Tunnel fire exercise in the Northern Link

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ABSTRACT

A full-scale exercise took place in the Northern Link tunnel network in Stockholm in September 2022. The exercise scenario was dynamic and consisted initially of a traffic incident involving three passengers cars. It was an escalating scenario and following the incident, one of the three cars was set-up to catch fire. At a later stage, the extent of the exercise increased further when two vehicles downstream of the initial incident were assumed to crash due to limited visibility. Emergency services taking part in the exercise included the fire brigade, police, the local road assistance unit and tunnel operators. The drill provided the emergency services a rare opportunity to practice in a tunnel environment. The exercise also provided opportunity for the tunnel owner to test their tunnel systems, including the fixed fire-fighting system (FFFS). The authors of this paper were responsible for planning, coordinating and leading the exercise. Within this paper, lessons learnt from both the perspective of emergency services taking part in the exercise and tunnel owner acting as observer are shared. The paper also aims to share insights and lessons learnt from a planning and conducting perspective. The drill stressed the need for future exercises. This was highlighted by several emergency service organizations. The exercise clearly shows that the majority of practicing organizations generally have low orientation skills within the tunnel network. In addition, the exercise highlighted that there is a need to practice how active safety systems, e.g. ventilation and FFFS, should be used. That this requires collaboration between rescue service personnel and control operators is clear.

KEYWORD: Tunnel fire, road tunnel, full-scale exercise, electric vehicle fire, emergency service response, fixed fire-fighting system, escalating incident scenario

INTRODUCTION

According to Swedish legislation, full scale tunnel exercises should be conducted at a minimum once every fourth year. With this background, a full-scale exercise took place in the Northern Link tunnel network in Stockholm in September 2022.

Due to the importance of a tunnel network with the magnitude of the Northern Link, emergency services rarely get to exercise within such environment. Hence, the exercise provides a rare possibility to practice and find improvement opportunities.

AIM

Aim of exercise

Except for meeting the legal requirement of recurring full-scale exercises, the aim of the exercise was to confirm that emergency services were able to carry out emergency operations within the tunnel.

The prospect was also to conduct a learning exercise regarding:

- Communication, coordination and coorperation between different emergency services.
- Processes and safety systems being used in the tunnel network including the FFFS.

In addition to above, each emergency service organizations had specific goals with the exercise not mentioned within this paper.

Aim of paper

The authors understand that each tunnel network, and tunnel owner is different, and that emergency service structures differ depending on location. However, many challenges regarding exercise are common within all parts of the world, highlighting the importance of sharing knowledge. As such, the paper herein aims to share lessons learnt both from the perspective of emergency services taking part in the exercise and from the tunnel owner acting as an observer. The paper also aims to share insights and lessons learnt from an exercise planning, and conducting, perspective.

NORTHERN LINK TUNNEL NETWORK

The Northern Link tunnel network is located in the north part of Stockholm, Sweden. The Northern Link consists of a road tunnel network with a combined total length of 13 kilometers. The longest tunnel is around 4 kilometers. Number of lanes differ from one to four. Traffic in all tunnels are unidirectional.

The network consists of two main tunnels and several shorter tunnels connecting to the main tunnels. Most of the tunnels were opened to the public in 2014. An overview of the tunnel network is shown in Figure 1.

Figure 1: Overview of the Northen Link tunnel network

The tunnel network is fitted with longitudinal ventilation, CCTV and a fixed fire-fighting system (FFFS). The longitudinal ventilation system consists of jet fans amounted to the ceiling of the tunnel. Brandskyddslaget AB took part in the design of the FFFS which consists of a deluge system. Sprinkler heads are of sidewall type. The FFFS for the Northerns Link project was designed with off-the-shelf products due to time constraints. The system is designed for a minimum water density of 5

mm/min (= 5 litres of water per square meter and minute). Each section of the FFFS covers about 80 metres of the tunnel with two sprinklers mounted "back-to-back" at 5 metre intervals.

The geometry of the tunnel network is complex and emergency services can enter the tunnel network from several tunnel openings. Based on emergency plans in place, during a fire within the tunnel network, emergency services are not to approach the fire through the incident bore. Instead, emergency personnel are supposed to reach the fire location through cross-passages between the tunnels.

