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Prehospital medical management in Swedish road tunnel incidents

Johan Hylander

Department of Surgical and Perioperative Sciences
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To my colleagues in green

Table of Contents

Abstract

Background: The complexity of modern road tunnel systems may delay an efficient rescue effort. Capable decision-making is needed to limit time to care. The Swedish ambulance commander, responsible for the on-scene ambulance personnel, may lack education and experience from managing road tunnel incidents. Their competence is sometimes questioned by fellow emergency services commanders. Such marginalization may obscure the medical focus and give the ambulance commander a subservient role. The ambulance commander's role and lack of knowledge need to be explored and addressed to potentially improve their competence in managing road tunnel incidents.

Aim: The overall aim of this thesis was to explore the possibilities of strengthening the decision-making ability of ambulance commanders to create more efficient rescue efforts in road tunnel incidents.

Methods: In studies I and II, interviews were conducted with ambulance commanders (n=18) in Norway and Sweden concerning their experience in managing real and simulated road tunnel incidents. In study III, interviews were conducted with participants (n=19) from organizations that collaborates with the Swedish ambulance services in road tunnel incidents, about their opinions on how the ambulance commanders can improve their incident management. In study IV, an e-learning course was created based on the findings of studies I–III. The course influence on the ambulance commander's ability to make decisions in road tunnel incidents was tested through an intervention study (n=20) which contained two simulations of major road tunnel incidents.

Results: In study I, the requirement of familiarity with the tunnel system and involved organizations tasks were highlighted as important for the Norwegian ambulance commanders in their leadership role. In study II, the Swedish ambulance commanders described their leadership role as greater than that at the incident site, e.g., caring for their colleagues and being proactive, although having limited time allocated for these tasks. Findings from study III highlighted the importance of risk management and a shared terminology when responding to road tunnel incidents to avoid time-consuming misunderstandings. In study IV, the main finding was that none of the participants entered the dual-tube road tunnel correctly at the early stage of an incident. Secondly, the e-learning course did not significantly impact the ambulance commanders decision-making capabilities.

Conclusion: The resilience of ambulance services to road tunnel incidents requires a knowledgeable and decisive ambulance commander. Inter- and intraorganizational obstacles limit the ambulance commander to become familiar with the tunnel environment, generating ambiguous decision-making. Tailored assessment methods and educational material may improve the ambulance commander situational awareness. Findings also indicate that the ambulance services command structure may be less than optimal in its current form. A senior ambulance commander, hierarchically equal to corresponding emergency services command structures, could possibly strengthen prehospital medical management in unfamiliar and complex settings such as the currently studied.

Sammanfattning

Bakgrund: Våra vägtunnlar blir alltmer komplexa vilket kan leda till fördröjning av räddningsinsatsen. Skickliga beslut behöver fattas för att minska tiden till vård. Sjukvårdsledaren, ansvarig för ambulanspersonalen på skadeplatsen, anses sakna utbildning och erfarenhet från att leda skadehändelser i vägtunnlar. Deras kompetens ifrågasätts ibland av befäl från samverkande blåljusorganisationer. Denna typ av marginalisering kan leda till att det medicinska fokuset hamnar i skymundan och att sjukvårdsledaren får en underställd roll. Sjukvårdsledarens roll och kunskapsbrist behöver utforskas och adresseras för att potentiellt stärka deras kompetens att leda skadehändelser i vägtunnlar.

Syfte: Det övergripande syftet med denna avhandling var att undersöka möjligheterna att stärka sjukvårdsledarnas förmåga att fatta beslut, för att skapa mer effektiva sjukvårdsinsatser vid skadehändelser i vägtunnlar.

Metod: I studie I och II genomfördes intervjuer med sjukvårdsledare (n=18) i Norge och Sverige avseende deras erfarenheter av att leda verkliga och simulerade skadehändelser i vägtunnlar. I studie III genomfördes intervjuer med deltagare (n=19) från organisationer som samverkar med den svenska ambulanssjukvården vid skadehändelser i vägtunnlar avseende deras uppfattning om vad sjukvårdsledaren behöver för att förbättra sitt sätt att leda. I studie IV utvecklades och testades en internetbaserad utbildning som baserats på fynden i studie I—III. Kursens påverkan på sjukvårdsledarens förmåga att fatta beslut vid skadehändelser i vägtunnlar testade genom en interventionsstudie (n=20) som innefattande två simuleringar av stora skadehändelser i vägtunnlar.

Resultat: I studie I framkom det att förtrogenhet med tunnelsystemet och samverkande organisationers uppgifter var viktigt för de norska sjukvårdsledarna i deras ledarroll. I studie II beskriver svenska sjukvårdsledare ledarrollen som något som är mer omfattande än att enbart leda arbetet på skadeplatsen, som exempelvis att bry sig om sina kollegor och arbeta förbyggande, trots att de fick begränsad tid avsatt för dessa uppgifter. Det huvudsakliga fyndet i studie IV var att ingen av deltagarna beslutade att gå in i tunnelsystemet (som har separata tunnelrör) på rätt sätt i det inledande skedet av en skadehändelse. Ett av

de sekundära fynden var att den internetbaserade utbildningen inte hade en signifikant påverkan på sjukvårdsledarens förmåga att fatta beslut.

Slutsats: Ambulanssjukvårdens motståndskraft mot skadehändelser i vägtunnlar kräver en kunnig och beslutskapabel sjukvårdsledare. Intra- och interorganisatoriska hinder begränsar sjukvårdsledarens möjlighet att bli förtrogen med tunnelmiljön vilket leder till ambivalens i beslutsfattandet. Utvärderingsmetoder och utbildningsmaterial som är skräddarsydda efter sjukvårdsledarens behov kan förbättra sjukvårdsledarens situationsförståelse. Fynden indikerar även att ambulanssjukvårdens ledningsstruktur kanske inte är helt optimal i dess nuvarande form. En mer senior sjukvårdsledare, hierarkiskt likställd med samverkande blåljusorganisationers ledningsstruktur kan möjligtvis stärka sjukvårdsledningen i den främmande och komplexa miljö som har studerats i denna avhandling.

List of abbreviations

EMS	Emergency Medical Services
JESIP	British Joint Emergency Services Interoperability Programme
MCQ	Multiple Choice Question
METHANE	Major incident, Exact location, Type of incident, Hazards, Access/egress, Number of casualties, Emergency services
MIMMS	Major Incident Medical Management and Support
RTCC	Road Traffic Control Center

Definitions

A few common terms are used in this thesis and are hereby defined to clarify their meaning.

Ambulance commander: used in this thesis as an umbrella term to describe the senior ambulance commanders in the included papers (cf. medical on-scene commander, paper I and senior ambulance officer, paper II), to increase readability and avoid confusion regarding terminology.

E-learning: learning conducted via electronic media, especially on the internet (1).

Emergency medical services: services specially designed, staffed and equipped for the emergency care of patients (2).

Emergency services: the organizations that deal with incidents and urgent problems, such as fires, illness, or crime, e.g., fire and rescue services, ambulances, and police (3).

Golden Hour: a concept that emphasizes the urgency necessary for successful treatment of injured patients and is not intended to represent a fixed time period of 60 min (4).

Incident management: those processes, decisions and actions taken to resolve an emergency incident and support recovery that will be enable the community to return a "new normal" (5)

Major incident: any incident in which the location, number, severity, or type of live casualties requires extraordinary resources, e.g., a tunnel fire (6).

Major incident medical management and support (MIMMS): a course that provides an "all-hazard" approach to the major incident scene response and to dealing with multiple casualties, irrespective of the nature of the incident (6).

Swedish Transport Administration: a governmental organization responsible for the operation and maintenance of Sweden's roads and railways (7).

List of publications

This thesis is based on the following studies that are referred to by their Roman numerals in the text.

I. Hylander J, Saveman B-I, Björnstig U, and Gyllencreutz L. Prehospital management provided by Medical on-Scene Commanders in tunnel incidents in Oslo, Norway–an interview study. Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine, 2019;27:78.

II. Hylander J, Saveman B-I, Björnstig U, and Gyllencreutz L. Senior ambulance officers in Swedish emergency medical services: a qualitative study of perceptions and experiences of a new management role in challenging incidents, BMJ Open, 2020;10:e042072.

III. Hylander J, Saveman B-I, Björnstig U, Gyllencreutz L, and Westman A. Time efficiency factors in road tunnel rescue as perceived by Swedish operative personnel–an interview study. International Journal of Emergency Services, 2022;11(2):312-324.

IV. Hylander J, Gyllencreutz L, Haney M, and Westman A. Effect of an e-learning course on ambulance commander decision-making in road tunnel incidents: a web-based randomized trial. Manuscript.

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Preface

Before reading this thesis, the following information should be known about the author. As a registered nurse with specialist competence in prehospital care and a physician, he has

a) experience of prehospital care.
b) been educated in prehospital management leadership.
c) no practical experience of prehospital medical management in road tunnels.

The aforementioned factors may have influenced the author's preunderstanding during the analysis and interpretation of the results from the qualitative data collected in this thesis. However, the author's professional background is at the same time an advantage, as it has aided him in understanding the organization and unique challenges of the emergency medical services (EMS).

Introduction

08:52 AM, March 17, 2022, Stockholm, Sweden.

Morning in the Swedish capital. Rush hour. Traffic flows steadily through one of the city's road tunnels. Suddenly, the traffic comes to a halt. The driver of a recreational vehicle fails to react in time to the changed pace and crashes into an electrically powered vehicle in front of him. Consequently, the recreational vehicle begins to burn. Toxic smoke starts to fill the tunnel. The fire-suppressing systems of the tunnel are activated, both to buy time to respond for emergency services and to limit the fire from spreading. The road tunnel system closes for incoming traffic to limit the number of would-be casualties. Soon, the occupants of the recreational vehicle evacuate on foot, and the driver of the damaged electric vehicle manages to make a U-turn and drives out of the tunnel. Fire and rescue services arrive and extinguish the fire. The recreational vehicle is towed away, and the road tunnel re-opens for traffic.

This incident ended without personal injuries (8). Further, the involved individuals followed the first principle of road tunnel rescue: self-evacuation. However, not everyone can always evacuate. A notable example is the 1999 Mont Blanc Tunnel Fire, in which 39 people succumbed to poisonous smoke and fire. Since then, almost 25 years have passed. Longer and more complex road tunnels systems than the Mont Blanc Tunnel exists, and more are scheduled to be operational within the next decade. Further, with the ongoing "green" transition towards fossil-free emissions, alternative energy carriers have been introduced to the transportation sector. A transition that presents new risks in the management of road tunnel incidents.

To date, Sweden has been spared from major road tunnel incidents. However, the aforementioned and, under the circumstance, lucky, scenario may serve as an important reminder that road tunnel incidents do occur. It also spurs further reflection: Are agencies responding to road tunnel incidents in Sweden properly trained in managing such a daunting task as a major road tunnel fire? Moreover, do the emergency services commanders have the necessary knowledge and decision-making capabilities to facilitate a timely rescue effort? If not, what would they need to become better equipped? This thesis explores the role of EMS, particularly ambulance commanders, in rescue efforts into this rather unique environment.

