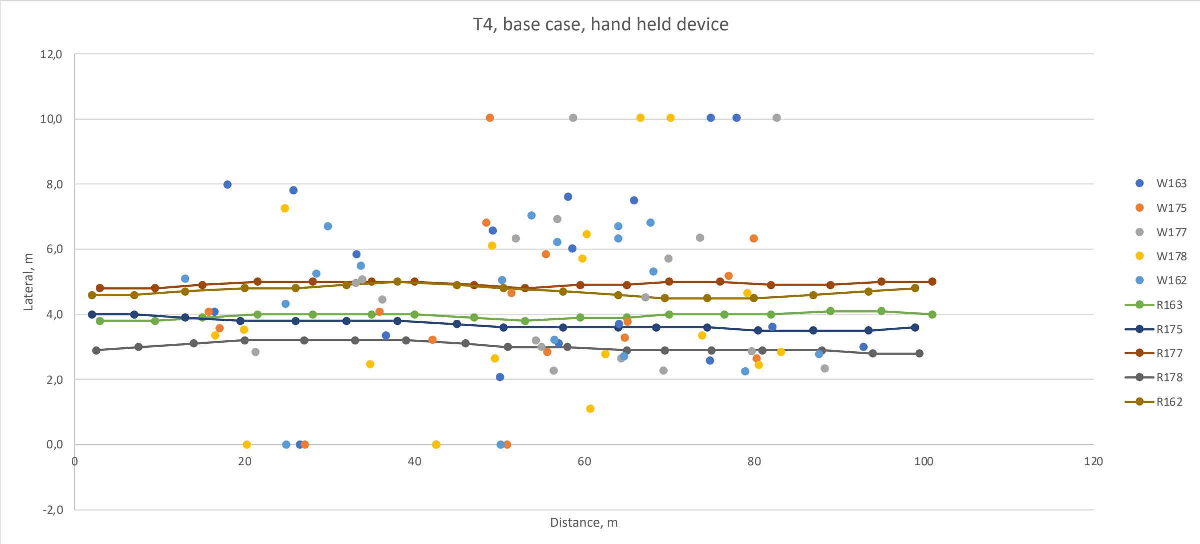

Figure 10. Trial 4 in the base case with hand-held device. W indicates Wi-Fi position and R indicates real position, also marked with line.

As can be seen from the figure, the spread is relatively large also in this case. Table 3 reports the mean value and standard deviation of the difference between real position and Wi-Fi-based position for the five people in the trial.

Table 3. Calculated mean distances between real and Wi-Fi-based position for the base case and handheld mobile device.

Subject No.	**Locations between 10m and 100 m.**	
	Mean value, m	**Std. deviation, m**
163	9,6	7,7
175	14,0	10,6
177	15,4	10,4
178	14,3	12,8
162	16,0	17,0
All	**13,9**	**12,1**

Location in the base case with single individuals, with handheld mobile phone device and stopping in the tunnel

In trials 27–28 and 30–31, the movement was carried out with an inserted pause. Table 4 reports the accuracy of the positioning for the time the research subject was standing still. Figure 11 illustrates the variation in the calculated position in relation to where the research subjects de facto stood during the break. Three of the research subjects stood at 50 m and the fourth at 60 m.

Table 4. Comparison of mean and standard deviation of difference in distance between Wi-Fi-based position and true position for trials 27–28 and 30–31, standing still research subject.

Trial No.	**All locations**	
	Mean value, m	**Std. deviation, m**
T27	14,5	11,0
T28	11,6	8,0
T30	17,4	6,9
T31	4,7	2,8
All	**12,1**	**8,9**

