THE BEST THING FEDRO HAS PROVIDED US WITHIN RECENT YEARS! EXPERIENCES FROM OVER 50 OPERATIONAL CONCEPTS FOR SWISS ROAD TUNNELS

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ABSTRACT

After a fire, various defects are discovered in the operating and safety equipment (OSE) of a tunnel! A truck enters a tunnel with an extended crane and damages the OSE in the entrance area! The system control of the tunnel ventilation fails! What to do?

In Switzerland, Regional Units (RU) are responsible for operating the national road tunnels. They are regularly confronted with these or similar issues. The options for further action are many: tunnel closure, tube closure, lane reduction, operation under minimum requirements or normal operation with/without measures. Other questions also arise: Act immediately or later? Who should be informed? Who decides?

The operating concepts (OC) for road tunnels enable the RU to correctly assess the situation in the event of system failures or external events (accident, fire, …), make quick decisions and involve the right people. This ensures the safety of road users and maximizes the availability of high-performance roads.

RU and planners can use the OC to optimize spare parts inventory. Components with long permissible downtimes do not need to be procured as spare parts. Components with short permissible downtimes or components whose failure would lead to operation under minimum conditions or to a tunnel closure must be available quickly and kept in stock as spare parts.

OC developed during the planning phase enables the planner to align his concepts at an early stage to clarify the availability and safety requirements of the project and agree them with the client. These include redundancy concepts, failure strategies and refurbishment concepts.

This article will share the experience of IG BeSt (ILF Beratende Ingenieure AG / WSP Ingenieure AG) from over 50 implemented OC and answer the question of why a RU employee describes them as the best that Federal Roads Office (FEDRO) has provided to RU in recent years.

Keywords: operational concept, operation under minimal requirements

1. INTRODUCTION

Modern road tunnels are highly complex infrastructure facilities. Their safe and efficient operation requires numerous technical, organisational and personnel resources. In cases of technical malfunctions, accidents or fire incidents, operators - the regional units (RU) - must quickly decide on measures to ensure the safety of road users and maintain the availability of national roads. Operational concepts (OC) for road tunnels, developed by the Federal Roads Office Winterthur in close collaboration with IG BeSt (ILF Beratende Ingenieure AG and WSP Ingenieure AG) and operators (RU VI and RU VII), provide a structured and practical foundation for this purpose. They enable the systematic evaluation of technical failures and external events, the derivation of suitable measures, and the targeted involvement of the relevant stakeholders. This significantly eases the burden on the RU and ensures clarity in critical situations, allowing for swift decision-making. This increases safety for all road users and ensures high route availability with minimal tunnel closure times and reductions in traffic capacity. This article highlights the practical advantages of operational concepts and illustrates their importance in tunnel project planning and operation. These insights are based on over 50 operational concepts implemented for Swiss road tunnels, as well as feedback from operators. The aim is to familiarise clients, planners and operators with the significance and benefits of these concepts.

2. OPERATIONAL STATES OF ROAD TUNNELS

Operational concepts for road tunnels distinguish three key states of operation, each of which has different requirements for measures, responsibilities and decision-making processes. These states are crucial for the structured evaluation of technical faults and events during tunnel operation.

2.1. Normal Operation / Permissible Deviation From Normal Operation

In this state, either no technical fault is present, or a technical fault or system failure exists that deviates from the target state, but which does not endanger road users' safety. Tunnel availability is maintained.

Generally, no special measures are necessary. However, faults must be resolved within a defined outage period (I0–I3, i.e. 24 hours to six months, see table 1).

Responsibility lies with the regional unit’s incident commander (ELG). In some cases, immediate action is required (e.g. manual switching) to ensure the safety of road users until repairs are completed.

Examples include individual failures of tunnel lighting or the failure of an HVAC-System.

Table 1: Permissible Outage Times
(* According to the OC, the permissible outage time does not begin with the first occurrence of a fault, but only once the damage has been clearly identified.)

Class	Intervention	Permissible Outage Time*	Significance for Operation
I0	immediate	6 to 24 hours	Critical faults must be resolved quickly. Immediate actions are usually required.
I1	short-term	< 72 hours	Fault of moderate urgency. Measures must be taken within three days.
I2	medium-term	< 3 weeks	Fault with lower risk. May require unscheduled lane/tube closures.
I3	long-term	< 6 months	Tolerable fault with minor impact. Resolutions can occur as part of regular maintenance.

2.2. Operation Under Minimal Requirements

This state involves a technical fault or system failure, in which case road user safety can only be ensured by immediate additional support measures, such as traffic metering, mobile ventilation or the closure of one driving direction. These measures restrict tunnel availability and increase the risk of traffic disruption. During this operational state, responsibility shifts from the regional unit’s incident commander to the FEDRO incident commander (ELA).

Supporting measures and restoration of affected systems must be initiated immediately. No specific deadlines are set for resolving faults. The tunnel will remain in this operational state until the repairs are complete and any remaining faults can be assessed as permissible deviations from normal operation.

Examples include the failure of smoke extraction or fire detection systems in one tunnel tube of unidirectional tunnels

2.3. Tunnel Closure

In this state, road user safety cannot be guaranteed due to major faults or damage to the operational and safety equipment (OSE), even with supporting measures in place. The tunnel must therefore be closed to eliminate risks. This will lead to traffic disruption with potentially regional impacts. In this case, responsibility immediately shifts from the ELG to the ELA.

The tunnel will only reopen once safe conditions have been re-established. Examples include the failure of smoke extraction or fire detection systems in bidirectional tunnels with bypass options.