Background

The following segments are presented in a particular order to present the complexity of the road tunnel environment. Knowing the environment is essential for understanding the potential number of injured and likely injuries. Furthermore, familiarity with the environment is necessary when planning suitable entry/egress routes, establishing casualty clearing points, or considering risks. Together, environmental knowledge and ambulance commanders' education are in this thesis seen as vital components in achieving situational awareness, which in turn is required to make informed decisions. Decisional aspects concerning other emergency organizations, from incident occurrence and dispatch to arrival at the incident scene, are also presented.

Road tunnel incidents and associated injury patterns

Man-made tunnels have been used differently across the centuries, for example as sewers (Mesopotamia and ancient Rome), in construction (Giza pyramids, Egypt), and to transport water (Eupalinos, Greece) (9–11). In the latter part of the industrial revolution and with the introduction of steam-powered locomotives, the use of tunnels changed towards a means to facilitate transportation of people and goods (12). Following the invention of automobiles, the need for specially designed road tunnels increased. This led to the construction of large road tunnel projects through the Alps, for example, the Mont Blanc and St. Gotthard Road tunnels (13). These tunnels are also infamous. In 1999, a truck transporting flour and margarine caught fire for unknown reasons in the Mont Blanc Road tunnel, killing 39 people (14–15). Two years later, two trucks (of which one was transporting tires) collided in the St. Gotthard Road tunnel, with the ensuing fire claiming 11 lives (13). Since the introduction of a European Union legislation on road tunnel safety, Europe has not seen road tunnel fires of a similar magnitude (16).

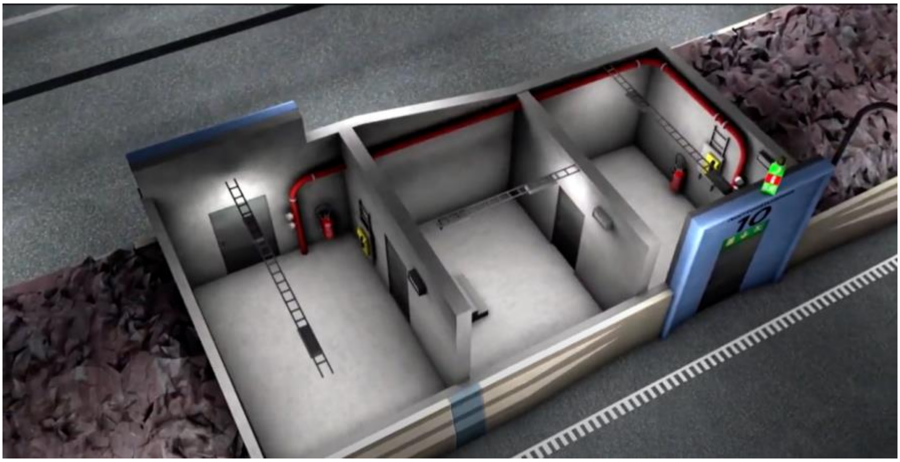
However, road tunnel fires remain a problem worldwide and continue to cause casualties. For example, during December 2022, at least two major road tunnel fires occurred in Asia, the urban expressway tunnel in Gwacheon, South Korea, and the rural Salang tunnel in Afghanistan, which caused 24 deaths and injured approximately 70 people (17,18). In a Nordic context, The Oslofjord Tunnel in Oslo has seen numerous fires, most of which involve heavy goods vehicles. In these fires, 32 people were hospitalized, including some with smoke inhalation injuries (19–21). Consequently, EMS should be prepared for major road tunnel incidents, such as fires or traffic crashes, particularly in rural areas, where distance is a factor regarding time to response and transport time.

Major road tunnel incidents have been less frequent than for open roads (22,23). However, major incidents in road tunnels may develop to more complex scenarios. Road tunnel structures may yield unique injury patterns, including complex trauma mechanisms and prolonged extraction times. This is illustrated by the Sierre coach crash in 2012, in which a bus crashed into the wall of the tunnel, close to an emergency layby. Emergency service personnel worked for 8 h to free the trapped and severely injured occupants. Of the 55 occupants, 28 (including 22 children), were killed (24).

Crashes may also occur in areas around tunnel portals (25–27). An example is the 1988 coach crash in Måbødalen, Norway, when a coach crashed into the tunnel portal. Of the 34 occupants (23 children and 11 adults), 12 children and three adults were killed (28). Mehri and colleagues (29) described a sort of visual impairment that affects drivers when adapting their eyesight when entering a road tunnel, known as the *black hole effect*, which may lead to an increased risk for incidents. The recent car crash in Torsbuås, Norway, is another interesting example. An ambulance responding to a vehicular fire outside a road tunnel was hit by a truck shortly after exiting the road tunnel, severely injuring a physician in the ambulance (30). Therefore, incidents are prone to occur even outside the actual road tunnel, which is important to consider when setting up casualty clearing points, or command posts.

Road tunnel egress routes and emergency exit layouts may also pose a risk for secondary incidents. Some dual-tube road tunnels have emergency exits that lead directly to the opposite tube (Image I). Escaping road tunnel users risk getting struck by oncoming traffic, resulting in another unique trauma mechanism. Findings from trauma register studies (31,32) indicate that pedestrians struck by motor vehicles presented with a high rate of severe injuries to the head, pelvis, thorax, and lower extremity, conditions that require timely access to definitive care at a hospital with surgical/orthopedic capabilities.

Image I. Layout of an emergency exit between two tunnel tubes in a Swedish dual-tube road tunnel. Illustration by the Swedish Transport Administration (33).



In addition to traumatic injuries, confined road tunnel structures may also yield several other time-critical injuries, for example poisoning from toxic fumes. The toxicity of smoke produced from road tunnel fires can be illustrated by the 2013 road tunnel fire in the Gudvanga Tunnel, Norway. A truck caught fire in the 11.4-km-long mono-tube tunnel, trapping 67 people, of whom 28 sustained acute smoke inhalation injuries during on-foot evacuation in the smoke-filled tunnel. This was partly caused by the tactic of reversing the fans in the tunnel to change the direction of smoke evacuation to facilitate firefighter access (34). One should be aware of the environment and assess the number of casualties before making an informed decision.

Subsea road tunnels have specific safety concerns, for example tunnel collapse and subsequent flooding. A notable example is the 2012 road tunnel fire that occurred in Skatestraum, Norway. A tank trailer was carrying 35,500 L of petrol, of which 16,500 L was loaded onto a trailer which broke off from the truck and crashed into the tunnel wall. The petrol ignited, and the resulting build-up of smoke and multiple explosions caused seawater to leak into the tunnel, and five of the 17 people in the road tunnel were treated for minor injuries (35,36). The incident report indicated that because of the quick and decisive action of road tunnel users, no fatalities occurred (35). In contrast, research findings indicate that road tunnel users are prone to staying in their vehicles or even filming the unfolding events (37,38). This indicates that people may behave irrationally during a time of crisis, which should be considered by ambulance commanders.

The aforementioned road tunnel systems primarily consist of mono and dual-tube constructions. Increasingly complex road tunnels are under construction, for example the subsea Rogfast Road Tunnel project, which will consist of multiple tunnel tubes in an intricate system of on/off ramps, roundabouts, and maintenance tunnels (Image II) upon its completion in the early 2030s, be the longest (26.7 km) and deepest (392 m) road tunnel systems in the world (39).

Image II: Overview of the Rogfast subsea road tunnel project, Stavanger, Norway. Source: Norwegian Public Roads Administration (40)

Similarly, in the Swedish capital Stockholm, the Stockholm bypass road tunnel project is ongoing. The finished road tunnel system will be 18-km-long and consist of 50-km tunnels in total (41). As such, emergency services should be familiar with road tunnel structures in their catchment areas. As illustrated by the 2022 full-scale exercise in the Northern Link Road tunnel network in Stockholm, Sweden, a lack of familiarity with the road tunnel system can lead to considerable loss of time to reach the incident site (42).

Time to treatment in road tunnel incidents

Time is an important factor in prehospital care and identifying potentially life-threatening conditions in polytraumatized (injuries involving multiple organs or systems) victims (4,6,43). Post-traumatic deaths follow a bimodal to trimodal distribution, with peaks at the initial minutes after impact, after a few hours, and following days/weeks (4,44). A timely and early rescue effort aims to lower these peaks. The optimum time to treatment is yet to be established (45–47). For the last four decades, the term "Golden Hour" has been a cornerstone of trauma care worldwide, which emphasizes prompt transport to hospitals for definitive care for persons with severe traumatic injuries (4,48).

The race against time may be hindered by prolonged extraction time, and people trapped in their vehicles after a crash have both a higher rate of traumatic injuries and higher mortality rate compared to people not trapped after a crash (cf. The Sierre bus crash) (24,48,49). Further, in a full-scale road tunnel exercise during the autumn of 2022, this "golden" period was not met, as it took some ambulances up to 2 h to reach the incident site where multiple vehicles had crashed (42). Road traffic collisions are a major cause of traumatic brain injuries worldwide (50). Intracranial bleeding is a common and serious consequence of traumatic brain injury (51–53). Owing to the enclosed structure of the human skull, intracranial bleeding has limited room to expand before the brain becomes compressed, which in turn affects the injured person's level of consciousness. Surgical intervention may be required to relieve the intracranial pressure (54). Therefore, a short time to definitive treatment (neurosurgical intervention) is warranted.

Post-traumatic bleeding has been described as the leading cause of preventable deaths in trauma victims (55,56). Early detection and rapid initiation of treatment is, therefore, favorable to potentially reverse further deterioration of the injured person's condition. Therefore, timely access to injured persons is desirable for initiating medical treatment, including intravenous or intraosseous access and fluid resuscitation. Further, early administration (intravenous or intramuscular) of tranexamic acid, which inhibits the enzymatic breakdown of blood clots, may improve survival in post-traumatic bleeding (57). Failure to initiate treatment may result in the deterioration of the injured person's condition, which is undesirable (58). Surgical intervention may be required for definitive treatment.

Traffic incidents are also a common cause of traumatic chest wall injury (59). Thoracic trauma may result in rib fractures, and multiple adjacent rib fractures may lead to dislodgment of a segment of ribs, called flailed chest, which can lead to severe pulmonary restrictions, prompting intubation and mechanical ventilation (60–62). Other pulmonary complications following trauma may include traumatic pneumothorax and hemothorax, which may require the placement of a chest tube to drain air or blood to improve ventilation and oxygenation (63).

A traffic incident may also evolve into a fire. Burning vehicles consume oxygen and produce asphyxiant gases (due to large amounts of plastic in modern vehicles and air condition liquid), such as carbon monoxide and hydrogen cyanide (64,65). Exposure to these gases, even at low levels, may result in unconsciousness and death from hypoxia (66). Further, exposure to airway irritants like hydrogen chloride and hydrogen fluoride may lead to disorientation and evacuation difficulties (34,67). These findings are important, as road traffic users with underlying medical conditions may have decreased walking speed, increasing the risk of getting caught in the smoke (68). Rapid assessment and initiation of prehospital treatment for smoke inhalation, including administration of antidotes and oxygen therapy, are necessary to reverse hypoxia (69,70).

Situational awareness

Situational awareness in this thesis is seen as a key component for effective decision-making related to knowledge of 1) incident management, 2) the dynamic and complex road tunnel environment, and 3) trauma mechanisms and asphyxiant gases.