The Northern Link is provided with emergency exits, i.e., cross-passages, every 150 meters. Tunnels are located on different elevations and the distance between tunnel bores is extensive in some parts of the network, including the parts around the fire incident. Some of the cross-passages are extensive and have an elevation difference of over 15 m.

PLANNED EXERCISE SCENARIO

The exercise focused, among other things, on the risks with electric vehicles and operation of the FFFS. This because the number of electric vehicles is increasing and there is a risk of re-ignition in electric vehicles due to the battery configuration. In addition, the FFFS was installed within the tunnel 2014, to allow for queuing but the emergency services ability of working with the system is rarely tested.

Active safety systems within the tunnel were available and functioning during the exercise. Activation of the FFFS and the emergency ventilation system and other emergency system is part of the existing response plan in case of a fire. Based on the actions of the emergency services and the tunnel operator, systems can therefore be activated and deactivated.

Expected overall sequence of events

Overall conditions for the scenario are described as follows:

- Evening time, same season as actual practice day (September).
- Initial accident – collision between an electric driven passenger car and two passenger cars with an internal combustion engine in the Galaxtunnel (northbound tunnel), see location in Figure 2. Length and height differences within the cross-passages is extensive in this part of the tunnel network. The tunnel consists of a single lane at the location of the initial accident.
- Cars involved within the accident block parts of the tunnel tube where the initial accident occurs.
- People are stuck in cars involved in the accident.
- A fire breaks out in one of the cars (electric vehicle).
- FFFS activates and impulse fans are activated since response plan "fire" is activated.
- Secondary accident – two more passenger cars collide downstream of the initial event.
- Two "maintenance workers" are stuck in operating space downstream of fire.

Figure 2: Fire location during exercise

Initial accident
The incident consists of a collision between an electric car and two passenger cars with the consequence of a fire in the electric car after a certain time. That one of the vehicles is an electric vehicle is evident if typing in the registration plate number in the database. People are trapped in the cars and when the emergency services arrive, several people show symptoms of exposure to hydrogen fluoride (HF), some of whom have serious symptoms.

The FFFS is activated, after control room personnel manually activates the fire emergency plan. The FFFS limits the spread of the fire but does not extinguish the fire completely. In the event of a fire in an electric car's battery pack, the car's body and the battery's casing prevent the FFFS from directly acting on the fire source and cooling the battery. A battery fire normally requires extensive amounts of water in order to reduce the temperature during a thermal runaway. Due to the risk of the electric car re-igniting, a re-ignition is also simulated during the exercise some time after the emergency services have extinguished the initial fire.

The initial accident occurs just downstream of cross-passage 3 (CP3), see Figure 3. Passengers in the electric vehicle start evacuating and no occupants remain within the vehicle during the exercise. Instead, it is simulated that the driver in the electric vehicle escapes to cross-passage 3. In each of the crashed cars that do not catch fire, there are two smoke-injured occupants left who cannot leave the vehicles on their own because they are trapped or have suffered neck/back injuries.

Secondary accident
Several cars are simulated to drive past the initial accident after the fire has started. Two of these cars collide downstream of cross-passage 4 (CP4). A location leading to passengers in the cars being exposed to smoke from the fire. In one of the cars involved in the secondary accident, three injured occupants are not able to leave the car themselves. Passengers in the other car evacuate towards cross-passage 4 and 5.

Maintenace workers in ancillary space downstream of fire
While the events described above occur, two contractors are simultaneously in the ancillary space between cross-passage 3 and cross-passage 4. The workers are conducting simple maintenance work and are not expected to evacuate towards the cross-passages.

