A Service Analysis of the Mont Blanc Tunnel Fire

James Catmur, J C and Associates

Kevin King, BAE Systems

Mike Parsons, AAIP, University of York

Fathi Tarada, Mosen

Abstract *On 24th March 1999 a transport truck caught fire while driving through the Mont Blanc tunnel between Italy and France. Other vehicles travelling through the tunnel became trapped and fire crews were unable to reach the transport truck. The fire burned for 53 hours and reached temperatures of 1,000°C producing toxic smoke. Authorities compounded the problem by pumping air from the Italian side, feeding the fire and forcing poisonous black smoke through the length of the tunnel. A total of 39 people were killed. In the aftermath, major changes were made to the tunnel to improve its safety. This paper analyses the accident from a Services perspective, examining which critical services were in use (fire alert service, tunnel control service, ventilation service, etc), and which contributed in some way . The Safety Critical Systems Club (SCSC) Service Assurance Guidance v3.0 is used to guide the analysis and provide structure to the work, producing a service hierarchy map, criticality levels and identification of assurance needs. The improvements put in place after the accident are assessed to see the effect on the service assurance involved.*

1 Introduction

This paper aims to show how a paradigm of Service Assurance combined with a suitable stepwise methodology enables analysis of organisational structures that contributed to a severe accident in the Mont Blanc tunnel. It also allows the service improvements made after the accident to be evaluated to see how they affect the overall assurance position.

A road tunnel is a good example to apply the technique of Service Assurance to because a tunnel provides a pure service (in this case the service of point-to-point travel) to a range of road users with no tangible product being delivered.

1.1 Service Assurance

Many current safety systems rely on functionality provided by services which are designed, developed, operated, and maintained outside the immediate boundaries of the system. In many cases, overall system design is essentially about managing the interactions between various service functionalities which co-operate to produce a useful effect in an operational scenario.

This approach is highly applicable to the idea of a *tunnels-service,* i.e., the provision of a suitable through-route for road vehicles to run on, the signage for the driver, and supporting maintenance and development of the tunnel infrastructure. All the services contributing to the overall *tunnels-service* need to be provided to the appropriate level of quality and safety, and tangible assurance artefacts are needed to show this is the case.

This work looks at how such a services view of tunnels can be applied in a retrospective study of the Mont Blanc Tunnel Fire accident and shows how this can lead to a useful assurance framework that highlights not only the contributory factors to the accident but also subsequent improvements to the tunnel systems and infrastructure to improve the overall *tunnels-service*.

In recent years there has been increasing interest in the topic of safety-related services. There is a range of literature produced over the years looking at assurance of services. Some of this has been produced by the SCSC Service Assurance Working Group (SAWG) itself and has been presented at conferences such as the SCSC Safety-Critical Systems Symposium (Catmur et al 2022, Durston et al 2019, Elliot and King 2019, Harris et al 2019, King et al 2020). The SAWG also produces a guidance document on service assurance which has undergone evolution over the years (SAWG 2020, SAWG 2021, SAWG 2022). There is also an interesting paper considering a service perspective for education, research, business and government, produced by the University of Cambridge Institute for Manufacturing (IfM) and International Business Machines Corporation (IBM) (IfM and IBM, 2008).

1.2 Rationale

The main reasons why this approach is useful are:

1. Tunnels are operated and maintained as a service provision for the user.
2. A tunnel does not produce or modify anything material for its user.
3. A service-based approach to assuring safety provides a different, useful, and important perspective.
4. A service-based approach to safety includes the impact of organisations, agreements, and contracts. It is the only safety assurance approach to do so.

5. It is recognised that collaborative working of technology, organisations, people, and processes all contribute to safety and need to be part of the picture.
6. A service approach recognises the concept of time-limited contracts which are appropriate for road operation and maintenance.
7. There is a significant shift to a service-based approach in many areas of technology and commerce, and hence it is worth exploring an established service delivery example.

1.3 Limitations of study

We aim to provide an illustrative example as some contract information is no longer available or commercially sensitive and not available in the public domain. Where necessary we have proposed some of the missing details. This does not detract from the application of the service assurance methodology.

2 Introduction to Service Assurance

Service Assurance is a different way of producing trust or confidence in something which is not product-based; it is based on information about organisations, contracts and other information relating to the delivery of the service. For this reason, it is a much more appropriate method of gaining confidence in something where there may be no tangible deliverables. Tunnels (strictly the journey through the tunnel) is such an example, where we need to have confidence that it can be undertaken safely but nothing material is "handed over" to the person making that journey in a vehicle.

2.1 Definitions

Some service-based definitions are given below:

Term	Definition
Operational Level Agreement (OLA)	Defines the interdependent relationships in support of a Service Level Agreement (SLA). The agreement describes the responsibilities of each internal group toward other groups, including the process and timeframe for delivery of their services. The objective of the OLA is to present a clear, concise and measurable description of the service provider's internal support relationships.

Term	**Definition**
Service-Based Solution (SBS)	An SBS comprises the systems, organisations, processes, and resources to deliver and manage the services through the duration of the contract life. It may consume other services.
Service Catalogue	A Service Catalogue is the commercial document that lists and describes the services offered for consumption. It is constructed by the Service Provider and typically does not give any service implementation details.
Service Consumer	A Service Consumer consumes (i.e., makes use of) one or more Services
Service Contract	A Service Contract is the legal agreement between Service Provider and Service Consumer. Note that the Service Consumer may not be involved in defining the service or the SLAs at the outset; they may be provided, pre-defined and pre-packaged by the Service Provider on a take-it-or-leave-it basis
Service Definition	The Service Definition describes the services available for consumption which may include technical and/or commercial aspects. It may include deliverables, prices, contact points, availability, ordering, and processes to request Services. This may include a Service Catalogue.
Service Level Agreement (SLA)	An SLA is the agreement between the Service Provider and Service Consumer that defines the level of service (e.g., in terms of availability, performance, and quality) that the Service Consumer will receive. It often has targets for each service described in the Service Catalogue. It usually specifies responsibilities of the Service Provider and Service Consumer and defines the penalties in the event that the specific targets in the SLA are not met.
Service Provider	A Service Provider provides (i.e., offers to consumers) one or more Services.

2.2 What is a Service?

The way that a Service is normally described or defined is different from the specifications and descriptions more commonly used in safety-related systems. An individual Service (sometimes called a *Service Component*) is typically offered by a *Service Provider* via an entry in a *Service Catalogue*. The Service Catalogue usually describes the capabilities/functionality offered to a *Service Consumer* without providing much (or indeed, any) of the implementation detail, in fact it is unusual for the design and implementation of the Service to be visible to the Consumer. Note that service catalogue is a commercial document as well as a technical one and it may give information such as the hours a service is available, level of support, etc.

A Service Level Agreement (SLA) is used to define the level of service being offered, this may include functional and non-functional properties such as capacity, performance, and availability. SLAs often describe (commercial) penalties on the Service Provider for not meeting key elements of the agreements. Typically, penalties are framed in terms of service credits, but may be also in different terms.

Service Contracts between the Provider and Consumer provide the overriding legal and commercial picture and typically refer to Service Catalogues, Statements of Work (SoW) and SLAs.

The boundary between a Service Consumer and a Service Provider is typically both an organisational and commercial boundary as well as a technical one. A Consumer may not be involved in the specification and development of a Service and instead may select a commodity or standardised Service (i.e., something already widely available). Alternatively, they may be involved in the creation of new, tailored, or bespoke services.

2.3 Service Context and Service-Oriented Architecture

Figure 1 gives the context of Service Provision and Consumption:

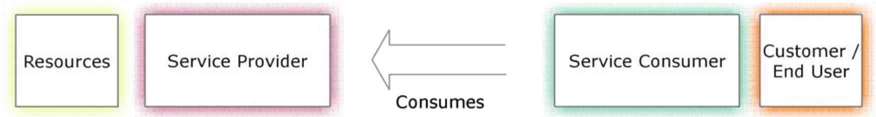

Fig. 1. Context of Service Providers and Consumers (SAWG 2022)

2.4 Simplified View of Tunnel Services

This paper is concerned with the service analysis of the Mont Blanc Tunnel. This is necessarily a simplified view but serves as a very useful and real example of how the service assurance approach may be applied.

Note that services are used extensively in a highways network, not only for provision and maintenance of the highway, but also for areas such as breakdown and accident management.