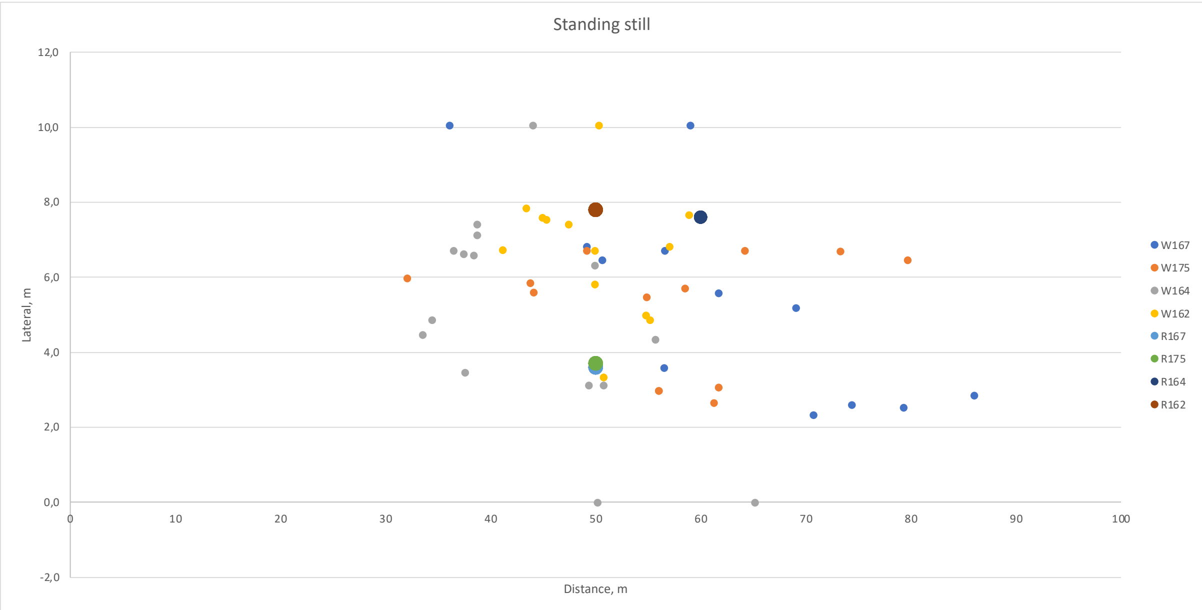

Figure 11. Trials 27–28 and 30–31 in the base case with hand-held device. The more heavily marked points indicate the place where the four research subjects stood still. Note that the lower heavily marked point is actually the location of two research subjects (two points in almost the same location).

It can be stated that there is still a significant variation between the real position and the location calculated by the Wi-Fi technology. The variation for an individual research subject is, however, quite large, where the person in trial 31 (subject 162) has a clearly better precision compared to the others who have both a higher average distance and a greater variation in calculated distances.

DISCUSSION

Using wireless technologies is today frequently used to track people for the purpose of surveying areas of interest, duration of stay at certain locations in buildings, etc. It has, however, not been widely explored for the purpose of tracking people in emergency situations and enabling an incident commander to use this information for tactical reasons. Before the experiment, the Wi-Fi technology was deemed as a promising technique to do so. Partly because people in general carry Wi-Fi enabled devices (mobile smart phones), and partly because the owner (at least ideally) does not have to do anything to allow the tracking given that Wi-Fi is enabled. Still, it must be emphasized that the technology is still in an early phase given the stated purpose and type of environment, and much is still needed to determine the characteristics for an optimal performance of the system.

The sample data collected during the experiment, which is presented in this paper, suggest that the Wi-Fi technology alone cannot be used to precisely assess or predict the position of an individual (or a group) in a tunnel. Possibly and expectedly, precision and accuracy may be improved with either even more capable access points or complementing technologies (such as Wi-Fi coupled with Bluetooth).

In the current experiment the selected access points provided a basic type of output data for analysis. It can be expected that with more high-end type of access points a better precision may be achieved. Localization is in the current analysis performed using a trilateration process meaning that the predicted point is determined using differences in distances between devices and access points. A triangulation procedure can in combination most likely enhance the precision, as triangulation uses angular information to predict a position. However, the currently used access points did not have this feature. Using better access points is of course preferred but has to be evaluated with respect to the increased cost if looking from a practical perspective.

Consequently, relying on the current technology in a research based application, i.e., to collect data on people movement to be used for modelling/predictive purposes, does not seem possible. In other words, the Wi-Fi technology alone is not accurate enough to be used for data collection with the purpose to establish, for example, relationships between movement speed and population densities, flow rates through components such as cross sectional emergency exits in tunnels, etc.

The above do, however, not mean that the technology cannot be used to provide value during the operation of a road or rail tunnel, as the need for accuracy is much lower. It must be emphasized that in these facilities, distances to safe locations are typically in the order of a couple to many hundreds of meters. Whereas the results of the experiment demonstrate a difference between the real and by the Wi-Fi technology assessed position around 20 m, this is still well within the expected distance between two emergency exits in a tunnel. The distance is higher than indicated in other studies, however, for different environments.

What is also important for the operator of a road and rail tunnel is the direction the people in the tunnel is moving. Looking at the results and in particular the difference between the predicted and the real positions in the experiment the first impression is that the predicted locations are scattered along the travel paths, cf. figure 8. But looking at the data more precisely there is a trend that the predicted locations follow the subject as he/she moves in the tunnel. This pattern will most likely be clearer in a larger scale, when the distance moved exceeds the range for an access point. Having a longer experimental travel distance the trend would be more obvious and, as mentioned, the distance between emergency exits in a real tunnel can be one magnitude higher.

All the results presented in the paper assumes there is an active communication between the device and the WLAN. This implies the user to have agreed to connect to the tunnel network. In many cases this cannot be expected and a passive connection between the network and the device is likely to be the normal situation. However, the difference in the current experiment conditions would be that the frequency of connections between the device and the network would be lower as the device then talks less often to the network in the passive mode. The ability to predict the specific position using the Wi-Fi technique would not change. But, having less information the ability to determine the precise location and direction of travel of an individual may be affected. Still, having more data points will provide a more certain prediction. The data available from the experiment will enable the analysis of passive versus active communication, hence this remain to be analyzed.