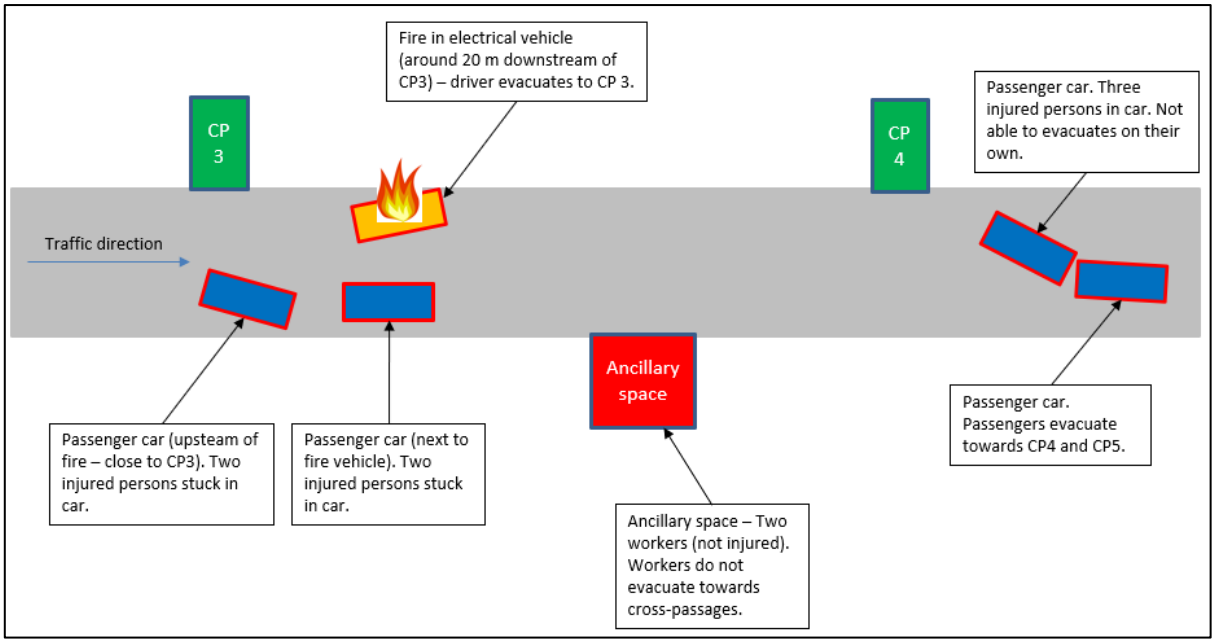

Figure 3: Setup of exercise scenario

PLANNING PROCESS

Exercise management group and documentation

The planning of the exercise started in 2021, around a year before the exercise was conducted. For the exercise, there was an exercise management group that consisted of representatives from the various actors who were supposed to participate in the exercise. The group met continuously in 2022 to plan and coordinate the exercise. In addition to these meetings, informal and formal meetings and discussions were held between the authors of this paper and responsible people within the organizations taking part in the exercise.

During the planning phase, the authors shared several documents with the exercise management group. This includes a general exercise plan describing the scenario along with practical management instructions for the exercise among other things. The document has been distributed in several revisions.

Management tabletop exercise

In May 2022, a theoretical management exercise was carried out as a "tabletop exercise". The exercise was carried out digitally with the authors being the drill leaders. The focus of the exercise was on the initial phase, as this part of the procedure was deemed not possible to practice fully during the full-scale exercise. During the tabletop exercise, it was played out how each organization was expected to act from the time the initial event occurs until the emergency services are underway at the scene of the accident. A specific purpose of the tabletop exercise was to find the strategic locations where resources needed to be located before the full-scale exercise started. This is due to the facility's complexity with several tunnels and a part of the tunnel network being open for public traffic during the night of the exercise.

Site visit

A site visit was conducted where representatives from all organizations who were supposed to participate in the exercise were given the opportunity to partake. The representatives got the opportunity to study the tunnel environment, study cross-passages and visualize the activation of the FFFS. During the site visit, the setup of the accident sites was also discussed. A complementary site visit was also carried out later with the aim of evaluating in more detail how the accident sites would be constructed during the full-scale exercise.

CONDUCTED EXERCISE

Organizations taking part

The following organizations took part in the full-scale exercise:

- Traffic Stockholm (TS) – the tunnel operator.
- SOS and ambulance – including emergency medical services (EMS) and emergency medical dispatchers.
- Police – including both field personnel and alarm center personnel.
- Fire brigade – including both field personnel and alarm center personnel.
- Local road assistance unit

All in all, slightly less than 100 people took part in the exercise. In addition to the personnel taking part in the exercise, several observers and spectators were witnessing the exercise. All spectators were located upstream of the fire incident.

Use of markers

During the exercise, several markers were used. Markers consisted of both real people and mannequins. The people who participated as damage markers were local volunteers. Markers being placed at the height of, or downstream, of the fire in the affected tunnel tube were mannequins. Markers placed upstream of the fire and in cross-passages were made up of real people. A total of nine real people and seven mannequins were used in the exercise.