Situational awareness may be defined as “knowing what is going on around us” (71). Situational awareness is also a key non-technical skill, i.e., an important skill for efficient decision-making in a time-sensitive setting, such as the aviation or military (71). Situational awareness has been further developed and implemented in the healthcare sector. It is used in both operating theatres and adapted for use by incident commanders (72,73).

In the field of disaster medicine and mass casualty incidents, Busby and Witucki-Brown (74) have widened the aspect of situational awareness to include trauma mechanisms and the dynamic and complex environment. This is in line with the importance of being familiar with the road tunnel environment and can set the environment into a greater perspective when making decisions, which further indicates the value of incorporating the environmental aspect of educational material concerning incident management.

Further, situational awareness may be divided into three levels according to Endsley and is the foundation for informed decision-making (75).

- Level I, perception of elements in the current situation–accurate information regarding the location of an incident and the number of injured people, e.g., the tunnel tube in which the incident has occurred.
- Level II, comprehension of the current situation–tries to create a holistic picture of the specific environment, e.g., taking the tunnel setting into account.
- Level III, projection of the current situation–the ability to plan further, e.g., planning on how to evacuate injured people in an appropriate manner.

Education aimed at enforcing levels I and II of situational awareness may pave the way for informed decision-making. As initial decisions may be made by inexperienced personnel from the first ambulance at the incident site, some prior knowledge of the road tunnel structure may be beneficial, as described above, to facilitate the identification of risks and injury outcomes and consider alternative options, such as where to appropriately establish a casualty clearing point.

Educational conditions for achieving situational awareness
The educational level of ambulance staff in Sweden ranges from emergency medical technicians to registered nurses with one (or several) 1-year sub-specialization in for example prehospital care or anesthesiology. Ambulances are staffed with one nurse, one emergency medical technician, or two nurses. All ambulance staff in Sweden can provide advanced life support. Regarding education in incident management, a mandatory 2-day course is conducted on the functions of the ambulance and medical commanders (76), with an emphasis on being able to report according to the METHANE-mnemonic: Major incident, Exact location, Type of incident, Hazards, Access/egress, Number of casualties, and Emergency services (6). After completing this course, the newly employed ambulance staff are expected to initiate command and control at every type of incident, from collisions between two cars to a major road tunnel fire. The actual course does not take the

environment of an incident into consideration and utilizes an "all-hazardous approach."

The use of protocols and guidelines is well established in the field of prehospital medicine to support the EMS personnel in decision-making, e.g., regarding transporting people with traumatic injuries to the correct level of care (77), when to activate massive transfusion protocols to alert the receiving trauma hospital of incoming trauma victims (78), or when to initiate/terminate cardiopulmonary resuscitation (79). More experienced paramedics have been reported to not adhere to guidelines to the same extent as their less experienced colleagues (80,81).

As highlighted earlier, there is no focus on the environment in the general education on incident management, only on generic guidelines and protocols. Correct guidelines and training are important for supporting EMS personnel in their decision-making process. For road tunnel rescue, there are no national guidelines or protocols for the Swedish EMS. This may affect the decision-making capability of ambulance commanders. Further, when the ambulance commanders attend road tunnel exercises, their management role has been questioned by their counterparts in other emergency services, and their lack of road tunnel knowledge has been described as a collaborative obstacle (82,83).

Bennet et al (84) indicated that EMS personnel's usage of skills such as situational awareness should be explored further. Situational awareness includes knowledge of the environment (road tunnel) and of incident management (to initiate command and control in every incident). To make proper decisions regarding road tunnel incidents, training, and knowledge of probable injuries (including triage, treatment, and transport) is also required. However, the most important aspect in achieving situational awareness seems to be the specific knowledge of the road tunnel environment.

Decision-making in road tunnel incidents

Incident detection and initial key decisions

When an incident, e.g., car crash or fire, occurs in a road tunnel, the road traffic control center (RTCC) is informed via an automated detection system. This system detects stationary vehicles, smoke, and fire. Further, road tunnel users may also use existing emergency phones (connected to the RTCC) or dial the national emergency number using a cell phone.

The automated system sends a signal, prompting the RTCC operator to view the camera footage of a specific tunnel section. The operator acts on the information presented and chooses the best course of action using different situational protocols and action plans for situational support. Important decisions, such as closing off a lane, or the entire tunnel system, are made as early as possible. When the appropriate action plan is activated, additional safety systems in the tunnel are started, e.g., information is displayed with flashing lights, prompting road tunnel users to change lanes or evacuate the tunnel. Simultaneously, radio messages with similar information are broadcasted via the car stereo of the road traffic users (85). These procedures are used to limit the number of road tunnel users that may become involved in the incidents. However, as shown in the 2011 Oslofjord (Norway) road tunnel fire, road traffic users may disregard signs and flashing lights, and still enter the tunnel system (86). The existing safety systems are used to facilitate self-evacuation and mitigate the consequences of an incident, rather than to prevent them.

Norway has three separate numbers for different emergency services (e.g., 113 for ambulance). If a road tunnel incident occurs, emergency dispatch centers collaborate (87). In Sweden, if road tunnel users call the national emergency number (112), they will be connected to the emergency dispatch center (88). The operator who receives the call begins to collect information to try to understand the extent of the incident. In a major incident, every caller has only a fractional description of the situation (89). Therefore, the operator must try to piece the incident together in a timely manner to initiate an incident response.

Simultaneously, to the initial call, another operator contacts emergency services, such as police and fire and rescue services, and dispatches EMS to the incident. The responding emergency services dispatches units in response. Depending on the width of the incident, the larger the incident, the more resources are allocated to the incident scene. Different organizations are involved in a road tunnel rescue effort, and efficiency is crucial, despite every organization having a set of goals and priorities, e.g., firefighting or evacuating road tunnel users, as Image III illustrates.

Image III. Positioning and tasks of the emergency services during a road tunnel fire. Illustration: Swedish Transport Administration (90)

In a tunnel incident, the responding emergency services commanders meet at a joint command post to plan the rescue effort. In a time-sensitive setting, decisions regarding medical management (sort, treat, and transport injured persons) should be combined with other collaborative decisions, and critical decisions should be made within 30 min of arrival (cf. The Golden Hour/Period) (6, 91,92). However, there is no uniform management structure among the emergency services in Sweden. The police and fire brigade have senior officers (cf. in Swedish "regional insatsledare") with added management training that can assume responsibility of their organization at the incident site from the first arriving unit (93). This counterpart is not nationally available within the Swedish EMS organization (91). This unsynchronized management structure may impact the efficiency of rescue efforts.

Ambulance commanders' roles in decision-making

As previously mentioned, road tunnels may yield a wide spectrum of time-sensitive injuries, and distinguishing those with the most critical injuries is important (94). The ambulance commander's competence (e.g., the ability to make appropriate decisions) is key to efficient rescue efforts, as the tunnel structure may hamper the EMS accessibility. Optimal decision-making is important to facilitate early access to the incident site. Considering the lack of available educational courses with explicit focus on the tunnel environment, ambulance commanders' competence may be inadequate.

Ambulance commanders must make decisions based on limited information, which may lead to them being mentally unprepared when arriving at the incident site (95). The initial and incomplete information is difficult to handle for EMS personnel and may result in misdirected thought processes and wrong conclusions (96). Simultaneously, the decision-making process is iterative in nature and should adapt to a consistently changing situation (80,97). As aforementioned, proper situational awareness is a key component of effective decision-making.

EMS use different systems worldwide to support incident management. Two systems are common. The incident command system, predominately used in the United States, and the major incident medical management and support (MIMMS) system developed in the United Kingdom. The MIMMS concept is based on seven components: command/control, safety (self, scene, survivor), communication, assessment, triage, treatment, and transport (6). Particularly, communication between emergency services is highlighted (98). The incident management system used by the Norwegian and Swedish EMS is based on MIMMS, with regional differences. In both countries, the first ambulance at the incident site assumes “command and control,” including assuming the roles of ambulance and medical commanders (6). The ambulance commander is responsible for communication and collaboration with police and fire and rescue services (a role that is usually held by the same person throughout the incident), and medical commander is responsible for sorting (triage) injured persons and overall responsibility for medical treatment (a role that may be assumed by a physician with adequate management training) (6,91).

Rationale

Thus, the ambulance commanders' competence in managing road tunnel incidents seems insufficient. Further exploration of their management role and creation of learning materials addressing the environmental challenges may improve situational awareness and increase decision-making capability, which in turn may facilitate access to those in dire need of help and potentially save lives.

Aim

The thesis aimed to explore the possibilities of strengthening the decision-making ability of ambulance commanders to create more efficient rescue efforts in road tunnel incidents. The specific aims of each study were as follows:

Study I: To shed light on the EMS experiences from real tunnel incidents described by the Oslo medical on-scene commanders.

Study II: To explore the perceptions and experiences of senior ambulance officers new management role in challenging incidents, such as those occurring in road tunnels.

Study III: To investigate how collaborative partners to the ambulance services perceive the rescue effort and to identify factors that may influence its efficiency, in order to create a basis for future reduction of time to definitive treatment and form a basis for future training programs.

Study IV: To evaluate whether participation in a purpose-built e-learning course affects ambulance commanders' abilities to make appropriate decisions in simulated road tunnel incidents.

Methods

Table I shows a summary of the studies included in this thesis.

Table I. Overview of studies I–IV.

Paper	Design	Respondents	Analysis	Outcome measures	Progress
I	Semi-structured interview study	n=6 participants, individual interviews	Qualitative content analysis	Understanding of how Norwegian ambulance commanders conducted incident management in road tunnels	Published 2019
II	Semi-structured interview study	n=12 participants, interviews conducted in pairs	Qualitative content analysis	Understanding of how Swedish ambulance commanders conducted incident management in road tunnels	Published 2020
III	Semi-structured interview study	n=19 participants: 17 participants in five FGD and two individual interviews	Qualitative content analysis	Identification of factors affecting the time and efficiency of road tunnel rescue efforts	Published 2022
IV	Intervention study	n=20 participants: 10 participants each in the control and intervention groups	Quantitative	The ambulance commander's ability to make adequate decisions by measuring choice of decision and time spent making each decision.	Manuscript

FGD: focus group discussions.

Design

In this thesis, both qualitative and quantitative designs were used. Studies I–III were conducted using an inductive methodology to identify ambulance commanders' requirements in managing road tunnel incidents, i.e., hypothesis generation. Study IV was deductive and built upon the findings of studies I–III. Thus, study IV was also a hypothesis test. In studies I–III, semi-structured interviews were analyzed using qualitative content analysis. Study IV was conducted using a quantitative approach, focusing on evaluating an educational program through an interventional study. Therefore, the methodology used in this thesis was mixed (both qualitative and quantitative) to better understand what ambulance commanders should do to make informed decisions in managing road tunnel incidents and to test if the collected data improves the decision-making ability of ambulance commanders in road tunnel incidents.

Study context

The studies included in this thesis were conducted in both Norway and Sweden despite the lack of major road tunnel incidents in Sweden to date. Nevertheless, the coach in the aforementioned 1988 crash in Måbødalen, Norway, transported Swedish school children. Consequently, Sweden has been indirectly affected by road tunnel incidents. Considering the numerous road tunnels in Norway, it was essential to start in Norway to gain a better understanding of the unique challenges that road tunnels had to offer.