2.5 The Service Assurance Guidance

The Service Assurance Guidance Document v3.0 (SAWG 2022) provides a framework for safety assessment of services, together with principles and objectives for assuring them. The main elements are:

The Introduction explains why services in a safety context are problematic. It covers background aims and scope, and the target audience. The overall approach is that the document is positioned as guidance; it may be used for developing (domain-specific) standards and further guidance for services. It discusses views of what a service is and what service characteristics are. It also introduces service terms used in the document.

The Assurance of Services section begins by introducing some of the challenges of assuring services to describe what is different about services (as opposed to systems) from an assurance view. It introduces further concepts and terms relevant to assurance of services. Finally, it lists some basic assumptions.

The key part of the document, Service Assurance Principles, states the *Six Service Assurance Principles*, including brief supporting descriptions and explanations. These are:

1. Service assurance requirements shall be defined to address the service-based solution's contribution to both desirable and undesirable behaviours
2. The intent of the service assurance requirements shall be maintained through the service definitions, service levels, the service architecture and the agreements made at service interfaces
3. Service assurance requirements shall be satisfied
4. Unintended behaviours of the service-based solution shall be identified, assessed and managed
5. The confidence established in addressing these principles shall be commensurate with the level of risk posed by the service-based solution
6. These principles shall be established and maintained throughout the lifetime of the service-based solution, resilient to all changes and re-purposing

It then defines objectives which support each principle; these are seen as a route of demonstrably meeting the principles. There is also a mapping of the principles to service characteristics.

The concept of Levels of Service Assurance (LSA) is described next. The levels are then used to scope the applicability of objectives, so tailoring what is required for each level of service risk.

The Capturing Justifications and Evidence section provides evidence tables covering aspects of service scoping, design, analysis, implementation, and change. These tables suggest evidence techniques and containers for meeting the objectives. The concept of Assurance Wrappers is introduced and explained. Some further service assurance challenges and some solutions are discussed.

A brief discussion of possible assurance techniques is given in the Analysis Techniques section with the most promising techniques identified for further work.

The document also provides extensive supporting sections including the following topics: (i) Service 'Mode' Changes, (ii) What Happens when Services Go Wrong? (iii) Further work, (iv) a set of 'Hazop'-style guidewords for services,

(v) a set of service-related Incidents and Accidents as identified from publicly available sources and (vi) a workflow for analysing services.

3 The Fire

3.1 Technical Characteristics

At 11.6 km long, the Mont Blanc tunnel is one of the longest road tunnels in the world with two-thirds (7.64 km) lying in French territory and one-third (3.96 km) in Italian territory. Although a tunnel under Mont Blanc was first considered in the 19th century, the idea only gained real attention in the early 1900s when preliminary designs were presented to politicians from both France and Italy. However, the political turmoil across Europe that led to World War I and subsequently World War II delayed re-consideration of a tunnel until the late 1940s, with drilling eventually beginning in 1959. By August 1962 the teams drilling from each side met making the tunnel a reality, with it finally opening to traffic in July 1965.

At the time of opening the Mont Blanc Tunnel was three times longer than any other road tunnel across the world, earning it the nickname "The World's Longest Shortcut" (Figure 2). It also reduced the journey distance between Paris and Rome by 150km.

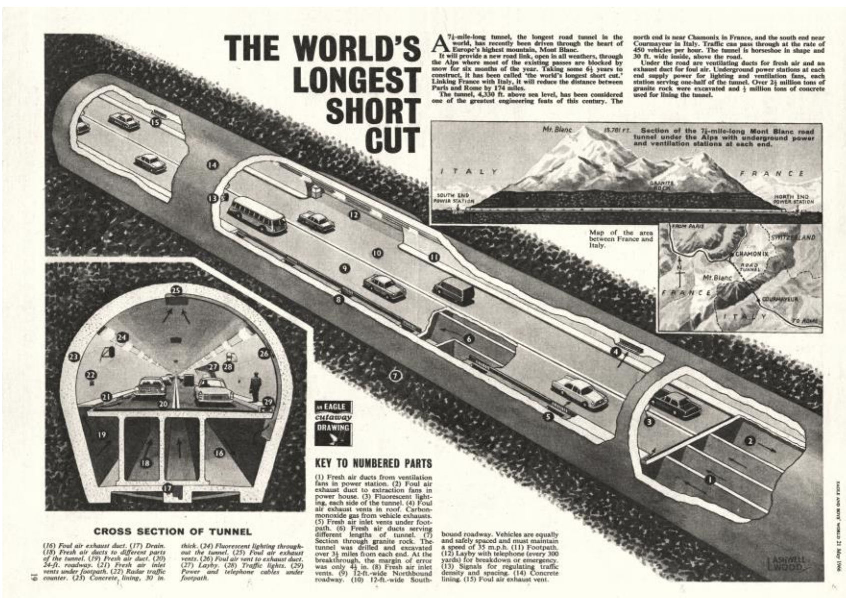

Fig. 2. "The World's Longest Short Cut"

Compared to similar two-way road tunnels the Mont Blanc tunnel is relatively narrow at 7m (Figure 2, bottom left); some recent two-way tunnels are as wide as 9m.

It is also important to highlight that the tunnel is at a high altitude compared with others, being 1,274 m above sea level at the French entrance and 1,381 m at the Italian entrance. This is relevant because heavy goods traffic reaches the tunnel entrances after having climbed long and quite steep roads to get there.

The tunnel consists of a single bore running through mountains which are more than 2,000 m thick above the tunnel for more than half of its length.

Similar tunnels such as at Saint-Gothard and Fréjus have shafts intermittently positioned to provide ventilation. Mont Blanc does not, as this was considered impossible, meaning that to ensure adequate ventilation to dilute exhaust gases, fresh air could only be taken into the tunnel from either end, circulating through shafts under the roadway and distributed into the main tunnel through air vents spaced every 10m and located at the level of the road surface on one side of the road (Figure 3).

A separate duct located under the road surface is used to extract polluted air through vents positioned every 300m along the tunnel.

Several features were installed into the tunnel as part of its original design to enable safe travel. Lighting, emergency telephones, and refuges (known as *garages,* 3.15 x 30 m long with turning places) located every 300m, that alternate between the two sides of the road. There were also traffic signals positioned every 1.2km through the tunnel.

Fig. 3. Tunnel construction showing ducting under the roadway (GEIE-TMB, 2022)

The two concession companies made significant changes to the tunnel facilities since it first opened, primarily to aid safety and comfort but also to increase capacity. In 1979, due to the increase in heavy goods traffic the ventilation system was adapted with the duct, originally used to extract polluted air, repurposed to be reversible, allowing for the introduction of extra fresh air into the tunnel. Further improvements included systems installed to selectively concentrate fume extraction where needed most; shelters installed every 600m; pressurised water systems for firefighting and the complete replacement of the lighting systems.

By March 1999, studies were underway or in planning to consider systematic automated management and automatic detection of incidents.

It is important to point out that although other bi-directional road tunnels around the world may have lower volumes of traffic (although not all), they were generally no better equipped from a safety perspective at the time of the incident.

3.2 Operational Characteristics

To manage the day-to-day operations of the tunnel from the outset it was agreed that two separate concessions would be created, Société du Tunnel du Mont-Blanc (STMB), which later became the Autoroutes et Tunnel du Mont-Blanc (ATMB), under French jurisdiction and the Società Italiana per il Traforo del Monte Bianco (SITMB) under Italian jurisdiction. It was agreed that although the territorial split was 65% French, 35% Italian, each concession would be accountable for half of the tunnel.

Since its first opening, there had been a marked increase in traffic flow. By 1999 small vehicle traffic had more than doubled from the original estimated usage, which although significant, is modest compared to other tunnels today. Heavy goods vehicle traffic however had increased more appreciably, by a factor of 17 over 34 years, showing the relative importance of the tunnel for trade between the two countries. In 1998 the tunnel was projected to take c.960,000 heavy goods vehicles, however in reality it accommodated almost 2 million (c. 5,600 vehicles per day).

The traffic regulations in place at the time stated that moving vehicles must be at least 100 m apart and restricted to 50-70km/h. However, there was no provision for the distances between stationary vehicles. Dynamic signage was originally placed in the tunnel but was subsequently removed by the two concessions.