Evening of exercise

Before the exercise started, all practitioner and exercise management gathered at a location close by the tunnel network. At this time, observers, spectators and people who would be acting as markers in the tunnel also gathered. Around 150 people were present at this time. At this gathering, the drill leader held a briefing regarding, among other things, the following:

- Basic principles for the practice where each practicing unit received an info card. The info cards indicated basic technical exercise information and described how the units were expected to act in the initial stage of the exercise. The start card indicated where the practicing unit would be located at the start of the exercise, based on the previous management tabletop exercise. Practicing units were assigned fictitious lead-up times to the starting position after being alerted. During this time, the unit was not allowed to leave its starting position but could communicate with other units and organizations. The info card also included basic safety rules for conducting the exercise.
- Safety briefing for people who would be in the tunnel environment during the exercise.
- Communication in the event of a real accident or in the need to interrupt exercise.

During this time, the accident sites within the tunnel were being prepared, see Figure 4 and Figure 5 below. The car used as an incident fire vehicle had covered side windows, shown in Figure 4, a closed tailgate and the front window removed. It was transported into the tunnel network at the evening of the exercise. The car was fully burnt in a safe environment the day before the exercise. In order to simplify transportation before and after the exercise and to protect the underlying roadway during the fire it was placed on a platform. After being fully burnt out the day before, the car was filled with wood pallets and fiberboard being used as fuel during the exercise.

In order to practice a scenario with a re-ignition, similar to an electric vehicle fire, fiberboard and Bengal torches were wrapped in plastic and placed under the incident car. The package was connected to a remote ignition mechanism allowing the exercise management to ignite the fire underneath the car after initial extinguishment of the fire inside of the car. The setup of the package used during the exercise is shown in Figure 6 and a test burn of a similar package setup is shown in Figure 7.

After the briefing, practicing units went to their respective starting locations and parts of the exercise command group drove to the prospective outer command location. Parts of the exercise management group were also already situated at command centres.

Figure 4: Preparation at initial accident (fire vehicle to the right).

Figure 5: Setup at secondary accident

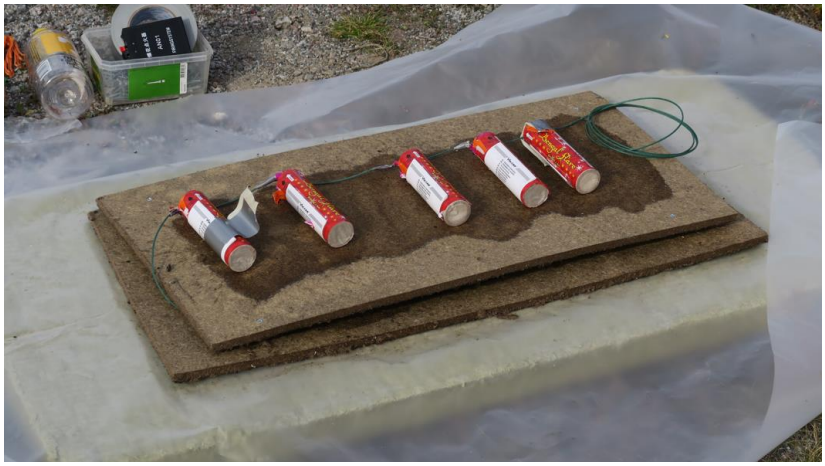

Figure 6: Re-ignition preparations (fiberboards and bengals wrapped in plastic). Photo Per Rohlén.

Figure 7: Test burn of similar package used during exercise. Photo Per Rohlén.

Conducted exercise

The start of the exercise was the initial accident. Thereafter the exercise followed the sequence of events shown in Table 1.

Table 1: Sequence of events

Event	Comment / sequence
Start (initial accident)	After all organizations announced that they were ready, the exercise was initiated by the drill leader notifying the local exercise leader at Traffic Stockholm (TS) to intiate the exercise. The start of the exercise was slightly delayed due to the time-consuming arrangement of the accident sites in the tunnel and the exercise started a few minutes after midnight. At the start of the exercise, control personnel at TS received an alarm about stationary traffic in the tunnel, meaning the exercise was started. Around 1 minute after the exercise started, the drill leader initiated for a fictive road user in the tunnel to also contact SOS.