As the first study was conducted in Norway, some differences and similarities should be clarified between the neighboring countries, Norway and Sweden. Norway has over 1,100 road tunnels including the (current) longest road tunnel in the world, the 24.5-km-long Laerdal Tunnel (99). In Norway, two types of tunnels are used: a mono-tube (the traffic runs both ways in the same tube) and a dual-tube (the traffic is unidirectional). However, mono-tube tunnels are more common. As such, the rescue effort is conducted differently, depending on the tunnel structure. Approximately 1% of the country's road tunnels (>500-m in length) are in the Oslo area (100). The longest of these is the Oslofjord Tunnel, a 7,300-m long, subsea, mono-tube tunnel with an average daily traffic of 9,000 vehicles (101,102).

When study I was conducted, around 1.3 million people were living in the catchment area of the Oslo EMS. The Oslo EMS had approximately 45 (34 during the night) ambulances, three air ambulances, and two physician-staffed ambulances distributed over 15 ambulance stations in and around Oslo. Further, a senior ambulance commander (in Norwegian “operativ leder”), a dedicated position for prehospital medical management, with the authority to lead the Oslo EMS, was available around the clock (103).

The Oslo EMS utilizes a variant of MIMMS when conducting incident management. The first arriving ambulance assumes the role of the ambulance commander (in Norwegian “Innsatsleder helse”). The role of the medical commander (in Norwegian “Medisinsk leder helse”) is assumed by a physician (with specialized education in incident management) upon arrival at the incident site (104). As aforementioned, the Oslo EMS have a dedicated unit for incident management, a single responder vehicle (with special markings) staffed with a paramedic with in-depth knowledge of incident management, a senior ambulance commander (in Norwegian “operativ leder”) who wears a distinct brassard and may assume the role of ambulance commander from the initial unit (104). Similar to the MIMMS concept, the police have an overall on-scene command, i.e., an overall responsibility at the incident site. In Sweden, this responsibility is shared among the emergency services commanders. The Norwegian and Swedish variants of the ambulance commander share some similarities but work differently. For example, the Norwegian ambulance commanders have more authority than their Swedish counterparts. Further, the Norwegian ambulance commanders meet regularly with their tactical counterparts in the police and fire and rescue services for collaborative discussions in a forum called “Operativt lederforum” (105).

Sweden has 25 road tunnels (majority of the dual-tube variant) governed by the Swedish Transport Administration (106). Only a few longer tunnels are of the mono-tube variant, for example, the Muskö tunnel, south of Stockholm (107).

The Swedish EMS also use a variant of MIMMS. This medical management system, Prehospital Management Leadership, is a 2-day compulsory course for the Swedish EMS personnel. This system is similar to the Norwegian system, where the first arriving ambulance assumes the roles of ambulance commander (in Swedish “sjukvårdsledare” and medical commander (in Swedish “medicinskt ansvarig”) (76,108). The equivalent of the Norwegian senior variant of the ambulance commander (operativ leder) does not exist in Sweden. However, an additional 2-day in-depth course of prehospital management leadership, is offered in some regions in Sweden to strengthen the incident management organization. This course has not been implemented at the national level (91). In some larger metropolitan areas in Sweden, the EMS have been influenced by the Norwegian management function and recently implemented a similar senior function (ambulance commander) to improve incident management. The ambulance commander can assume the role of the initial ambulance commander from the first arriving ambulance. This function of the ambulance commander was implemented in late 2018. The ambulance commander was dispatched to incidents where collaboration with other agencies was necessary, for example, major traffic incidents or road tunnel incidents.

Research methods

The qualitative method used in this thesis (studies I–III) takes a phenomenological approach, which may by defined as "study of structures of consciousness as experienced from the first-person point of view" (109). The qualitative methodology was used to understand the issues linked to ambulance commanders' way of handling and role in the incident management of road tunnel incidents. In this process, obstacles and facilitators of incident management can be identified. By interviewing participants, there is a possibility to gain a personal response. By using open-ended questions, the participants can more freely describe their take on a specific issue. In comparison, using quantitative methods like surveys may have a predefined theory and issues with limited space for an elaborate answer, and variation in tone (e.g., fear) is not apparent in the text, which may lead to misinterpretation.

Studies I–III were conducted using different interview techniques (e.g., individual- or group-based). Common to the interviews was the use of semi-structured interview guides, one for each study. Each interview guide had open-ended questions to spark discussions and vivid answers. The interview guides were created prior to the actual interviews and were not modified during the study. The interview guides consisted of questions like "Could you tell me about how you act at an incident site?" (study I); "How were joint decisions made in collaboration with other organizations?" (study II); or "How does your organization work with senior ambulances services officers?" or "If the ambulance service asks for assistance, how does your organization respond?" (study III). The questions were dimensioned towards the ambulance commanders' experiences (studies I and II) and what they required to improve their incident management skills (study III).

For studies I and II, the participants were asked to recollect a specific road tunnel incident to talk about. If the participants had no experience of road tunnel incidents, they were asked to focus on exercises in road tunnels or in similar environments (the participant chose if the event was similar or not). In study III, the participants focused on real road tunnel experiences and/or generic examples chosen by them. All participants were recruited using purposive sampling, from a population with already established sample criteria, for example ambulance commanders (110).

All the interviews were recorded and transcribed verbatim. The collected data were analyzed using the Qualitative Content Analysis method (111–113). The content analysis process is characterized by de-contextualization and re-contextualization of the transcribed text (113). An example of this process is presented in Table II. In the de-contextualization process, the text is broken down into smaller pieces, from the larger meaning unit (a sentence or paragraph of text relevant to the aim of the study) via a condensing process down to codes (112,113). In the re-contextualization phase of the method, all codes are sorted based on similarities or differences into subcategories and categories (111, 113). In this process, the co-researchers also read and discussed the upcoming subcategories and categories together as a way of limiting the effect of the preunderstanding. Using this non-linear process, the text is analyzed on manifest and descriptive levels (111,112). Further, the analysis may also involve interpretation of the de-contextualized text to "make the participants voices heard" (113) and restrain the preunderstanding from interfering in the analyses.

Table II. Example of the analysis process (raw data from study III).

Meaning unit	Code	Subcategory	Category
All kinds of triage systems are used. It could be a coding system using colors, such as red, yellow, and green. It could be stated plainly, or it could be a combination of both.	Different kinds of triage systems	Identifying those persons in need	Achieving situational awareness

Study I
Six individual interviews were conducted with Norwegian ambulance commanders in June 2018. Seven ambulance commanders were employed in the Oslo area at the time of interviews. Therefore, it was close to that of the total sample. All participants were men, trained as paramedics, and had 15–25 years of experience. The interviews were conducted in Norwegian and Swedish at the participants' workplaces and ranged from 30–85 min.

Study II
Originally, participants from two cities with several existing or planned road tunnels in their catchment area were to be included. However, owing to the lack of available participants, only one city was included in this study. Interviews were conducted with ambulance commanders in pairs with 12 of the 14 ambulance commanders employed in the region at the time, during 2019. Of the 12 ambulance commanders (one woman and 11 men), eight were specialist nurses (registered nurses with 1-year specialization in anesthesiology or prehospital emergency care), and four were emergency medical technicians. The ambulance commanders' work experience in the EMS ranged from 6–25 years. The interviews were conducted in Swedish and ranged from 55–74 min.

Study III
Personnel from fire and rescue services, police, infrastructure owners and emergency dispatch centers who had coordinating or managing roles in road tunnel incidents were included. Potential participants were recruited using email (which was obtained through contact with the station commander or a similar role). A total of 19 persons (five women and 14 men) participated, with their work experience ranging from 2–30 years, with a mean value of 12 years. Focus group interviews were conducted with each organization in 2020. The groups were originally

planned to include five participants from each organization. However, due to a lack of available personnel, the number of participants in each group ranged from two to four. The lack of available personnel may partly be explained by the start of summer vacations in Sweden. As the participating organization staff was limited during this period, it became increasingly difficult to recruit participants. Further, as participants were asked to participate without reimbursement, it may have contributed to the slow recruitment process.

In addition, individual interviews were conducted with two police officers, one from each region. An emergency dispatch center declined participation owing to a lack of available personnel. Most of the interviews were conducted online. The interviews were conducted in Swedish and ranged from 41–68 min.

Study IV

This study was designed as a complex intervention study. Complex studies include several components, delivery methods, and evaluation methods (114). For this study, an intervention course focusing on the tunnel environment, a control course, and two simulations were developed. The included participants (n=20) were divided into control and intervention groups. To measure the effect of the educational intervention, two follow-up (assessment) points were placed at one and six months after the participants had completed their respective courses. The actual study covered the evaluation of the e-learning course and its effect on the decision-making ability of ambulance commanders (Please see the Results section). In this section, the content and validation processes of the developed courses are presented in more detail.

Participants

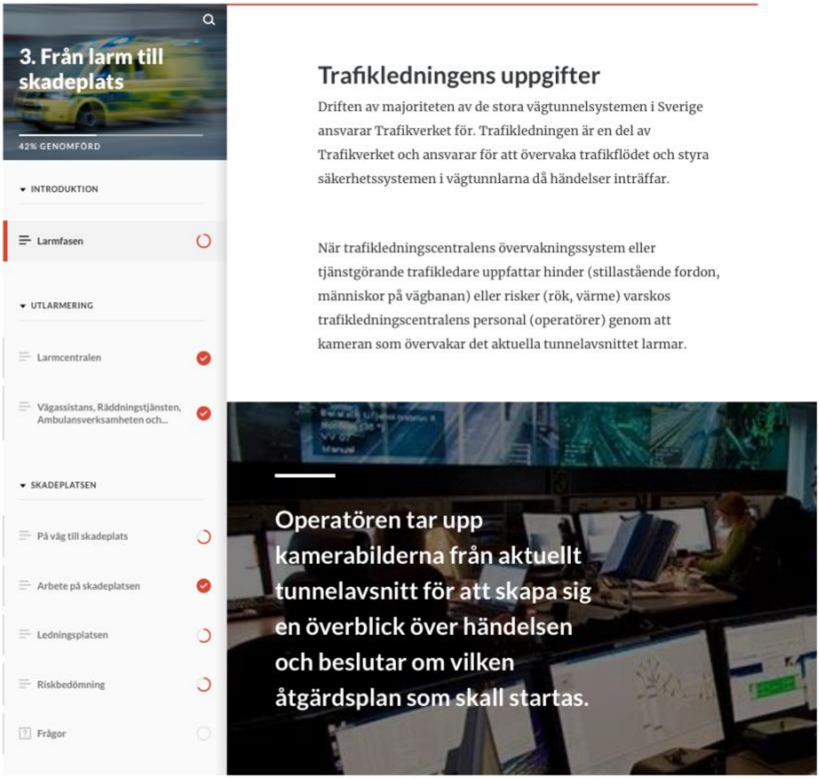
Participants who would assume the role of ambulance commanders in road tunnel incidents, who were employed as emergency medical technicians or registered nurses, who were not involved in the development of the e-learning course, and who did not have post-traumatic stress disorder or anxiety (diagnosed or self-perceived) from road tunnel incidents were included in this study.