In the tunnel, there were traffic lights every 1200 m. During the fire these lights were switched to red a few minutes after the alarm was sounded, but they did not reduce the toll of the disaster, either because some of the lights in the tunnel did not work or because they were not respected (the lights were not very visible).

In 1995, radio broadcasts were installed in the tunnel. First, to transmit communications on service and safety frequencies; then to allow messages to be broadcast to users on two French and two Italian public frequencies. The radio broadcasts were not used to communicate with users after the fire alert.

3.3 Concerns around the Tunnel Operation Prior to the Fire

The initial joint French-Italian enquiry report (Duffe et al, 1999) picked up several concerns relating to the operation of the tunnel before the fire. There were two separate command and control stations, one for each half of the tunnel operated by its respective concession; the tunnel safety regulations were partially obsolete; the smoke extraction capacity was half that of comparable tunnels; there was no independent safety passageway to facilitate the transit of emergency services or the evacuation of users, and the rescue services were organised differently on each side of the tunnel.

Furthermore, the separate concessions were not made aware of the existence of a French regulation from 1981 which defined the safety conditions to be applied in road tunnels, particularly that safety installations in older tunnels should keep pace with the evolution of traffic. This was because the bi-national agreements governing the operation of the tunnel did not refer to any specific safety regulations.

It is also important to understand that before the fire the two concessions often found it difficult to coordinate investments in tunnel infrastructure. The studies underway were agreed upon jointly and concerned improvements to the whole tunnel but these were only in planning when the fire occurred.

3.4 The Timeline

On the morning of 24 March 1999, after a relatively unblemished operating record, a Belgian heavy goods vehicle with a refrigerated trailer made from combustible isothermal foam (here after called ‘the truck’) entered the tunnel travelling South-East from France to Italy. It was carrying 12 tonnes of flour, 9 tonnes of margarine, and 550 litres of diesel (Bailey, 2004)

The events of the incident from the time at which the truck entered the tunnel are summarised in Table 1.

Table 1. Summary of Events

Time (C.E.T.)	**Event**
10:46 Wed 24th	The truck entered the tunnel from the French side
10:52	Oncoming drivers noticed smoke coming from the truck and began flashing their headlights at the driver. By this time the truck was around 3km into the tunnel. An obscuration detector was activated and the operator’s screens at the French control station showed smoke in the tunnel.

Time (C.E.T.)	Event
10:53	Noticing the smoke coming from underneath the truck's cabin the driver pulled over and attempted to fight the fire himself. At this point the incident was not considered a fire emergency as there had been 16 other truck fires in the tunnel since it opened, in each case extinguished by the driver. The difference on this occasion was the driver being forced back when the truck burst into flames, forcing him to flee the scene through the Italian entrance to the tunnel. The nearest sensor of the fire detection system, operated by the Italian concession, had been taken out of service the night before.
10:54	A driver from one of the nearby vehicles who had escaped to refuge 22, raised the alarm.
10:55	The fire alarm was triggered by tunnel employees who stopped further traffic from entering. By this time a further 10 cars and 18 trucks had already entered the tunnel from the French side. Some of these cars managed to turn around in an attempt to retreat back to French territory. However, air was flowing through the tunnel from the Italian side rapidly forcing dense smoke from the fire down the tunnel and quickly making navigating the road impossible. Turning around was not an option for the trucks and neither was reversing out of the tunnel.
11:00	Without oxygen from clean air, car engines began to stall leaving 50 people trapped in vehicles close to the fire. Most rolled up their windows and waited for rescue, but some escaped, and where not overcome by the heat or toxic components of the smoke (mainly cyanide), sought refuge in the fireproof shelters built into the walls of the tunnel. Fire crews responded – two French fire trucks from Chamonix and an Italian one from Courmayeur.
11:11	A second crew of Italian firefighters arrived at their end of the tunnel.
11:15	The first French fire truck managed to reach a point 2.7 km from the truck on fire, however a combination of failed lighting and abandoned vehicles made it impossible for them to get closer to the truck.
11:20	The first Italian fire crew managed to get within 300 metres of the truck before being forced to abandon their vehicles and take shelter in one of the fireproof refuges, 0.9 km from the truck. As they took refuge the fire began to spread with burning fuel flowing down the road surface, causing tyres and fuel tanks on abandoned vehicles to explode, and sending deadly shrapnel in the air.

Time (C.E.T.)	Event
11:25	The second Italian fire crew had to abandon their vehicles, ending up searching on foot for their trapped colleagues. Realising the cubicles were offering little protection from the smoke, they began searching for the doors that led to the ventilation duct.
11:30	The second French crew could only reach 4.8 km from the truck before they were stopped by the heat and smoke. By this time, smoke had reached the French entrance to the tunnel, 6 km from the truck.
11:54	A rescue mission was instigated using the fresh air channels located under the road, saving the lives of some people, however that took over 6 hours to enact.
13:04	French specialised emergency plan was activated for the tunnel.
13:35	A separate 'Red' plan was activated following the blockage of the rescue workers.
18:35	The civilians who had managed to escape their vehicles to the relative safety of the refuges were sadly not out of danger as the fire doors on the cubicles were only rated to survive for two hours and it took over 7 hours to reach those people. 6 civilians were eventually saved from refuge 17.
16:00 Friday 26^{th}	The fire is finally brought under control

The fire burned for 53 hours and reached temperatures of 1000°C with the extreme temperatures mainly due to the margarine on the trailer. It has been assessed that the trailer was equivalent to a 23,000-litre oil tanker. The fire spread o other cargo vehicles nearby that also carried combustible materials (Figure 4).

Fig. 4. Wreckage inside the Mont Blanc Tunnel (Bettelini, 2022)

Thankfully, the heroic efforts of the firefighting teams and a security guard, who perished in the fire after evacuating 10 survivors on his motorcycle, 12 of the 50 people trapped in the tunnel survived being evacuated to the Italian side. All 15 of the trapped Italian firefighters were also eventually rescued, 14 of them recovered but sadly their commanding officer died in hospital. Investigation discovered that most of the victims died within 15 minutes of the fire first being detected.

Due to weather conditions at the time, airflow through the tunnel was from the Italian side to the French side (Bailey, 2004). The shape of the tunnel led to it acting like a chimney, an effect compounded by the authorities pumping in further fresh air from the Italian side, feeding the fire and forcing poisonous black smoke through the length of the tunnel. Only vehicles closer to the entrance on the French side of the tunnel were trapped, while cars on the Italian side of the fire were mostly unaffected.

The intensity of the heat was evident as after extinguishing the fire it took a further five days for temperatures to cool down enough for debris to be removed from the tunnel.

3.5 The Aftermath

The tunnel underwent major enhancements before it re-opened in 2002 (Bailey, 2004). Improvements include computerised detection equipment, extra security bays, a separate, sub-road surface, escape tunnel and a fire station in the middle of the tunnel. The safety tunnels have clean air flowing through them via vents, separate to the main tunnel. The security bays now have direct video contact with the control centre, so they can be informed about what is happening in the tunnel more clearly.

Remote sites for safety inspection of all heavy goods vehicles were also created on each side of the tunnel way before the tunnel entrance. These remote sites are also used as staging areas, to smooth the flow of commercial vehicles.

Most importantly the management of all services relating to tunnel maintenance and operations were subsumed under a single operating authority that was jointly owned by the French and Italian authorities, The Gruppo Europeo di Interesse Economico del Traforo del Monte Bianco (GEIE-TMB).

4 Service Analysis Pre-Fire

4.1 Services Identified

For this paper, it was important to identify the services in place for the Mont Blanc tunnel at the time of the fire. Specifically, those services whose fallibility may have contributed to the incident.

Evidence of the services in place from when the tunnel opened in 1965 through to the time of the tunnel fire in 1999 is limited. There are a handful of academic papers and articles that consider aspects of the tunnel operation in relation to the fire that were published after the incident (e.g., Bettelini 2022, Bailey 2004, Lee & Ghazali 2018) and of course there is the official accident report (Duffe et al 1999).

To operate any road tunnel the consensus (e.g., Bettelini 2022, Lee & Ghazali 2018) is that tunnels need signage, lighting and ventilation, all managed by control staff in some form of control facility. Importantly, considering that accidents do happen, it is also crucial to have an effective, maintained firefighting capability. Each of these aspects can be considered as a service and should have adequate assurance.