Alerting based on traffic accident	Alerting of units (fire brigade, police, ambulance and road assistance) initially took place based on a traffic accident in the tunnel. After the drill leader received information confirming that units had been alerted from the police, ambulance and fire brigade, the drill leader informed personnel in the tunnel to start the fire. Shortly thereafter, a fire was started. This happened around 8 minutes after start of exercise.
Fire and activation of emergency plan "Fire"	Shortly after the fire was initiated (about 4 minutes), the "Fire" emergency plan was activated and the FFFS was activated. Initially, the wrong deluge zone was activated. Instead of the zone affected by the fire, the zone downstream of the fire was manually activated by personnel in the control room. The correct zone was activated about 6 minutes after the start of the fire. After the correct FFFS zone was activated, the temperature of the smoke appeared to decrease and the size of the flames decreased. However, the fire continued inside the car and flames were also visible outside the vehicle. It should be mentioned that as the sides of the car were intentionally covered, the fire was relatively shielded. After the fire was noted, all units were redirected to the adjacent tunnel bore which was not affected by the fire, as this is the emergency services' regular routines in case of a tunnel fire. Additional units from all emergency service organizations were alerted. It is noteworthy, however, that a unit from the fire brigade drove towards the fire-affected tunnel and requested the opening of the roadblock. The roadblock opening was denied by the exercise management based on the technical rules established before the exercise . During this time, calls were also staged from a fictitious person (maintenance worker) who was in the ancillary space between cross-passage 3 and cross-passage 4. The call was made to TS (tunnel operator).
Start of emergency operations at fire location	Units made their way from the non incident tunnel bore through the cross-passages to the incident tunnel bore. The first unit from the fire brigade started operating at the scene of the accident approximately 18 minutes after the start of the fire. The fire brigade initially began to work in an environment with the FFFS in operation. After arriving at the fire location, fire brigade personnel started extinguishing the fire. After the FFFS was turned off and the fire brigade had stopped extinguishing the fire it was still smouldering. The fire was thereafter left unattended for some time and started growing again without any interference of the exercise management personnel. Fire brigade personnel therefore had to perform additional extinguish. Once again, after extinguishing the fire the second time, the incident car was left unattended. In order to simulate an electric car fire, the exercise management therefore activated the secondary fire (underneath the car) and the intensity of the fire increased again. When noticed by the fire brigade personnel, the fire was extinguished a third time.
Outer command location setup	The outer command site was set up at a parking lot just north of one of the entrances to the tunnel network. First on the scene of the emergency services management vehicles were the fire brigade. Shortly afterwards, management

	vehicles from ambulance arrived, and a few minutes later, lead vehicles for the police arrived.
Secondary accident downstream of fire	Exercise management staged a call from evacuees to TS approximately 13 minutes after the start of fire. The caller stated that he was within cross-passage 4 and that he had crashed his car after driving past a burning car. TS then notified the fire brigade that the secondary accident site was downstream of the fire. The emergency services likely lost this information. Therefore, it took an extensive amount of time before the emergency services arrived at the secondary accident scene. After arriving at the secondary accident site, the rescue work continued without any major complications. In general, after having troubles with initial wayfinding, the communication and coordination at the accident sites was efficient among the emergency services.
End of exercise	The exercise was scheduled to end no later than 02:00. Due to the long intervention times, the decision was made to continue practice for another 15 minutes. After the end of the exercise, the drill leader held a short evaluation at the outer command location where each practicing organization got a chance to comment on what they had experienced and how they thought the exercise played out. A similar evaluation was held by the deputy drill leader at the site of the initial accident in the tunnel. After that, all practitioners left the area and cleaning was carried out.

Figure 8: Fire location, before activation of the FFFS

Figure 9: Fire location, after activation of the FFFS

RESULTS AND EVALUATION

In addition to the evaluations that were carried out directly after the end of the exercise, the various practicing organizations also had internal evaluations after the exercise. Furthermore, the exercise management group has met and jointly evaluated the exercise. Some main conclusions from these evaluations include:

- The place of the accidents within the tunnel were perceived as suitable due to the hardship with wayfinding within the network and difficulties to attack incident tunnel bore from adjacent tunnel bore.
- Full-scale exercises of this size are appreciated since it gives an opportunity to test personal protective equipment, vehicle functions and technical equipment in a realistic environment.
- It was perceived as difficult for units at the outer command post to obtain an overall picture of the situation in the tunnel.
- Orientability in the tunnel is generally low.
- It was difficult to understand for the rescue personnel and unclear to the emergency medical dispatchers that the car on fire was an electric vehicle.