Participants were recruited via e-mail invitations (“the weekly newsletter”) and short presentations at the organizations’ morning briefings. A total of 23 participants were recruited, 20 to be included in the study and three in reserve in case of dropout before the start of the intervention. Before the actual intervention started, three of the intended participants withdrew from the study (without stating any reason), and those three in reserve were included as participants. Therefore, 20 participants were included in this study. Participants were randomized into two groups using a random number generator (10 in each group). A randomization key with identification details was stored in a locked place.

E-learning course design (the intervention)
The course was linear in its design and modelled after William Haddon's method of dividing traffic incidents into three phases: pre-crash (modules I and II), crash (modules I and II), and post-crash (modules III–V) (115). This course was gamified, i.e., it included elements of gameplay to make the activity seem more interesting (116). Further, the course was designed according to the cognitive theory of multimedia learning (117–119). This theory for designing multimedia-based materials emphasizes a combination of video images, texts, and audio cues to facilitate learning (Image IV). The content of the e-learning course was drawn from findings of the relevant literature and participant requirements, identified in studies I–III.

Each module had quizzes of different formats, for example multiple choice questions (MCQ) or drag and drop. Participants were provided immediate feedback if they had completed the quiz or not. Completion of the questions in the quiz was required before the participant could advance to the next module.

Image IV. Example from the learning module III.



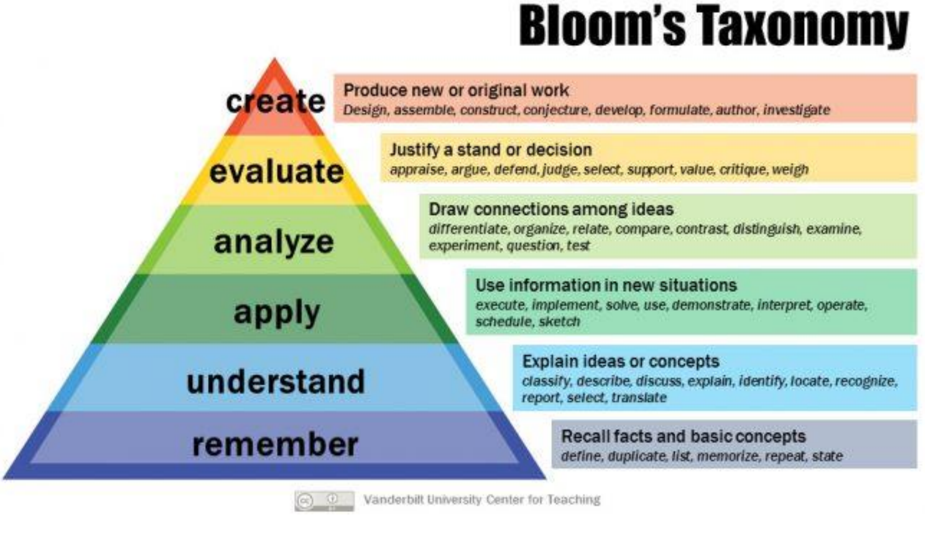
The course consisted of five modules with different learning materials:

1. Background and learning objectives.
2. Tunnel environment, focusing on the tunnel structure, safety installations and specific risks.
3. From dispatch to arrival at the incident site, covering each organization's tasks from the moment of dispatch until arrival.
4. Focal point of the rescue effort, focusing on the needs of those injured and covering methods of sorting the injured.
5. After the rescue efforts have been made, describing a mental model for reflection and emphasis on success and areas of improvement.

E-learning course content (the intervention)

The first module was constructed such that the participants could understand the aim of the e-learning course and objectives. The objectives were divided into overarching themes and individual objectives. The overarching themes were linked to the results of studies I–III. For example, in study I, the participants mentioned safety concern in road tunnel incidents, to meet this concern an objective was "more confident personnel." Another theme was "strengthen the decision-making capability," as the ambulance commander's decision-making had been described as uncertain (82). The individual objectives were organized according to the revised Bloom's taxonomy (120), a method to structure how participants handle knowledge; they must *understand*, *analyze,* and *evaluate* (Image V). These steps are relatively high up on the presented hierarchical structure. However, in a clinical setting, EMS personnel should understand (for example, signs and symptoms of smoke inhalation injury), analyze (differentiate symptoms from similar medical conditions and initiate treatment), and evaluate (evaluate if the treatment had the desired effect). The same applies to decision-making. An individual objective covered the different types of tunnel systems used in Sweden. The participant had to *understand* (how the rescue effort differed in different road tunnel systems), *analyze* (decision-making in different road tunnel systems), and *evaluate* (risks for the EMS personnel).

Image V. Bloom's revised taxonomy. Source: The Vanderbilt University Center for Teaching (120).



The second module was related to the tunnel structure. The participants were introduced to the mono and dual-tube tunnel systems in Sweden. The rescue efforts in these tunnel systems have important differences. For example, the mono-tube variant is uncommon and may lack otherwise common safety features such as fixed fire suppression systems (107). Further, the participants were provided with information concerning the existing security systems in the Swedish road tunnel systems, for example, ventilation, information signs, emergency lighting, and emergency exits (121).

In the third module, the participants were introduced to each organization's initial tasks during a road tunnel incident. The description of each organization was based on the data collected from studies I–III. The aim was to provide participants with a better understanding of how incidents are identified, and which measures the organizations take in the immediate response. This module also addressed the time from the alarm to the on-scene arrival. For example, possible planning including potentially using the tunnels monitoring system as cameras, the RTCC personnel's role in the early stages of the tunnel as closing lanes (redirecting traffic) or closing tubes (stopping further traffic to and on the incident site). This description was meant to provide participants with an understanding of how the initial stages of the incident response unfold. Further, it provided the participants a sense of where they could turn for questions, for example, concerning the actual moment of impact or which security measures should be taken. (RTCC operators may potentially answer these questions.). In a chapter called "risk assessment," the participants were introduced to various risks. For example, people's behavior when evacuating road tunnels (122). From the viewpoint of scene safety, the unaffected road tunnel tube is regarded as a safe environment. Some risks were identified in studies I–III, for example, loud noises in the road tunnel could interfere with the ability to communicate at the incident site.

The fourth module covered principles on how to identify which injured people are in most need of care, how each organization may contribute to helping those injured, and specific injuries that may arise from road tunnel incidents. The lack of a common system for sorting injured persons (triage) was identified in study III. Although, many triage systems are used worldwide, and none have been proven to be superior to the others, the triage Sieve was used in this module (123). In the Swedish EMS, different triage systems are used. This system is predominantly used in Europe, Australia, and the United Kingdom and focuses on the injured person's ability to walk and breathe, respiratory rate, and pulse rate (123,124). An incident scene triage system, for example, triage Sieve, may be used to coarsely sort the injured to find those in the most acute need of care at the incident site. However, when injured people are inside an ambulance, a secondary form of triage occurs. In Sweden, most emergency departments and EMS use the Rapid Emergency Triage and Treatment System (RETTS). Vital signs (respiratory rate, pulse rate, blood pressure, level of alertness, and temperature) are measured along with the chief complaint, which results in formulation of a priority (125–127). For this module, however, triage Sieve was chosen, as personnel from other organizations may have limited training in medical care. Finally, the participants (Norwegian ambulance commanders) from study I asked for an overview of each organization's tasks to increase their understanding of each other to facilitate collaboration and decision-making. To increase the overall knowledge of medical conditions and injures linked to the tunnel environment, learning materials addressing this were included. This knowledge may also affect the decision on where to transport the injured people. As the ambulance commander has an overall responsibility for the EMS at the incident site, identification of time-sensitive injuries is important to prioritize transport to an adequate hospital, for definitive care at, for example level-1 trauma hospitals or alert the hospital of injured that show signs of exposure to chemicals. Therefore, this module contained basic and advanced principles for the treatment of, for example, cyanide poisoning and smoke inhalation (69, 128).

The fifth and final module addressed how to learn and reflect on incidents. This element was included as participants in studies I–III asked for evolutional meetings to address the shortcomings and successes of the rescue effort. Further, some organizations (for example, the RTCC) established after-action reports from most tunnel incidents. The reports were then evaluated, and if necessary, changes were made to the incident plans. Similarly, fire and rescue services had evolutionary briefings after road tunnel incidents to discuss the rescue efforts adjacent to the event. However, this was not the case for the EMS. This module presented the pedagogical model, after-action review, originally developed by the United States military to reflect on incidents with an emphasis on areas of improvement and successes (129). The system has been adapted for use in fire and rescue services in the United States, Australia, Norway, and Sweden (130).

Course for the control group

The control course consisted of a 23-min pre-recorded lecture on basic incident management. The participants were introduced to the subject by a brief historical briefing of major incidents where incident management has been described as particularly important, for example, the 2011 bombing in Oslo and Utøya island shootings in Norway, and the 2017 truck attack in Stockholm, Sweden (131,132). The participants were reminded of the initial ambulance tasks at the incident site, e.g., assuming the roles of ambulance and medical commanders. The lecture focused on the ambulance commanders' tasks according to the MIMMS, with emphasis on the METHANE mnemonic, which is a part of the standard operating procedure for prehospital incident management in Sweden. The lecture did not include any tunnel-specific elements or procedures (6).

Simulations (for evaluating the interventional education)
Simulations were used to add a more realistic scenario than a paper-based examination. The simulations included text, images, audio, video, and animations, to add a sense of realism. Too much media presented at the same time may result in a strenuous situation for the participants, thereby counterproductive to learning (118). However, in a real clinical situation, many processes occur simultaneously. The "information overload" may mirror a real setting in the sense that participants will try to focus on solving a specific task.

Simulations were created using Microsoft Powerpoint (v. 16.71) and modified using software from Storyline 360 by Articulate Global. The two simulations followed the same linear, forward-moving only, and decision-based pathways. In the first slide, the participants were informed that they would act as ambulance commanders in a road tunnel incident. Next, they were provided with information on the ambient conditions at the time of the incident, traffic flow, in which tunnel and tunnel tube the incident had occurred, and the point of departure (a given ambulance station). Simultaneously, the participants were subjected to a pre-recorded audio file that mimicked a real dispatch call (including an alarm signal). The first question for the participants to decide the best course of action was, "What is the suitable route to the incident site?" After a few seconds, another slide containing the multiple choices was presented to the participants. This started a hidden timer, which stopped when the participant had chosen a decision and clicked "next" to go to the next question. Considering the linear design of simulations, the participants could not affect the development of the scenario. Between the questions and during the participants' progression through the scripted scenario, they were subjected to audio and visual cues with information of the unfolding event, such as radio calls with updated status reports, and video sequences from the road tunnel environment. Each participant decided on the best course of action at 15 independent decision points (Table III). The decisions were based on performance indicators developed by Gryth et al. (133), results from studies I–III, and focus group discussions among stakeholders (134).

Table III. Decision points used in both simulations.

Decision no.	Content of decision
I.	Suitable route to the incident site?
II.	Ask for more information?
III.	Location of assembly point?
IV.	Enter the road tunnel?
V.	Fist task upon arrival in the unaffected tube?
VI.	Content of your METHANE-report?
VII.	Second task after METHANE-report has been given?
VIII.	Risk assessment?
IX.	Where is it safe?
X.	Level of care? (shared decision with ambulance commander)
XI.	Guideline for response?
XII.	Location of casualty clearing point?
XIII.	Content of your second METHANE-report?
XIV.	Which organization/s are responsible for searching the tunnel?
XV.	Suitable egress route?