That consensus enabled us to hypothesise that the service structure at the time of the accident would most likely have been analogous to the hierarchy set out in Figure 5[1], with separate service structures in the two halves of the tunnel: French and Italian. We have shown the possible structure of the services for the French (ATMB) half of the tunnel as our hypothesis is that the Italian service structure would have been analogous to the French, so to ensure the hierarchy is legible we have left the Italian half un-developed.

[1] Given the elapsed time since the fire we cannot be certain how these services were structured, but the available material suggests a service structure akin to this.

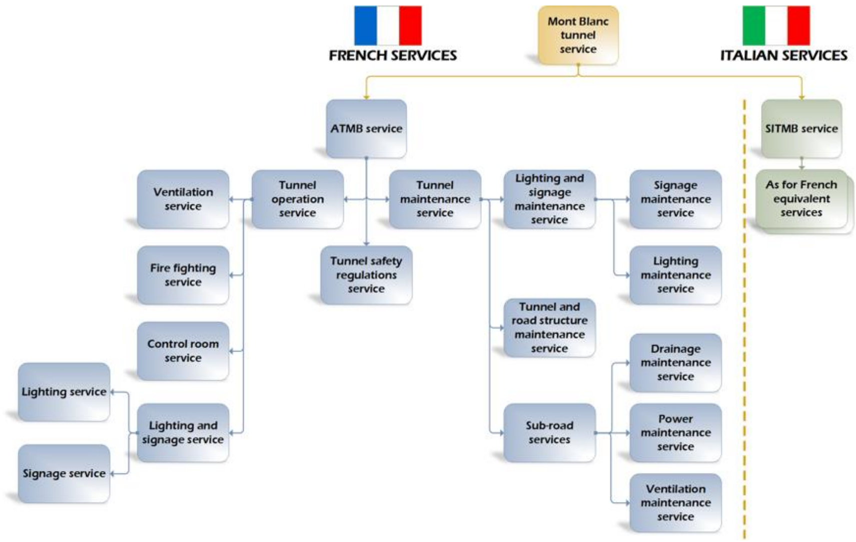

Fig. 5. Mont Blanc Tunnel Service Hierarchy

4.2 Applying the Service Assurance Guidance

The Service Assurance Guidance v3.0 (SAWG 2022) provides a structure that enables services to be assured against each of the *Six Service Assurance Principles* through approaches aligned to the *Service Objectives* that underpin each principle. The structure enables us to consider services from several perspectives; how they inter-relate, in what could be considered a service stack or hierarchy, the level of safety risk inherent in the use of a service and how much assurance is offered by each service provider or needs to be developed by the relevant service consumer to address assurance shortfalls.

Key for our analysis of the services supporting operation and maintenance of the Mont Blanc *tunnels-service* before the fire was our understanding of the service hierarchy (Figure 5), an assessment of the Levels of Service Assurance and awareness of the quality of assurance evidence in place for each service in the hierarchy.

4.2.1 Levels of Service Assurance

The term Level of Service Assurance (LSA) has been developed by the SAWG as it is understood that, in a services context, the type of service and manner in which it is consumed will require differing levels of assurance. Classifying[2] a service with a LSA formalises this approach, so it becomes explicit as to what is required to meet a particular level of safety risk inherent in a service. Five levels of LSA have been developed (Table 2), the higher the level the more objectivity you need to assure the associated service.

Table 2 – Levels of Service Assurance (SAWG, 2022)

Level of Service Assurance	**Definition** **(Service Consumer View)**
LSA 0	No safety aspects present in the service, so no objectives assigned
LSA 1	Minor safety aspects with little impact of failures (minor injury possible but unlikely)
LSA 2	Safety aspects with some impact of failures (several injuries possible)
LSA 3	Significant safety aspects with service with major impact (could indirectly lead to multiple injuries or a single death)
LSA 4	Service is safety-critical[3]: service failures could have catastrophic impact (could directly lead to multiple deaths)

LSAs are allocated in a top-down fashion, starting with the highest-level service element in a hierarchy (i.e., the service visible to the consumer) and then flowing down to sub-ordinate services. Importantly, an allocation rule is applied, whereby at least one of the subsidiary services inherits the LSA from its parent service[4].

We postulate that applying the LSA rules from the Service Assurance Guidance to each service in our assumed hierarchy for the Mont Blanc tunnels-service (Figure 5) gives us the LSAs overlayed in Figure 6.

This is a proposal of the LSA with respect to the tunnel user, and we suggest operations services have a higher LSA than maintenance ones, as they are closer to the user. LSAs for staff including emergency services personnel may also have a different balance.

[2] It is important to note that the LSA is determined first by the service consumer; the service producer then shows how the service meets this.

[3] It is acknowledged that the term ‘safety-critical’ as related to services is not a formally defined term. We suggest ‘a service whose failure may result in one or more of the following: death or serious injury to people; loss or severe damage to equipment or property, or widespread environmental harm’

[4] So, for example if the top-level service is LSA3, then at least one of the next level down services in the hierarchy is also LSA3 (or possibly LSA4).

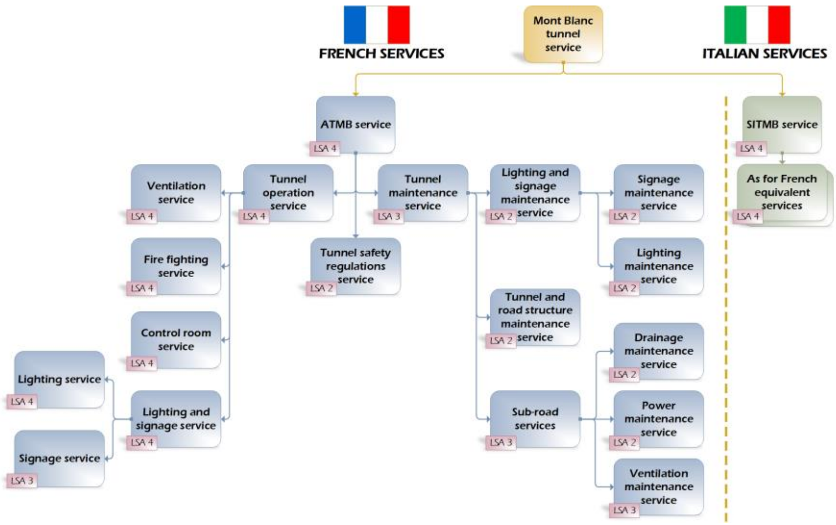

Fig. 6. Mont Blanc Tunnel Service Hierarchy with assessed Levels of Service Assurance

4.2.2 Completeness of Service Assurance Evidence

The Service Assurance Guidance v3.0 (SAWG 2022) has established the concept of *service assurance wrappers*, as a mechanism to bridge the gap between what is required to support achievement of an LSA and the actual evidence available. Assurance across the service boundary needs to meet the assessed LSA, but it is unrealistic to expect that assurance to be provided wholly by the service provider. *Service assurance wrappers* need to cater for differing scenarios.

This has led to service assurance wrappers being expressed as having a key characteristic of ‘thickness’. The spread of service assurance between the provider and the consumer informs the ‘thickness’ of the wrapper[5].

Wrapper complexity is, however, not a simple function of the class of wrapper as it will also be influenced by the degree of dependence on the consumed service and the nature of its integration into the overall hierarchy of services.

Applying the service assurance wrappers approach to our hypothesis of the service hierarchy for the Mont Blanc *tunnels-service* we were able to specify the

[5] Full thickness (class 3) wrappers address the situation where assurance requirements are not flowed down to the provider and minimal (or no) assurance is supplied by the provider. Medium thickness (class 2) wrappers need to map the assurance evidence from the provider to the context and level of risk the service is exposed to by the consumer. Thin (class 1) wrappers are applied where the service provider is a capable, ‘safety-aware’ supplier that either fully understands the consumer’s domain and the use of their service within it (Class 1a) or at worst is still able to provide a safety-assured service even if they are unaware of the consumer’s domain (Class 1b).

applicable types of *wrappers* we would have expected and their respective thicknesses (Figure 7). We will consider later whether such wrappers existed and their veracity.

It should be noted that an organisation that develops an assurance wrapper may be the service consumer itself, the service provider, or a third party. However, the consumer of a service remains accountable for the claims made in the associated assurance wrapper. At the highest level of the architecture, where safety risk can be understood, this will be the ‘Duty Holder’ for the overall system. Before the tunnel fire there was no obvious single ‘Duty Holder’ in this context, rather ATMB and SITMB were acting independently with no overarching body co-ordinating the two organisations.