An initial analysis of group movement has been performed. Currently, the results look at the results from individual subject movement. However, there may be reason to investigate how the group's true positional average compares to the Wi-Fi-based equivalent. This would likely lead to a reduction in uncertainty providing a more precise prediction and need further investigations. This could be valuable information as based on reports from tunnel fire incidents, it is likely that people move in groups.

In the experiment, all the data treatment was done after the experiment was terminated, i.e., the predictions of the subjects' positions were not presented at the time of the experiment. A lot of trial data analyses had to be performed in order to find an analysis technique that provided a reasonable accuracy. This means that there is still room for further refinements of the analysis technique to a) find a better alignment between predicted and real positions, and b) to get the predictions presented with only a short delay between collection of data and presentation of locations. With such improvements it is reasonable to assume it will be possible to better determine in which direction people are moving and with what speed.

Given an emergency, such as a fire, in a road tunnel such information could thus be used by, for example, a traffic controller to direct the rescue services to a specific location in a parallel service tunnel and to provide information on how to use the forced ventilation to facilitate evacuation and rescue operations. Thus, enabling a prompt, efficient and safe intervention. With regard to the data collected, two aspects are positive in relation to this: 1) accuracy seem to improve when people are still (which they can be expected to be, particularly in the early events of an emergency), and; 2) accuracy does not seem to be particularly affected by the location of the device position (handheld or pocket).

FUTURE RESEARCH

The experiment shows that there are still room for providing a better understanding of the benefit of using Wi-Fi techniques for improving the base for decision for an incident commander in the case of a tunnel fire. The most important would be to find out how to improve the precision of the predicted position for a person carrying a mobile device. Initially there is a need to further clarify important aspects affecting the predictive position accuracy such as the difference between active and passive communication, localization algorithm/technique, etc. In the current experiment a few factors have been included but there is a need to get a better understanding of determining factors. In this effort a theoretical study using a variety of mobile phone devices should be included.

The overall improved accuracy would most likely be performed by using equipment having a better performance, but it can also need additional localization algorithms for predicting the position. Both are most likely to enhance the performance of the technique. In this effort also the use of triangulation as a predicting technique should be explored. The improved performance should also include the ability to determine the direction of movement and preferably strive to get as precise accuracy so the technique could be used for data collection of people movement for modelling purposes.

Another track for future research would be to explore combination of different wireless techniques to enhance the precision. Using both Wi-Fi and for example Bluetooth would be preferred. Using different technologies also put a focus on how to limit localization to relevant devices as the environment will most likely also include Wi-Fi-devices located in cars, tablets and computers.

As the technique to locate people is fairly new, the application of the technique from a practical point of view would also be needed to be investigated. The environment in a road or rail tunnel is very demanding for the electrical equipment is just one such problem needing to be solved. From a practical point of view also the problem of implementing the information gained into the current emergency procedures needs a clear identification of demands and requirements.

CONCLUSIONS

The experiment presented in this paper should be considered as an exploration of the Wi-Fi technology's ability to locate and track people in a tunnel environment from a practical point of view. It complements earlier, more theoretical studies, related to what should be technically possible with hands on data regarding what is achieved when deployed in a realistic setting. The results indicate that the ability to predict a position for an individual is generally around 20 m on average, or less. It has, furthermore, been shown that the possibility to determine a person's walking direction was fairly good even if the results are associated with a significant uncertainty.

The analysis of the data demonstrates that, in general, and in a set up similar to the test environment (given relatively many access points and active connection to the network), the technology may be used to improve tunnel safety as additional information about the location and approximate number of people between safe locations can be communicated to, e.g., fire rescue services. In the current form, the technology can, however, not replace traditional methods for data collection of people movement useful for research and modeling purposes. Nonetheless, and as indicated: there are room for future research which may put these conclusions in another perspective.

The findings presented in this paper are of value both when building new and upgrading existing tunnels. In both situations, the technology as such (Wi-Fi) will most likely be available in some form and, hence, it could possibly be used to track people both during normal operation and emergency situations. Knowing where people are, the sizes of groups, and in which direction they are moving is information that today cannot always be communicated via a CCTV-system, particularly not during fires. However, that information is highly important when a traffic commander is to, for example, decide on whether or not to activate a forced ventilation system, and in which direction to blow the smoke, etc. Particularly in bi-directional tunnels, as there is no predetermined "safe" exit direction. Obviously, there seems to be a great potential to upgrade tunnel safety in existing tunnels using relatively simple and inexpensive means based on new technology which may already be, or be planned to, installed.

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