The scenario for the first simulation involved a crash between a bus and passenger car, which resulted in numerous casualties. No risk element was added. In the second scenario, a recreational vehicle and multiple vehicles collided. An added risk element was the liquefied petroleum gas cylinder in the recreational vehicle. The second scenario evolved into a tunnel fire at a later stage. These two scenarios were chosen based on the experience that most fatalities in tunnel incidents result from traffic crashes and fires (135).

Validation of courses and simulations

The control course was validated by five EMS personnel with extensive prehospital experience outside the study region, which was recruited using convenience sampling. The validators provided written feedback concerning the course content and the perceived usefulness to ambulance commanders. Feedback included for example, “I would like clearer structure, both regarding your lecture and regarding the METHANE mnemonic.” Their feedback was incorporated into the course.

The e-learning course content was validated by stakeholders (n=8) from organizations (fire and rescue services, EMS, emergency dispatch center, infrastructure owners, and police) active in road tunnel rescue efforts. Further, the course was reviewed in its entirety by two stakeholders with in-depth education in prehospital management and extensive experience as ambulance commanders. Examples of feedback were, “[On safety features in the tunnel] maybe describe the ventilation and camera surveillance systems in more detail” and “The importance of early access or arrival next to the patients should be emphasized.”

An internal pilot study was conducted using the developed e-learning course. The pilot testing personnel consisted of the five previously mentioned EMS personnel who also validated the control course. The course was evaluated based on logical progression, suitable content, overall design, and language. The design was “appealing” and the course was “easy to navigate.”

The simulations were validated separately by the previously mentioned five EMS personnel and two stakeholders. Comments included, “The time pressure was noticeable. I chose to read instead of listening… I lost focus…But the same goes for a real incident.” and “Good that the scenario is adapted to the actual city where the study is conducted. For me who has no knowledge of the city, it becomes a bit difficult.” When the feedback was received and adequate changes were made, the final version was established by the co-authors.

Study sequence
Participants were sent individual emails with a unique link to their allotted courses. Before they could access the course content, they had to fill out a short questionnaire concerning demographics, such as work experience and educational level. They had 2 weeks to complete their allotted course.

After approximately one month, the participants were sent an email containing a link and invitation to complete the first simulation, which had to be completed in a single session. Participants were provided with two weeks to complete the simulation. The participants' decision responses to the 15 independent questions and the time taken for making each decision was recorded.

Six months after completing their allotted course, the participants were sent an email containing a link and invitation to complete the second and final simulation. Data were recorded in the same way as described above. After the participants had finished the simulation, they were redirected to an evaluation form and asked to subjectively rate (decreased, unchanged, or increased) if their allotted course had influenced their ability to make decisions or impacted their sense of security to act as ambulance commanders in road tunnel incidents. Due to a limited response rate and despite two email reminders, the data collection period was extended by 1 week. This extension yielded five additional responses.

Outcome
The outcomes were defined as choosing the correct decisions when presented with MCQ, and the time spent making each decision. The first primary outcome was correct or incorrect responses to a question concerning the ambulance commander's decision to enter the road tunnel. The second primary outcome was the number of correct responses from the 15 different decision points. Time to decision registration was a secondary outcome.

Data collection, sample size and statistical analysis
The test scores and time per decision were collected and transferred to a spreadsheet file. Sample size calculations were based on the assumption that the control group would achieve a test score of 10% correct answers. Further, the intervention group was assumed to achieve 75% correct answers, yielding a 65% difference between groups. Eight participants in each group were required to identify a difference with a power of 0.8 and a two-tailed alpha of 0.05 (Pearson's chi-squared test). Thus, ten participants in each group (n=20) were recruited to cover potential dropouts after inclusion.

For the statistical analysis, the IBM Statistical Package for Social Sciences for Macintosh (v. 28) was used. To compare the grouped averages between the control and intervention groups, two-sample tests of proportions were used. Multivariate logistic regression was used to assess the potential association between the main outcome and participant factors, and the potential association between the secondary outcome and participant factors.

Methodological considerations

The field of qualitative research includes different methods of collecting (for example, observations, interviews, or focus groups) and analyzing data (111,136). The initial steps of analyzing the collected materials are similar across the various qualitative methods, for example coding and categorization.

Using the method of Qualitative Content Analysis when analyzing collected data, the abstraction level may vary from latent to manifest (113). If the degree of interpretation becomes too abstract, the trustworthiness of the study may be jeopardized (112). To counteract this, identified categories, subcategories, and codes were discussed among the co-authors (from different professional backgrounds), and the interpretation was kept on a reasonable level to limit the potential effect of the preunderstanding bias. Trustworthiness is also broken down into *credibility* (describing participants accurately), *dependability* (the data remains stable over time), *conformability* (congruence in the data), and *transferability* (findings applicable in other settings) (137). By accounting for the methodological process, for example, how participants were selected, how data were collected, and how the analysis was conducted, the reader may judge the quality and trustworthiness of the studies (138,139). From studies I–III, the participants were described in as much detail as possible (without jeopardizing participants' confidentiality), and the analytical process was exemplified. Moreover, quotes from participants were included in the results (studies I–III) to show internal consistency. Therefore, it is up to the reader to determine the transferability of the results.

A potential weakness of study I is the limited number of interviews. Six of the seven ambulance commanders were interviewed, comprising almost the entire sample. Additionally, each interview was rich in descriptions and similar things were mentioned by the interviewees, indicating that data saturation had been reached. As described by Johnson and colleagues (140), data saturation should cover both quantity (thick description) and quality (rich description). Further, as the interviews were conducted in both Swedish and Norwegian languages, there was risk of misunderstanding. Language barriers were bridged by asking interviewers or participants about expressions that were unknown or unclear.

Studies II and III included both small- (pairs) and larger-group interviews. This method was chosen to encourage discussion among the participants. For example, a response to an open-ended question may spark follow-up discussions with other participants, resulting in different viewpoints being shared. A potential disadvantage of this method is that some people may talk more and provide less time or space for those prone to be less talkative. However, this was not observed.

In study IV, the content of the e-learning course (intervention) was based on different factors identified through interviews with personnel who had operational or operative experience from road tunnel incidents. Following the current guidelines for designing complex interventions, stakeholders from different organizational backgrounds participated in the development and validation of the course content (114).

The simulations included fast-paced scenarios that did not adhere to multimedia learning principles (cf. strenuous [118]). However, a decision was made to retain the strenuous element, as it added a sense of realism. Considering the different inputs (images, video clips, etc.), there is a risk of information overload (too much information to be handled at once), which may have affected the outcome. The simulations were designed to mimic a real road tunnel situation.

The design of the simulations involved MCQ, which the participants had to answer, and each question consisted of one question with five options, including one correct answer. The control group's estimated correct answer rate was 10%, which was lower than that of chance (1/5=20%) alone. This slightly conservative estimation is based on findings from studies I and II, in which the ambulance commanders described the lack of knowledge of tunnel-specific risks, which should lead to a hesitant approach. Further, the control group lacked tunnel-specific education, potentially making it harder to answer the questions correctly. In summary, participants in the control group may have had a preunderstanding that led to a more hesitant approach.

MCQ as a method of assessment was deliberate. First, as the method is common in medical education, participants would be familiar with it. Second, essays or short-answer questions would demand a level of interpretation and subjective assessment by an assessor. Nevertheless, using MCQ has some limitations. The written MCQ were assessed by those (five EMS personnel and two ambulance commanders) involved in validating the course content and simulations. However, those who assessed the questions were not experts in writing or evaluating MCQ.

The questions were designed to test knowledge (cf. Bloom's revised taxonomy) relevant to the ambulance commanders' decision-making in a road tunnel incident. For example, the question "Which site is most suitable as a casualty clearing point?" (Image VI) was designed to measure the ambulance commander's knowledge of the actual tunnel system and ability to keep up with the evolving scenario. For example, they should be able to apply the knowledge that the opposite tunnel tube is safe because of the earlier decisions (made by others) to close the tunnel for incoming traffic. Moreover, the safety of the opposite tunnel tube had been addressed several times in the e-learning course. Further, the ambulance commander should also consider which of the tunnel tubes the incident occurred in. Therefore, the option of choosing the closest connecting tunnel (alternative E) as a casualty clearing point is incorrect, as both the material and the injured are transported through this connecting tunnel (cf. Image III). Furthermore, the response options may also be too similar, which may result in misunderstandings. In summary, this example question is difficult to answer at multiple levels. Simultaneously, this decision (to establish a suitable casualty clearing point) should be made by the ambulance commander, under stress, during a real tunnel incident.

Image VI. Example question from one of the simulations.

Ethical considerations

The studies in this thesis were conducted in accordance with the Declaration of Helsinki and the European Union legislation and The General Data Protection Regulation (141,142). Personal information such as the names of participants, remained confidential. These names were not included in the transcribed text. Further, as the number of participants was relatively small, quotes from participants were pseudonymized and assigned to a number for example "participant 5." This was done so that managers or colleagues would not be able to identify the individual participants. As study IV was designed as a randomized trial, additional ethical considerations were made. A randomization key containing the email address of each participant was created. The key was printed and stored in a locked filing cabinet with a digital backup copy according to the Umeå University guidelines.

The participants in study I were informed, both verbally and in writing, about the aim of the study and the possibility of declining participation and withdrawal at any time without providing a reason. Written informed consent was obtained from all the participants. The respondents had no dependency on the researchers. As the study was not covered by the Swedish Act concerning the Ethical Review of Research Involving Humans (143), approval was not deemed necessary.

Regarding studies II and III, ethical approval was obtained from the Swedish Ethical Review Authority (registrations number 2019-03611). For study IV, ethical approval was obtained from the Swedish Ethical Review Authority (registrations number 2021-04810). As this study examined the effects of two educational courses involving healthcare provider behavior in a simulation, a trial registration was not deemed necessary, in congruence with the recommendations of the *International Committee of Medical Journal Editors* (144). Concerning study IV, participants with post-traumatic stress disorder or anxiety (diagnosed or self-perceived) caused by road tunnels were not included in this study, since negative experiences may manifest as post-traumatic stress disorder or anxiety, which can deteriorate health. The participants were provided with an individual pseudonymized log on details to the educational platform (e.g., user69 and a password). Each e-mail that was sent to the participants (both as a group and individual) were sent using the "blind copy" feature in Microsoft Outlook (v. 16.72), so the participants could not see who the other participants were. The participants were also informed that they could withdraw from the study without risking repercussions of any kind. They were also provided with contact information of the author and the data-handling officer at the Umeå University if they had questions or liked to withdraw from participation. Participants were also asked to acknowledge if they provided consent to participate by ticking a box with the text "I consent to participate in this study" before taking their allotted courses.