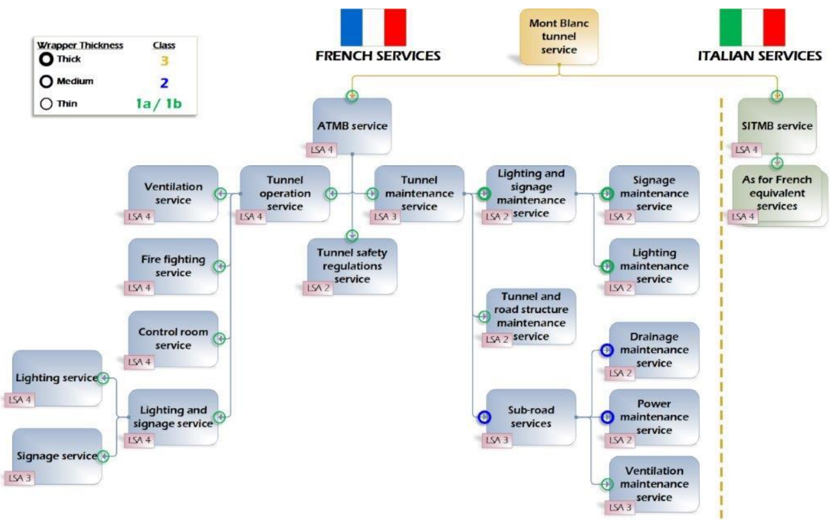

Fig. 7. Mont Blanc Tunnel Service Hierarchy with assessed LSA and Service Wrappers

4.3 Analysis in the Context of the Fire

Considering the available evidence (Duffe et al 1999, Bailey 2004), we believe elements of the history and characteristics of the tunnel (see Section 3.1 and 3.2) were important factors in how the 1999 fire incident evolved, e.g., the lack of ventilation shafts. Examining the accident timeline through the lens of service assurance we were able to determine which services may not have been fully assured and, importantly, the impact from the lack of coordinated services between the two halves of the tunnel.

From our hypothesis of the service hierarchy, LSA and Service wrappers (Figures 5, 6 & 7) we have been able to analyse the assurance deficits in the context of the fire. As we believe the service hierarchies on each side of the tunnel were analogous, we have focused our analysis on the services we believe were provided by ATMB for the French 'half' of the tunnel.

The overall service 'package' provided by ATMB is assessed to be at LSA4. If we follow the SAWG Guidance (SAWG 2022) it is correct to analyse that service first. However, it is broadly split into three areas of supporting services[6] where we believe the assurance evidence should sit, *tunnel operation services*, *tunnel maintenance services* and a *tunnel safety regulations service*; so, it is sensible to focus on these services (in LSA order) to understand the areas of deficiency in the ATMB service.

4.3.1 ATMB tunnel operation service (LSA4)

Our hierarchy (Figures 5, 6 & 7) breaks down the tunnel operation into four subordinate areas of service provision, a *control room service*, *lighting and signage service*, *firefighting service,* and *ventilation service*. We believe the reliance on these services requires them all to be assured to the highest level, LSA4. This directs to them needing to substantively meet the objectives of each of the *Six Service Assurance Principles*. Therefore, it is appropriate to expect, as a minimum, the evidence listed in Table 3 would be available from the service provider, or else need to be developed as part of an assurance wrapper (see section 4.2.2).

Assessing the four subordinate services against those evidence requirements enables us to highlight the areas of weakness in service assurance (see Table 3).

The most obvious weakness in respect of the ATMB service provision is that it stopped halfway through the tunnel. There were two separate command and control stations, one for each half of the tunnel operated by its respective concession with the *control room services* delivered by those stations not synchronised. On top of this lack of a co-ordinated service interface we can find no evidence of a common public emergency plan, with the rescue services organised differently on each side of the tunnel, working to separate emergency response plans, evident by the response times and actions as discussed in section 3.4.

The Italian authorities did not activate their specialised rescue plan, believing the accident had occurred on French territory. Meanwhile the French had two plans, their specialised emergency plan for the tunnel and a red plan to manage the rescue services. These plans required command posts, notably an operational command post (PCO) at the ATMB site. Sadly, the PCO did not have means of autonomous, direct communication with their Italian counterparts.

---

[6] Note that interactions between services are covered by Principle 4 - Unintended behaviours of the service-based solution shall be identified, assessed and managed: All undesired or unintended behaviours which may impact safety properties or safe behaviour of the overall system must be identified and assessed within the usage context.

Table 3 – Evidence for assurance of the ATMB tunnel operation services

Expected Evidence	Control room service (LSA4)	Lighting and signage service (LSA4)	Fire-fighting service (LSA4)	Ventilation service (LSA4)
✔ = evidence available OR service likely compliant, even if no clear evidence, **?** = no evidence in public domain and unclear if service was compliant, ✖ = service weakness or failure may have contributed to the fire				
An understanding of the context and intended use of the Service by all stakeholders	✔	✔	✔	✔
Clear understanding of the requirements, stakeholders and consumers of the Service	✖	✔	✔	✖
All the states or modes of operation of the Service, including degraded modes are clearly defined	✖	✔	✔	✖
Full awareness of any necessary industry standards, legislation or regulation applicable to the design of the Service, including where applicable reference to similar existing designs	✖	?	✔	✖
Relevant redundancy, standby modes and diversity in the Services design is documented and understood	✔	✔	✔	✔
A clear breakdown of the components of the Service, their interaction and their interfacing to other services or products is documented and understood	?	?	✖	✖
Documented understanding of the risks and hazards presented by the Service, including any controls or mitigations in place to manage those risks to an acceptable level, e.g. So Far As Is Reasonably Practicable	✖	✔	✖	✖
How the assurances that the services are acceptably safe are routinely tested, e.g. by independent audit	?	?	?	?
How the Services are staffed, and the quality of the staff	?	?	?	?

The poor coordination between the two concessions appears to have been true of many services, with the *ventilation service* and *firefighting service* each being key on the day of the accident: and varying investment in services over the long-term resulting in a ‘tunnel of two different halves’.

Looking at some of the key operational concerns predicted before the fire, it is not clear from the evidence we have seen that ATMB understood the break-down of the services they were accountable for and the need for those services to evolve to keep pace with the evolution of traffic. At the time of the fire the smoke extraction capacity was half that of comparable tunnels which, coupled with the lack of co-ordination, led to the Italian’s *ventilation service* pumping extra clean air into the tunnel unaware that it was simply providing more oxygen to feed the escalating fire and causing additional smoke logging of the tunnel.

The development of the fire and significant issues experienced by the rescue services show that the design of the tunnel had not taken sufficient account of the need to facilitate the transit of emergency services to the site of a fire or the evac-uation of users from it. It is our opinion that the *firefighting service* could only have worked if there was a far more adequate ventilation system to control the noxious smoke coupled with an independent safety passageway to facilitate fast transit to/from the scene.

4.3.2 ATMB tunnel maintenance service (LSA3)

As with the ATMB tunnel operation service, our hierarchy (Figures 5, 6 & 7) breaks down the tunnel maintenance into subordinate areas of service provision. We see there being three, *Sub-Road services* (LSA3) - including drainage, venti-lation, and power, *Tunnel and road structure maintenance service* (LSA2) and *Lighting and signage maintenance service* (LSA2). Although we see these ser-vices requiring lower levels of assurance it is still appropriate that they comply with the objectives of each of the *Six Service Assurance Principles*. We believe, as a minimum, the same evidence listed in Table 3 for the operational services would be necessary and available either from the service provider, or else needed to be developed as part of an assurance wrapper (see section 4.2.2).

We were unable to determine if any of the *maintenance services* were fallible in a way that may have contributed to the fire. The *maintenance services* were probably delivered in a way that supported the respective operational service and it was those operational services where the concerns lay over their fallibility.

At the time of the fire, the firefighting service was managed independently of the tunnel by the local fire services in Chamonix (French) and Courmayeur (Ital-ian) so there is no *firefighting maintenance service* in scope of our assessment.