Some conclusion from the writers regarding the tunnel systems also include the following:

- FFFS – As expected, the system was able to lower the size of the flames and decrease the temperature of the smoke. However, it was not able to fully extinguish the shielded car fire. This highlights the obstacles regarding shielded fires.
- Ventilation – Once the ventilation system was running, even not at full capacity, no backlayering was visualized. The capacity of the ventilation system is designed based on a much higher heat release rate than a single passenger car fire which also was evident during the exercise.

RECOMMENDATIONS

The execution of the exercise is considered to fulfill the overall purpose and the objectives. Based on the preparatory work performed and the exercise carried out, the following recommendations are given for future exercises, tunnel owners and for emergency personnel.

Exercise technique and preparation:

- Establish each organization's objectives early on.
- Determine the exercise scenario early in the planning process and determine that all stakeholders accept the scenario.
- If possible, determine early on what resources different organizations will provide. This includes both organizations taking part in the exercise and personnel acting as support.
- Clearly communicate expectations and critical points to key people. Follow up regarding expectations throughout the preparation phase.
- Make sure throughout the preparation process to follow up and ask control questions to responsible people. This is especially important the days before practice.
- It is important to ensure communication and operational reliability within the exercise management group during the exercise. Ensure that several means of communication are available.
- Ensure a margin for time to prepare accident sites at the time of the exercise. This to ensure that accident sites can be setup sufficiently and to minimize waiting time for practicing personnel.
- Ensure that escorting of units into the tunnel or tunnel network is well planned and prepared.
- To the greatest extent possible, allow practicing units to act with as little interference as possible from exercise management.

Exercise scenario for future exercises:

- The size of the exercise is recommendable also for exercises to come in order to practice communication and cooperation between organizations in an applicable way.
- As this exercise clearly shows that the majority of practicing organizations generally have low orientation skills within the tunnel network, it is obvious that orientation skills need to be practiced in the future as well.
- The exercise has highlighted that there is a need to practice how active systems, i.e. FFFS, must be used. That this requires collaboration between control room personnel and the rescue services is clear.
- In advance of a full scale exercises it is recommended to launch smallers drills and tabletop exercises in order to practise specific parts of an rescue operations. Examples are orientation drills in the specific tunnel systems and communication exercises between different rescue organisations.

Recommendations for emergency service, tunnel operators and tunnel owners:

- It was not clear to the tunnel operators nor the emergency services that the fire scenario was an electric car. This will obviously be easier to notice in a real fire event. However, the exercise highlights that there is a need for clarifying responsibilities of recognition and research regarding vehicles involved in accidents and fires.
- Due to the complexity of the tunnel network and high number of emergency units there is a clear risk that emergency personnel will try to access the incident tunnel bore. This was highlighted during the exercise when a fire brigade unit requested the opening of a roadblock into the incident tunnel. It is important that the tunnel operators are aware of this risk.
- Since the exercise clearly shows that the majority of practicing organizations generally have low orientation skills within the tunnel network, it is considered that, in addition to orientation skills needing to be practiced, better quality maps and drawings should be available for those concerned and that knowledge and routines for guidance to the correct places are available at the relevant control center.

- During a real fire event, a search operation should always be conducted downstream of where the fire occur. This could be done using CCTV or through search and rescue (SAR) activities. This procedure is already part of the fire brigades routines in case of a fire within the tunnel network.
- Differences in elevation between the tunnel bores sometimes require actions which may violate current routines due to carrying of equipment and people becoming demanding. This applies to both the collection point for injured occupants, as well as the fire brigade carrying extrication equipment and hose routing from the fire hydrant. Based on experience, possible new routines should be developed.
- An outer command site far from the scene of the accident entails a different way of working compared to most emergencies. The experiences should be taken into account for possible customized solutions. For example, the outer command site could have been in a control room as well as outside of the tunnel network.