Results

Study I resulted in increased knowledge of the medical management system used in Oslo, Norway. The use of ambulance commanders was described as a valuable improvement to the EMS in terms of both quality and efficiency, particularly in challenging contexts, such as tunnel incidents. Familiarity, or the slightly broader Norwegian term "kjennskap," with each other's organizations was also described as a valuable part of collaboration and made inter-agency communication easier. Ambulance commanders in Oslo talked about how they supported their colleagues at the incident site by coaching and providing instructions, as they had knowledge of different tunnels in the area. Some constraining factors were also found. For example, the ambulance commanders felt neglected when presenting ideas to their superiors. The participants also experienced a general lack of training among their personnel regarding tunnel incidents and wanted additional time for education and training, for example, using cancelled calls for tunnel incidents as training opportunities. They also asked for a special training course focusing on tunnel incident management. Participants, in particular, asked for learning materials regarding risk/safety issues with modern energy carriers.

Findings from study I, which were incorporated into the development of the e-learning course for study IV:

- Risk assessment, for example, fuel leakage or risk of explosion in busses powered by natural gas.
- Knowledge of the tunnel system, for example, location, type of tunnel system, and safety systems.
- Knowledge of each other's organizations and brief overview of each organization's responsibility at a road tunnel incident.
- Safety concerns, i.e., a tunnel environment is never "totally safe," EMS should act when the tunnel is "safe enough."

Study II provided an understanding of the medical management system used in Gothenburg, Sweden. The ambulance commanders described a holistic view on leadership that expanded beyond the incident site. For example, caring for their personnel's well-being, particularly after traumatic events, and having an overall encouraging role. The ambulance commanders also described some knowledge about risk objects, such as tunnels, and took a proactive role in drawing up response plans. The ambulance commanders talked about how they worked closely with their counterparts in fire and rescue services and the police. They also described the function of ambulance commanders as a valuable improvement to the EMS command structure during challenging incidents. However, they expressed some confusion regarding when the ambulance commander should assume command or support the initial command and control unit. National guidelines on the role of ambulance commanders was desired. Participants asked for learning material on safety issues in the tunnel, more specifically, how to determine if the tunnel was safe, as they did not want to risk their own or their colleague's well-being.

Findings from study II, which were incorporated into the development of the e-learning course for study IV:

- Risk assessment, for example, traffic flow and fire in e-vehicles.
- Lack of time to create proactive tactical plans.
- Unclear when the EMS could enter the tunnel, lack of consensus among commanders.
- Lacking in-depth knowledge of the tunnel structure.

Study III revealed how collaborative partners perceived factors that affected the time and efficiency of the rescue effort. The main finding was that participants asked for shared terminology when locating tunnel incidents to avoid time-consuming misunderstandings. Further, they highlighted that the lack of triage systems, training, and tactics could hamper rescue efforts. The results also provided insight into how the organizations involved in rescue efforts in road tunnel incidents operate. The participants specifically asked for in-depth education on how to identify the level of severity in injured persons and to assist if the emergency medical personnel were occupied with other tasks.

Findings from study III, which were incorporated into the development of the e-learning course for study IV:

- Use common terminology to avoid misunderstandings.
- Use tiered response, an appropriate number of resources to match the magnitude of the incident.
- Identify injured persons.
- Assess the risk, for example, leakage, smoke, or fuel type of the vehicles involved in the incident.
- Use a common method of sorting (triage) injured persons.

Study IV uncovered some aspects of the complex decision-making process of ambulance commanders in road tunnel incidents. The main finding was that none (0/20) of the participants correctly answered the question on how to enter the road tunnel system. This response was independent of participating in the e-learning or control courses. At the second assessment point, however, 1/7 (14%) of the control group and 2/8 (25%) of the intervention group chose to enter the road tunnel in the correct manner; however, this finding was not significant.

Moreover, the e-learning course participants did not perform better in any of the simulations compared to the control participants. Secondary results from the first assessment (1-month follow-up) indicated that an in-depth leadership course, female sex and practical experience were associated with more correct answers. Conversely, and slightly surprisingly, findings (albeit non-significant) from the secondary assessment (6-month follow-up) indicated that the in-depth leadership course was associated with poorer performance.

Despite the aforementioned findings, no participants reported that their respective courses had decreased their ability to make decisions or their overall confidence to act as commanders in road tunnel incidents.

Discussion

Overall discussion

This thesis aimed to explore the possibilities of strengthening the decision-making ability of the ambulance commander to create a more efficient rescue effort concerning road tunnel incidents. The identified possibilities can be viewed from different perspectives. First, from a *hierarchical* perspective, the ambulance commander's function in the current emergency medical system may be suboptimal in rescue efforts in complex environments, such as road tunnels. Findings from exploring the role of ambulance commanders in road tunnel incidents in both Norway and Sweden (studies I and II) indicate a gap in the EMS hierarchical structure compared with police and fire and rescue services. This skewed management level among organizations may put the EMS in an unfavorable position. This has also been highlighted by others in that the decision-making capabilities of the ambulance commander may not be considered equal in comparison to fellow emergency services commanders (82). Further analysis of the EMS command structure in relation to decision-making in complex environments is warranted. Would a command structure hierarchically equal to that of senior officers of both police and fire and rescue services be a possible solution for more fluent sharing of information? A possible starting point may be initiating collegial discussions among emergency services commanders, by using forums similar to the ones currently in use in Norway.

Second, from an *educational* perspective, the current educational system in prehospital medical management for EMS personnel is based on a 2-day long course, which takes an "all-hazard" approach. As described in this thesis, the environment (road tunnel) may affect both the risk assessment and injury patterns. The respondents asked for more knowledge concerning road tunnels and adhered risks. Therefore, it is important to consider both the setting and environment when making decisions. For the regional EMS, having access to learning material on "risk objects" in their catchment area may be beneficial, to lay the foundation for achieving situational awareness and making relevant decisions.

Third, from a *preparedness* perspective, the EMS might benefit from having commanders work more proactively. The role of the ambulance commander was described by the participants as going beyond the actual incident site. One aspect is working with preparedness in the sense of making an inventory of potential risk objects and formulating incident plans, for example, concerning complex road tunnels.

Fourth, merging the three perspectives may form the ability to better cope with complex incidents in road tunnels, in essence, creating a *resilient* organization. Organizational resilience may be defined as "the ability of an organization to anticipate, prepare for, respond, and adapt to incremental change and sudden disruptions in order to survive and prosper" (145). Exploring these perspectives would be beneficial to further identify intra-organizational facilitators and barriers towards a transition to a more adaptive EMS organization.

Study I

Here, the role of Norwegian ambulance commanders in road tunnel incidents was explored. The ambulance commanders described that they had "*Kjennskap*" (knowledge) of their own as well as their collaborating organizations structure, the tunnel environment, the geographical challenges in their catchment area, and their fellow incident commanders. This understanding provided them with a level of situational awareness that they could use to make informed decisions. Having this information (and knowledge) in the road tunnel response did, according to the respondents, ease potential friction among the incident commanders and could improve collaboration. Another aspect of easing the potential friction was the Norwegian way of expanding the aspect of "*Kjennskap*" in creating a feeling of camaraderie and, by extension, increase the level of trust and security to improve collaboration among the incident commanders. This finding has also been reported in other studies (146). Camaraderie may lead to an increased willingness to help fellow colleagues (146) and vice versa. A lack of trust may limit the will to collaborate (147). Thus, increased trust among incident commanders may be important for the ambulance commander's role to be fulfilled at the command post. These findings also support the idea that the ambulance commander's role is greater than it is at the incident site.

The participants emphasized the need for a more alert and offensive EMS for timely rescue efforts. In this aspect, knowledge of risks and the ability to mitigate these risks is essential. The Norwegian ambulance commander had a saying, “safe enough,” which emphasized that to minimize time to treatment, the EMS personnel should gain entry to the incident site when it is safe enough and not entirely safe, as the latter may result in unnecessary delays in treatment. This aspect has been further explored by Hollnagel, who advocated an “acceptable risk” approach, being aware of risks, and making decisions accordingly (148).

Study II

Here, the role of ambulance commanders in Swedish road tunnel incidents was explored. The initial ambulance personnel at the incident site were described as uncertain and in need of support from the ambulance commanders. Reviews from major incidents identify poor coordination, inexperience, and failure to follow existing procedures as reasons for unwanted outcomes (149–151). The mentoring, educational, and supportive roles of the ambulance commanders may be a way to keep EMS personnel up-to-date. For example, in Finland, paramedic field supervisors are used to strengthen the EMS command structure, and findings indicate that the coordinating role of paramedic field supervisors is important in hazardous situations (152). However, the lack of a mandate and national guidelines for Swedish ambulance commanders may obstruct the development of the ambulance commander’s role and, by extension, impact the effectiveness of prehospital medical management in road tunnel incidents.

The role of the ambulance commander additionally included a knowledgeable and a proactive role, although lack of allocated time was described as a limiting factor in becoming more proactive. In major incidents involving hazardous materials, response planning and regular exercises have been described as particularly important for an efficient medical response (153). The lack of available time to develop plans may negatively impact the possibility of achieving situational awareness, as the ambulance commander would have to start from the beginning, every time. A potential reason why the ambulance commander’s proactive role is not prioritized in the modern EMS may have a historical explanation. The EMS have gone from an organization often being co-located with the fire and rescue service to a stand-alone organization where the primary focus is production (i.e., regular ambulance duties, including advanced medical interventions) (154,155). This dissociation towards “production” may also be a partial explanation as to why the EMS seldom participate in tunnel exercises and lack knowledge of managing road tunnel incidents, as reported by others (83). Despite this, the regional EMS have taken a more proactive role in planning rescue efforts in complex underground structures such as railway tunnels since this study was conducted (personal communication, Christian Holm, 2021).

Study III

Here, collaborative partners' views on the EMS were explored to gain more knowledge regarding joint rescue efforts. The use of a common nomenclature was emphasized to avoid time-consuming misunderstandings and to facilitate communication among the involved organizations. Using different nomenclature may lead to poor situational awareness. Poor communication is a common conclusion in evaluations of major incidents (156). A constant flow of information may also make it difficult for the ambulance commander to identify critical information (cf. information overload), which reduces the possibility of situational awareness (157). Slater proposed an electronic real-time digital template for gathering and sharing information (158). Web-based applications developed by the British Joint Emergency Services Interoperability Programme (JESIP) already exist, facilitating the dispersion of initial information from the incident site, using the MIMMS principles (159). The JESIP was created in the wake of the 2005 London bombings to facilitate the achievement of shared situational awareness among responding emergency services to ease decision-making (158). A joint reporting structure, such as JESIP for emergency services and other actors, does not exist in Sweden. Shared situational awareness is also important for maintaining information quality among the different actors in disaster management (160). An application that covers tunnel-specific elements may be beneficial as an aide-memoir to achieve situational awareness and facilitate decision-making among the ambulance commanders and information sharing with fellow emergency service commanders in real time.

The participants described a lack of joint evaluation, and that it limited the possibilities to reflect and learn as a group. Retrospective studies on major incidents may focus on "what went wrong" and the positive aspects may be overlooked (148). By routinely drawing up after-action reports, even from minor road tunnel incidents, identifying areas of improvement and emphasizing the positive aspects may be important. In comparison, RTCCs, fire and rescue service, and police regularly write reports on incidents to identify areas of improvement. The Swedish EMS do not routinely write after-action reports on road tunnel incidents. This ought to be a task for a potential ambulance commander in the EMS to regularly follow-up incidents. By scrutinizing road tunnel incidents and writing constructive reports, ambulance commanders may identify potential knowledge gaps or risks that could be incorporated into guidelines for future responses. Internationally, structured reporting of major incidents by the EMS is lacking (156). The lack of validated templates for reporting prehospital incident management led the authors in their study to launch their own web-based reporting services, majorincidentreporting.net (156,161). A national registry for evaluating prehospital care in Sweden is under construction (162). The implementation of a registry on major incidents in Sweden may be used, for example, for structured follow-up by the EMS (after-action reviews), research (evaluation of incidents), or education (tabletop exercises and constructive discussions).