4.3.3 ATMB tunnel safety regulations service (LSA2)

If operational oversight took account of existing legislation when the tunnel opened to the public and kept pace with such legislation as it evolved, then a thin wrapper of an assurance case owned by the operating authorities on each side of the tunnel would seem appropriate. We were unable to find any supportive evidence in the public domain regarding the assurance of the *tunnel safety regulations service* before the fire. Therefore, we cannot comment as to whether legislative compliance was being maintained by ATMB. We did however find that ATMB do not appear to have picked up a 1981 change in French legislation requiring tunnel safety to keep pace with the evolution of traffic (Duffe et al 1999). We also cannot find supportive evidence in the public domain of any equivalent legislation or regulation governing the Italian concession. Therefore, we cannot comment as to whether legislative compliance was being maintained by SITMB

Had a service-based analysis been considered prior to the accident we believe the weaknesses in service assurance could have been identified and addressed.

5 Service Analysis Post-Fire

5.1 Services Identified

After the fire there needed to be changes in the operation of the Mont Blanc tunnel given the service failures we have identified (section 4).

Recent papers have confirmed that the basic services required as identified in section 4.1 remain valid (e.g., Bettelini 2022, Lee & Ghazali 2018). Tunnels will always require adequate signage, lighting, ventilation, control and firefighting, and these services, in our opinion, must be assured.

Crucially, the two governments saw the major issues caused by not having a joined-up control structure, so when the Mont Blanc Tunnel re-opened in 2002 a new single maintenance and operations services organisation, The Gruppo Europeo di Interesse Economico del Traforo del Monte Bianco (GEIE-TMB), was formed (Figure 8).

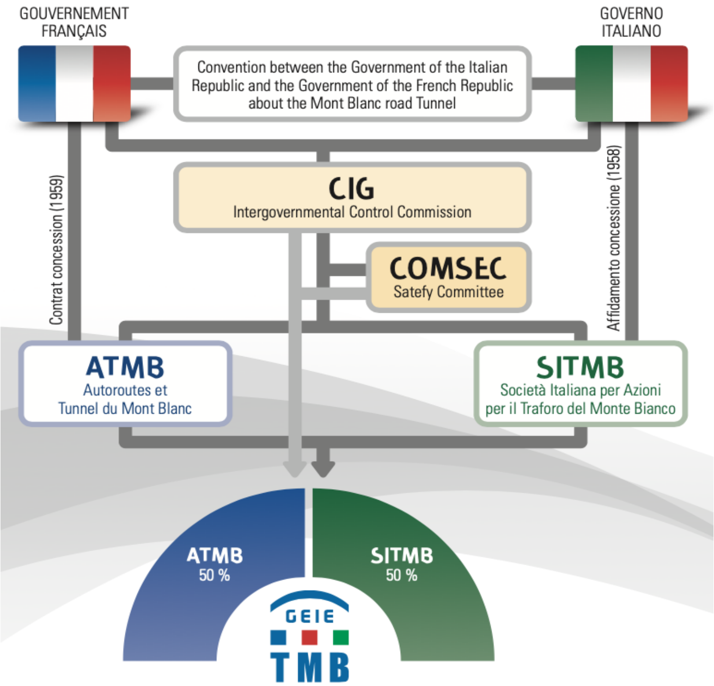

Fig. 8. The Single service structure post 2002 (GEIE-TMB, 2022).

Following our approach to identifying the service hierarchy before the fire, we have determined the breakdown of the GEIE-TMB services is likely akin to Figure 9.

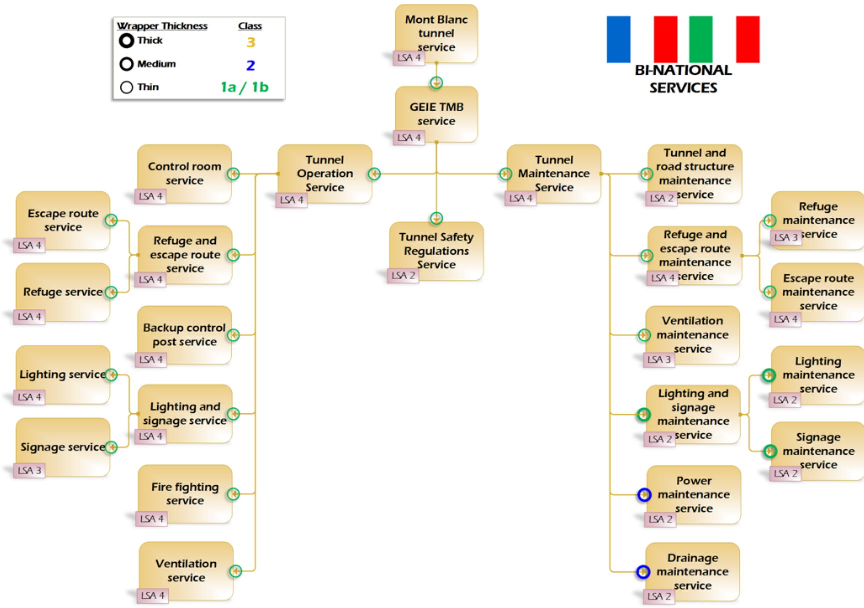

Fig. 9. Service Hierarchy – After the Mont Blanc tunnel reopened post-fire.

5.2 Applying the Service Assurance Guidance

The approach taken for applying the service assurance guidance to the services we believe were extant before the fire (Section 4.2) by considering each service against the Service Objectives that underpin each of the Six Service Assurance Principles remains valid for the services we have identified post-fire.

Equally the concept of LSAs (section 4.2.1) and quality of service assurance evidence (section 4.2.2) remain applicable and were considered in our analyse of the post-fire services. The assessed LSAs and wrappers for the post-fire services are shown on our hierarchy (figure 9). Importantly, our hierarchy of services post-fire shows they are now coordinated under a single organisation.

5.3 Analysis in the context of current operations

Evidence in the public domain (e.g., GEIE-TMB 2022) indicates that the operation of the tunnel has evolved significantly since the fire, and positively concerning safety. A case point being that all users of the Mont Blanc tunnel (and Frejus) are given a dual-purpose leaflet before they are allowed into the tunnel, informing them of “how to use the tunnel safely” and “what to do in an emergency” (figure 10).

Fig. 10. Double-sided service leaflet for all tunnel users (GEIE-TMB, 2022).

A review of the services as part of the formation of GEIE-TMB and the refurbishment of the tunnel after the fire identified the need to deliver greater assurance through:

- Computerised detection equipment.
- Extra security bays.
- The secure shelters having direct video contact with the control centre, so they can be informed about what is happening in the tunnel more clearly.
- The secure shelters being hermetically sealed and insulated, separated from the tunnel by two fire doors and an airlock system that prevents smoke from entering.
- A separate escape tunnel.
- The safety tunnels have clean air flowing through them via vents, separate to the main tunnel.
- A fire station in the middle of the tunnel.
- Two-headed fire trucks that could travel in either direction within the tunnel without needing to turn around.
- Remote, independently managed sites for safety inspection of all heavy goods vehicles some distance before the entrance on each side of the tunnel. These remote sites would also be used as staging areas, to smooth the flow of commercial vehicles.

These requirements have been addressed as set out in the new Mont Blanc Tunnel Service Charter (GEIE-TMB 2022), with the important safety features as summarised in figure 11.

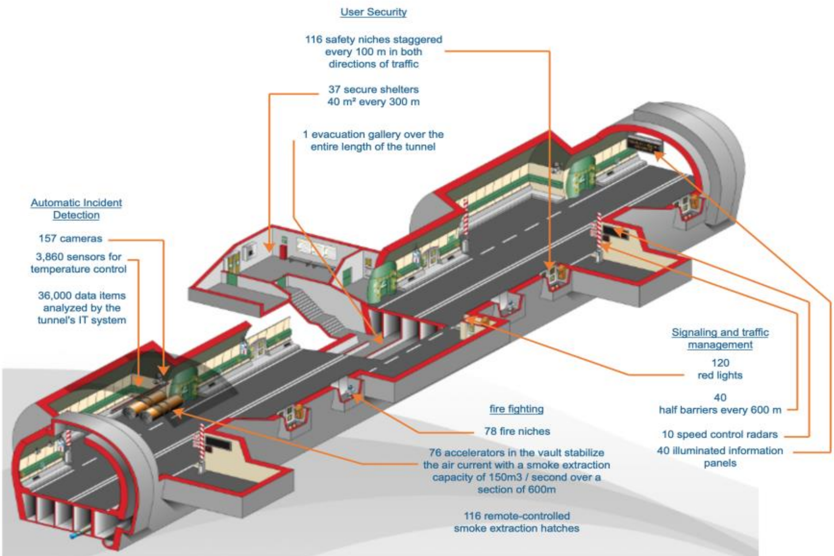

Fig. 11. 2002 revisions to the Mont Blanc Tunnel operation (annotated from GEIE-TMB, 2022)

Supportive evidence regarding the assurance of the improved services is not in the public domain. Therefore, we are not commenting on the assuredness of those services but by applying our knowledge of service assurance (SAWG 2022), we have been able to postulate where we believe the current services (figure 9) could be assured.