Study IV

Here, the effect of an e-learning course on ambulance commanders' decision-making in simulated road tunnel incidents was examined, and it was found that none of the participants correctly answered the question to enter the road tunnel system at the first assessment point. This is an interesting example of the concept of acceptable risk as described above. Being aware of risks and making decisions accordingly are part of dealing with risks. As this result shows, an absolute-safety policy may result in a retracted approach to decision-making at the sharp end (i.e., when the ambulance commander has to decide whether to enter/not enter the road tunnel), which may result in a delay of vital treatment. Further, a more active role does not advocate recklessness, but an increased awareness of risks associated with the tunnel environment and how these may be mitigated. For example, the decision to choose to enter the unaffected tunnel tube in the case of a fire in a recreational vehicle (cf. the scenario in simulation II) to gain access via the nearest connecting tunnel will move the ambulance commander closer to the actual incident site and not subject the commander to major risks (personal communication Ulf Lundström, 2023).

This study evaluated the choices made by ambulance commanders. It gave an understanding of "how," not of "why." The decision-making process remains unexplored. An in-depth study, not included in this thesis, with five (5/20) of the ambulance commanders who participated in study IV was conducted to gain an understanding of the decision-making process. Preliminary findings indicate that ambulance commanders wait for other incident commanders to decide for them, i.e., they take a subordinate role. Further, participants asked for detailed knowledge of specific tunnels, as ongoing renovations of the regional tunnel systems made it difficult for the ambulance commanders to remain up-to-date. These findings support the need for ambulance commanders to be “in the loop” regarding planned road tunnel renovations such that they can plan for access and egress routes in the case of an incident.

The educational value of the e-learning course (in its current form) may be limited. The reliability of the course may have been influenced by, for example, participants’ fatigue or stress levels. Another important aspect is how ambulance commanders’ decision-making abilities were assessed. MCQs were used for participants’ convenience, as the ambulance commanders were familiar with the concept because MCQs are commonly used in medical education, and that the participants would not have to provide lengthy written answers. However, the validation process of the MCQ may benefit from consulting expertise in formatting and assessing questions and answers. Further, as the method did not assess the cognitive process, a complementary method using interactive and oral assessments may be needed to measure competence. An example of this method is being implemented in medical education, where students are being examined by an assessor on competence, both involving decision-making, such as running a ward, and technical skills, such as administering a vaccine (163).

The results indicate the need for further development of the course. Current guidelines for developing and reporting complex interventions highlight the importance of assessing efficacy (Were the intended outcomes produced?) and effectiveness (Were the intended outcomes produced in the real world?) (114). The outcome in a broader sense was to influence the ambulance commander’s behavior. Education was used to gain situational awareness and assess tunnel-specific risk factors to make them choose to enter the road tunnel. This was not achieved in the first simulation, because no one chose to enter the road tunnel. However, some participants chose to enter the road tunnel during the second simulation. Exploring if this change in behavior was credited to the simulation or part of a reflective thinking is important. As identified by others, simulation-based education may provide learners with new competences (164). However, the learning process is individual. It also raises another question: are the available courses the ultimate way to educate commanders? Anecdotally, if educational courses do not meet the participant’s standards, it may be described as “unrealistic” with a further explanation on the nature of the exercise (cf. Swedish “övningstekniskt”). A potential challenge in creating future educational interventions is constructing simulations that are realistic enough to meet the participants’ demands. Further research is required in this field to prepare ambulance commanders for rare major incidents.

Conclusion

The resilience of EMS to road tunnel incidents requires a knowledgeable and decisive ambulance commander. However, inter- and intraorganizational obstacles limit the possibilities for the ambulance commanders to become familiar with the tunnel environment, collaborative organizations, and unique tunnel risks. Consequently, the ability for decisive action may be negatively affected and result in ambiguous decision-making. Additionally, assessments methods, educational material, and exercises tailored to the ambulance commanders' needs may improve their ability to assess a situation, and immersive simulations may be used to identify particularly difficult or time-consuming decisions. Findings also indicate that the EMS command structure may be less than optimal in its current form. A senior ambulance commander (cf. senior ambulance officer [6], suggested Swedish title: "Sjukvårdsinsatschef"), hierarchically equal to corresponding emergency services command structures, could possibly strengthen the prehospital medical management system in unfamiliar and complex settings such as the currently studied.

Clinical implications

The role of the ambulance commander in a road tunnel environment is multi-layered and may not fit all EMS personnel, for various reasons. A revision of the prehospital management system in extreme environments such as road tunnels is warranted. Unsynchronized management levels among the emergency services may be addressed using the following proposed additions to the Swedish prehospital medical management structure:

- Implementation of a senior function for incident management into the Swedish EMS (senior ambulance commander - suggested Swedish title: "Sjukvårdsinsatschef"). A role hierarchically equal to regional incident commanders within the fire and rescue services and police. This senior ambulance commander can act as a mentor and support the initial ambulance commander.

- Strengthen this senior function with in-depth education in decision-making, leadership, and management and allocate time to follow regional incident commanders from the fire and rescue services and police to gain insight in their way of managing incidents. To create a sense of "kjennskap."

- Implementation of tactical plans for regional risk objects, such as road tunnels, which regular EMS personnel can use to create a preunderstanding of the tunnel environment. This would also create a foundation on which informed decisions may be based.

- The senior ambulance commander role should also include administrative tasks such as creating after-action reports for reflection and continuous personal improvement.

- Establish regional fora for the emergency services to create an environment for fruitful discussions on incident management and interpersonal knowledge. A similar system has been described as important for the Oslo EMS, and a similar system already exists in Gothenburg. These fora may be beneficial for proactive discussions concerning complex settings other than road tunnels.

Future directions

As previously mentioned, in the coming decade, long, deep, and complex road tunnel systems will be developed worldwide. What about the more distant future? The United Nations predicts that the world population living in urban areas will increase from 4.2 to 6.7 billion people by 2050 (165). Megacities (cities with a population >10 million) already exist today, for example the largest city in the world, Tokyo, Japan, with >35.6 million inhabitants in its metropolitan areas (166). Congested living quarters may trigger an increased construction of underground dwellings and better usage of underground spaces (167,168). Therefore, the EMS should be prepared for even more complex underground structures, which may include road tunnels as access or egress points. A major incident in these tunnels may also limit access to these megacities. With the rapid technological progress and artificial intelligence, road tunnel incidents may be avoided altogether. If not, the systems may still aid ambulance commanders and fellow incident commanders in gaining situational awareness, for example, by relaying crucial crash data. Inspired by William Haddon's Matrix (115), the potential factors for increasing situational awareness (and by extension, decision-making) in future incidents are listed below:

Pre-crash: To limit death and long-term sequelae sustained in road traffic crashes in tunnels, the favorable thing would be to try to prevent them from occurring in the first place. Since 1997, the Swedish "Vision Zero" (that no one should be killed or seriously injured in road traffic incidents) has been a long-term goal in road traffic safety (169). Driver behavior can be linked to road tunnel crashes (170). By changing drivers' behavior, for example inducing speed limits and enforcing safe distancing between cars, the severity of road traffic crashes might be mitigated. A potential solution may be "geofencing" in and around (cf. *black hole effect*) road tunnels: a method in which vehicles are forced to slow down in certain areas using digital control of connected vehicles, a project that have shown potential and are currently in a development phase (171–173).

Crash: If a road traffic crash cannot be avoided, crash data such as deployment of airbags, use of seatbelts, direction of travel, speed, exact location, and identification number are important for the ambulance commanders. These data contribute to the situational awareness of ambulance commanders and help them understand the number of people involved in the crash, potential injuries, and risks (e.g., type of fuel). Systems such as the eCall-system already exist today and have been mandatory since 2018 (174). More development in this field is warranted, as more relevant crash data (e.g., telephone number to injured persons) should be collected and sent to the ambulance commanders and still comply with European Union data protection legislation.

Post-crash: If the affected tunnel tube is filled with smoke, fog, or water mist, it will be difficult to assess the number of injured or if it is unsafe (for example, due to a high level of carbon monoxide) to enter the road tunnel. To cope with the limited visibility, technical solutions aid in assessing the situation. After the Gudvanga tunnel fire in Norway, the tunnel system was retrofitted with a radar-system (175). This system penetrates smoke, fire, and fog to visualize people or vehicles (176). Another potential system is to track tunnel users' handheld devices using Wi-Fi (177). However, this system tracks the actual device(s), which may have been left in the car or dropped during evacuation. A potential aid in determining the severity of injuries is a technical aid that measures the injured person's vital signs, which can be used for triage or telemedicine. Different systems already exist, for example via mobile phones which use a combination of live video feed and artificial intelligence systems to measure the heart rate (178) or biosensors that collect information and send it to an app for live monitoring (179,180). Further, live video footage may also be used to guide bystanders or provide more information to dispatchers (181,182) Further technological development and validation studies are required; nevertheless, technical aids may be useful in the future to locate and/or communicate with injured persons to aid the assessment with urgency.

To aid ambulance commanders and EMS personnel in their risk assessment, CO monitors may be useful in determining the levels of CO in the road tunnel. CO monitors are used in, for example, some EMS in Germany (personal communication, Sebastian Ohneseit, 2023). Lessons learnt from exercises in underground mines showed that by training EMS personnel to smoke-dive, time to treatment was significantly improved from 2 to 1 h (personal communication, Jonas Marklund, 2023). Therefore, further investigation of the role of ambulance commanders and EMS personnel in road tunnel incidents is required.

Education: Exercises have been described as important for building confidence (183,184). However, exercises tend to follow a logic that differs from the actual events, are often costly, benefit a few individuals who focus on certain activities, and limit inter-organizational collaboration due to lack of incentive (185). When comparing table-top and full-scale exercise, researchers found that collaboration and trust (cf. “kjennskap”) were reinforced differently depending on the choice of method (186). Furthermore, large exercises are often expensive and may benefit a limited number of participants, particularly in a command exercise. To strengthen the preparedness of EMS personnel regarding road tunnel incidents, e-learning might be one way to form the basis of a sequential exercise ladder. The e-learning course may form the basis that all EMS personnel attend, and the next step may include table-top exercises, with the final step being a full-scale exercise. Another aspect of learning is the proper assessment of ambulance commanders’ decision-making capabilities. An interesting parallel to assessing medical students’ performance in certain tasks is using standardized methods, such as Objective Structured Clinical Examination or Entrustable Professional Activities (187,188). Using constructed collegial discussions, it is possible to assess whether the would-be ambulance commander possesses the necessary ability to reflect and discuss their decisions at a satisfactory level. This method can be used to complement written evaluations. A possible application could be to combine realistic simulations with interactive discussions with an assessor. Considering the developing rate in the field of technology, virtual reality may have potential.

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