Before we detail our analysis, it is important to discuss the European Union (EU) Council Directive that was published in 2004 as this has a direct bearing on the services currently operated in support of the Mont Blanc tunnel.

5.3.1 EU Council Directive

EU Council Directive 2004/54/EC (2004) on *minimum safety requirements for tunnels in the Trans-European Road Network* was devised as a direct result of tunnel fires in Mont Blanc and Tauern in 1999 and St Gothard in 2001. The Directive includes information and requirements on various tunnel services, for example, *Administrative Authority service*, *Inspection Entity service*, *Tunnel Manager service*, *Tunnel Risk assessment service*, etc. It is therefore useful to examine the services described within the Directive to see how they match the new Mont Blanc services which were developed in parallel[7].

The Directive does not state the service hierarchy, but one can infer a hierarchy from it. For example, the inspection entity service will probably be a sub-service of the Administrative Authority as the Directive states:

> "*Member States shall ensure that inspections, evaluations, and tests are carried out by Inspection Entities. The Administrative Authority may perform this function. Any entity performing the inspections, evaluations and tests must have a high level of competence and high-quality procedures and must be functionally independent from the Tunnel Manager.*"

In some cases, the Directive leaves the service structure open, for example:

> "*The Safety Officer may be a member of the tunnel staff or the emergency services, shall be independent in all road tunnel safety issues and shall not be under instructions from an employer in respect of those issues.*"

This means the *Safety Officer service* could be delivered by a member of the Tunnel Manager staff (and thus be a sub-service of the *Tunnel Manager service*) but somewhat confusingly it says the service shall also be independent of the *Tunnel Manager service*.

Our possible hierarchy of services mapped out in figure 9 is analogous to the requirements of the Directive. This is not the only possible service structure that achieves the overall safe tunnel service but would enable a service assurance process to be followed. We believe that it would be useful if future versions of the Directive contained example service hierarchies, to give greater clarity on how services can be assured.

We have found that a service RACI (responsible, accountable, consulted, informed) analysis of the services within the directive is useful and the technique could help provide clarity on the services and how they interact to deliver a safety tunnel service.

Within the Directive there is information on some of the safety requirements for each service, that a service assurance process could use. For example, the *Drainage service* safety requirements are (EU Council Directive 2004/54/EC 2004):

- *"Where the transport of dangerous goods is permitted, the drainage of flammable and toxic liquids shall be provided for through well-designed slot gutters or other measures within the tunnel cross sections.*

[7] The Directive entered UK law as Road Tunnel Safety Regulations 2007, with two amendments, Road Tunnel Safety (Amendment) Regulations 2009 and Road Tunnel Safety (Amendment) Regulations 2021, the latter of these severing the link to the EU legislation after the UKs exit from the EU.

- *Additionally, the drainage system shall be designed and maintained to prevent fire and flammable and toxic liquids from spreading inside tubes and between tubes.*
- *If in existing tunnels that requirement cannot be met or can be met only at disproportionate cost, this shall be taken into consideration when deciding whether to allow the transport of dangerous goods on the basis of an analysis of relevant risks."*

We note that the requirements for the *Ventilation service* do not include a similar one, to prevent flammable and toxic vapours from spreading between tubes, a requirement we have met in past tunnel designs.

The requirement that there be only one *Tunnel Manager service* is included in the Directive, but the Directive does allow for other services to be split in cross-border tunnels. The single *Tunnel Manager service* is the same service structure as was adopted by the Mont Blanc tunnel after the fire.

Requirements (supplemented, as necessary) for each service can then be used to review if assurance can be provided for each service, the LSA required, and if service wrappers are needed.

From our analysis of the service failings before the fire, two services were considered substantial contributors to the evolution of the fire and loss of life. The *Control Room Service*, and the *Ventilation Service*. We have taken these services and reviewed publicly available information to see if they can be assured, or not.

5.3.2 Control Room Service

EU Directive requirements for this service (EU Council Directive 2004/54/EC 2004) state:

- *"A control centre shall be provided for all tunnels longer than 3,000m with a traffic volume higher than 2,000 vehicles per lane.*
- *For all tunnels requiring a control centre, including those starting and finishing in different Member States, a single control centre shall have full control at any given time.*
- *Surveillance of several tunnels may be centralised at a single control centre."*

We believe this service to be LSA4. Based on publicly available information, we believe these requirements can be assured.

> "*Two control and command posts (PCC), which both have the same technical installations, are separately located at the two tunnel entrance aprons, North and South, and are used in conjunction with each other. The one referred to as "active" is under the supervision of two OST (safety and traffic operators) and carries out activities to check the flow of traffic in the tunnel and at the tunnel entrance aprons. The other, referred to as "traffic" (but able to replace*

the "active" one at any time), looks after traffic conditions on the access routes. The OST on duty at the "traffic" PCC also has the job of contacting any tunnel users who have reached the safe places." (GEIE-TMB (2022))

Crucially the two Control Rooms at each end of the tunnel are now linked, with an overarching understanding as to how they should coordinate services in the event of an incident, notably a tunnel fire. We would like to hope that such coordination coupled with the design improvements shown in Figure 11, would mean emergency services could reach the site of an incident promptly and not be hampered themselves by inadequate ventilation or immobilised vehicles blocking their passage.

5.3.3 Ventilation service

EU Directive requirements for this service (EU Council Directive 2004/54/EC 2004) state:

- *The design, construction and operation of the ventilation system shall take into account:*
    - *the control of pollutants emitted by road vehicles, under normal and peak traffic flow,*
    - *the control of pollutants emitted by road vehicles where traffic is stopped due to an incident or an accident,*
    - *the control of heat and smoke in the event of a fire.*
- *A mechanical ventilation system shall be installed in all tunnels longer than 1 000 m with a traffic volume higher than 2 000 vehicles per lane.*
- *In tunnels with bi-directional and/or congested unidirectional traffic, longitudinal ventilation shall be allowed only if a risk analysis shows it is acceptable and/or specific measures are taken, such as appropriate traffic management, shorter emergency exit distances, smoke exhausts at intervals.*

We believe this service to be LSA4[8].

"A device for stabilising the longitudinal flow of air, consisting of 76 jet fans placed in the roof, is activated in case of a fire alarm, and allows the longitudinal flow of air to be controlled and facilitates smoke extraction. Smoke extraction is ensured every 100 m by 116 outlets with remote controlled opening, to concentrate the extraction power for sections of 600 m. The smoke extraction capacity at the Mont Blanc Tunnel has been brought up to 156 m³/sec per 600 m." (GEIE-TMB (2022)

[8] It is not generally possible to definitively state the LSA level of a tunnel based on publicly available information, as this requires access to the risk analysis results and information on the specific measures that have been taken to make the risk acceptable.

The vastly improved *ventilation service* that is now in operation covers not just the main tunnel but also the separate evacuation gallery and 37 secure shelters with separate ducting providing the ventilation.

6 Discussion

Had the concept of service assurance been understood prior to the Mont Blanc Tunnel incident and importantly considered by the organisations charged with operating and maintaining the tunnel, we believe the respective governments would have sought change to several of the services in place. Notably in requiring:

- a joined-up approach to communication between the control room services.
- an overarching joint emergency response plan.
- a better understanding of traffic flow compared with the air flow capacity provided by the existing ventilation service.
- a means of communicating with people who may be trapped in the refuge areas.
- greater assurance of the materials being carried through the tunnel and the mechanical state of the vehicles doing that transporting.

However, there is a level of conjecture in here because of the limited pre-fire evidence available to us.

There is greater evidence available since the incident which we have been able to call upon to inform our analysis but even then, this does not consider the services offered pre- or post-fire through the lens of service assurance. Consequently, we have had to make assumptions in our analysis.

The SAWG Guidance (2022) indicates that the criticality of a service should be considered in the form of an assigned LSA with the evidence to assure that service being proportionate to the LSA. Where evidence is deficient the LSA should inform what evidence needs to be constructed in the form of an assurance wrapper. Our analysis shows that the key service failures that contributed to the tunnel fire were of the highest LSA and lacked sufficient assurance evidence either from the service provider or formulated in what could be considered an assurance wrapper by ATMB (or SITMB).

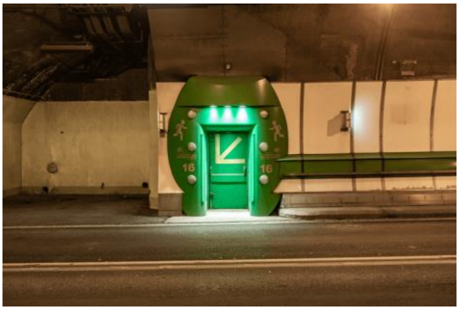

Fig. 12. Post-Fire emergency escape routes

Applying the guidance was able to highlight areas of concern in the service provision that should at least have prompted questions in the governing organisations who were accountable for those services. For example, users of the tunnel were not aware of the risks of remaining in their vehicles as opposed to seeking refuge in the available secure spaces. In the event of an incident the *Tunnel Operation service* should have been able to encourage users to vacate their vehicles and seek refuge. The problem, as Purser (2009) indicates, was that not only were there no such measures in place, but the refuges did not provide a means of escape to the outside and fresh air.

Our analysis indicates the lack of a *co-ordination service* was a significant factor in the way the accident played out and the introduction of an overarching organisation providing such co-ordination after the fire has gone a long way to addressing the service shortcomings we have considered.

One final discussion point which warrants consideration is the trade-off between tunnel safety and operational economics. The new tunnel safety measures (e.g., Figure 12) may be subject to commercial constraints. It is hoped that the independent *inspection service* and much improved regulatory oversight will ensure that GEIE-TMB maintain the managed flow of vehicles through the tunnel and the necessary quarantining and inspection of Heavy Goods Vehicles (HGVs) away from the tunnel entrance.

7 Conclusions and Further Work

Applying the SAWG Guidance (2022) on a real example has proved a valuable exercise in testing its true benefit. However, the limited assurance evidence available for the Mont Blanc Tunnel Fire, notably around the service provision pre-1999, and our need to hypothesise substantially on the service hierarchy, directs to further applications of the guidance to gain confidence in its practicality. Taking this work forward we will now look to identify accident examples where service failure or weakness played a contributory part but there is more assurance evidence available and potentially even an extant service hierarchy that can be critically analysed.

With regard to the application of the SAWG guidance in the early stages of the service lifecycle we must continue to promote its use across the safety-critical systems community. Related to this paper and specific to the safety of services supporting road tunnels, it would seem reasonable that we should offer to engage with the relevant organisations developing the service infrastructure for the forthcoming Stonehenge tunnel and Lower Thames Crossing.

Acknowledgments Many thanks to Mark Sujan for comments on a draft of this paper. Figure 2 is reproduced from flickr.com, https://www.flickr.com/photos/ausdew/38375386084/in/photostream/ All other figures are either reproduced from the respective referenced papers or original diagrams produced by the authors of this paper.

Best endeavours have been made to obtain permissions to use images. In all cases these are taken from public and widely-available sources.

Disclaimer All opinions expressed in this work are those of the authors and not their respective organisations. The analysis presented in this paper has no legal standing whatsoever. The purpose of this paper is not to discredit, contradict or challenge any existing accident analysis; the aim is simply to view the Mont Blanc Tunnel Fire incident through the lens of service assurance. The analysis is the authors' interpretation; they are not speaking on behalf of their employers

References

Bailey, C. (2004), One Stop Shop in Structural Fire Engineering, University of Manchester. https://web.archive.org/web/20181029052004/http://www.mace.manchester.ac.uk/project/research/structures/strucfire/CaseStudy/HistoricFires/InfrastructuralFires/mont.htm (accessed 1st October 2022)

Bettelini, M., (2022) 20 years after the Mont Blanc Tunnel fire – Lessons and legacy, Galleries and Great Underground Works No 142, June 2022.

Catmur, J., Parsons, M. and Sleath, M. (2022) A Step-by-Step Methodology for Applying Service Assurance in Nicholson, M and Parson, M, "Safer Systems: The Next 30 Years", SCSC-170, 2022, https://scsc.uk/r170:1 (accessed 01/10/2022)

Council directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network (2004) Official Journal L167, 30.4.2004, p. 39.

Duffe, P., Marec, M. and Cialdini, P. (1999) Joint report of the Italian and French administrative commissions of enquiry into the disaster that occurred on 24 March 1999 in the Mont Blanc Tunnel. République Française, Ministère de l'intérieur et Ministère de l'Equipment, du Transport et du Logement, Repubblica Italiana, Ministero dei Lavori Pubblici, 6 July 1999.

Directive 2004/54/EC of the European Parliament and of the Council of 29 April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32004L0054 (accessed 01/11/2022)

Durston, N., Parsons, M., Scott, A. and Simpson, A. (2019) The Principles of Service Assurance in Kelly T and Parsons M, "Engineering Safe Autonomy", SCSC-150, 2019, https://scsc.uk/rp150.6:1 (accessed 1st October 2022)

Elliott, S. and King, K. (2019) Service-based Safety Assurance: A provider approach in a challenging environment in Kelly T and Parsons M, "Engineering Safe Autonomy", SCSC-150, 2019, https://scsc.uk/rp150.6:1 (accessed 1st October 2022)

GEIE-TMB (2022) The Mont Blanc Tunnel Service Charter https://www.tunnelmb.net/public/files/301/carta-dei-servizi-ing-2022.pdf (accessed 06/11/2022)

GEIE-TMB (2022) One tunnel, two countries, fifty years of history, https://www.tunnelmb.net/en-US/history (accessed 1st October 2022)

Harris C, Parsons M and Simpson A (2018) Service-Based Safety Assurance in Kelly T and Parsons M, "Evolution of System Safety", SCSC-140, 2018, https://scsc.uk/r140/8:1 (accessed 1st October 2022)

IfM and IBM. (2008). Succeeding through service innovation: A service perspective for education, research, business and government. Cambridge, United Kingdom: University of Cambridge Institute for Manufacturing. ISBN: 978-1-902546-65-0

King, K., Parsons, M. and Sujan, M. (2020) A Service Perspective on Accidents in Nicholson, M and Parson, M, "Assuring Safe Autonomy", SCSC-154, 2020, https://scsc.uk/r154:1 (accessed 1st October 2022)

Lee, Y. S. & Ghazali, F. (2018). Major Functional Risks for Operation and Maintenance of Tunnelling Projects. ESTEEM academic journal. 14. 24-37.

Purser, D. (2009). Application of human behavior and toxic hazard analysis to the validation of CFD modelling for the Mont Blanc Tunnel fire incident. In: Proceedings of the Fire Protection and Life Safety in Buildings and Transportation Systems Workshop. 23-57.

Road Tunnel Safety Regulations 2007 (SI 2007/1520), Available at: https://www.legislation.gov.uk/uksi/2007/1520/made (accessed 06/11/2022)

Road Tunnel Safety (Amendment) Regulations 2009, Available at: https://www.legislation.gov.uk/uksi/2009/64/regulation/made (accessed 06/11/2022)

Road Tunnel Safety (Amendment) Regulations 2021, Available at: https://www.legislation.gov.uk/uksi/2021/552/regulation/made (accessed 06/11/2022)

SAWG (2020), Service Assurance Guidance v1.0, SCSC-156, published at SSS'20, February 2020, https://scsc.uk/r156:1 (accessed 01/10/2022)

SAWG (2021), Service Assurance Guidance v2.0, SCSC-156A, published at SSS'21, February 2021, https://scsc.uk/r156A:1 (accessed 01/10/2022)

SAWG (2022), Service Assurance Guidance v3.0, SCSC-156B, published at SSS'22, February 2022, https://scsc.uk/r156B:1 (accessed 01/10/2022)

Tarada, F. (2021), Road Tunnel Safety After the Mont Blanc Fire, Presentation to the Safety and Reliability Society, 30th March 2021, https://mosen.global/wp-content/uploads/2021/04/Road-Tunnel-Safety.pdf (accessed 01/10/2022)