In exceptional cases where there is no suitable bypass, tunnel closure may be avoided if the risks on the bypass route would be higher than in the tunnel. In such cases, operation under minimal requirements is initiated and the associated residual risks is accepted by FEDRO.

3. STRUCTURE OF THE OPERATIONAL CONCEPTS

The OC for road tunnels are modular and follow a proven, uniform structure. These consist of five main modules, each of which contains specific information and action guidelines.

3.1. Module 1: Imprint & Abbreviation Directory

This module includes administrative details such as the client, operator and owner, as well asa change log and distribution list. Of particular importance is the object-specific abbreviation directory, which clarifies all abbreviations used in the concept.

Winterthur branch / Regional Unit VII Tunnel

Tunnel Uetliberg

Closure! | Operation under minimum requirements required! | I0 = 6-24 h | I1 = < 72 h | I2 = < 3 Weeks | I3 = < 6 Months | Version 2.0 | Module 3 | M3_TUET_001

Overview of mandatory measures in the event of technical malfunctions

Nr.	Event	Classif.	Consequences	Immediate measure	Accompanying measures (functional replacement & risk reduction)				EVP-Nr.
①	②	③	④	Traffic/Operational and safety equipm./Infra./Information ⑤	Traffic ⑥	Operational and safety equipment ⑥	Infrastructure ⑥	Information ⑥	⑦
1.102.5	Failure of both transformers for the exhaust fans of one tube.		Total failure of the exhaust fans in this tube and thus total failure of the smoke extraction system.	**Information:** BLUR / VLZ: - Pol - ELG - NSU ELG: - StreMa - ELA **Traffic:** --- **Operational and safety equipment:** BLUR / GE VII BSA:Closure of one lane with TVR und VLS. **Infrastructur:** ---	**Function replacement:** NSU / Pol: Closure of a lane with scissor barriers and lane closure signage. **Risk reduction:** NSU: Signage indicating speed reduction to 60 km/h on open lane. GE VII / BLUR: Traffic metering with TVR.	**Function replacement:** BLUR / GE VII BSA: Manual ventilation control (see Module 4) FW: Provision of mobile SV including personnel if jet fans have failed at the same time. **Risk reduction:** ---	**Function replacement:** --- **Risk reduction::** ---	**Function replacement:** --- **Risk reduction:** Information to fire brigade ---	EVP 102 (MA)

① Table structure and numbering according to AKS CH
② Description of the technical malfunctions / system failure
③ Permissible downtime within which the fault must be rectified
Start time: Damage is known.
Failure to comply with permissible downtine: Information to ELA
④ Brief description of the consequences of the technical malfunction / system failure
⑤ Brief description of the immediate measures
Structured in traffic, operational and safety equipment , infrastructure & information
⑥ Brief description of the accompanying measures
Definition of responsibilities for each measure
⑦ Specification of the contingency planning number (EVP number)
Detailed information on the technical malfunction / system failure is described in the EVP (Module 4)

Figure 1: Explanations of the structure of Module 3 using an example (highlighted in light blue: failure with operation under minimum requirements) from the Uetliberg Tunnel (equipped with a semi-transverse ventilation system) [3] with a clear definition of responsibilities for each measure (underlined: e.g. BLUR – Urdorf Operations Control Centre)

3.2. Module 2: Tunnel Reflex Matrix

The tunnel reflex matrix is a key part of operational concepts, describing the automated responses of tunnel operations to specific events or conditions. It determines the actions triggered by the higher-level control system in the event of technical faults or safety-critical incidents.

3.3. Module 3: Overview of Measures

This central module provides a table listing all analysed technical faults and system failures. Entries are colour-coded as follows:

- **White:** Permissible deviation from normal operation
- **Light blue:** Operation under minimal requirements
- **Red:** Tunnel closure required

For each fault, the permissible outage time from I0 to I3 and the necessary immediate and supporting measures and responsibilities for each measure are clearly defined. In more complex cases involving immediate and supporting measures, Module 3 refers to contingency planning (CP), which is detailed in Module 4.

3.4. Contingency Planning (EVP)

Module 4 provides detailed descriptions of the complex faults defined in Module 3. Each CP includes at least:

- Description of the failure
- Consequences for operation and safety
- Detailed description of immediate and supporting measures
- Notes on tunnel availability and bypass options

The measures are categorised by traffic, OSE, infrastructure and information, and include concrete action instructions for responsible individuals.

3.5. Supplementary Documents

This module provides documentation on the standard operational and safety systems (OSE) of the tunnel, including the implemented redundancy concepts and failure strategies. It also contains notes and recommendations from the author of the OC, as well as information on the process of changes and mutations.

4. APPLICATION IN PRACTICE

Operational concepts for road tunnels are not just theoretical documents; they are essential tools for RU in their day-to-day work. They are applied in various operational situations. The possible use cases, along with their respective objectives, are compiled below.

Table 2: Typical use cases for operational concepts

Use Case	Example	Objective / Benefit
Technical fault / system failure OSE in normal operation	Failure of OSE such as: • Transformer • Escape route lighting • Ventilation control	• Assessment of impact • Initiation of appropriate measures
Support in event management	Events affecting OSE: • Fires • Accidents • Collisions with tunnel infrastructure	• Acceleration of event management • Evaluation and prioritisation of measures for route clearance
Tunnel renovations / modifications under traffic	Renovation of critical OSE with functional interruptions under traffic conditions: • MV switchgear • Ventilation control	• Preparation of work/measure planning • Fallback planning • Identification of optimisation potential
Spare parts inventory	• Definition of critical components based on delivery times & permissible outage times	• Optimisation of inventory • Maximisation of route availability • Synergy use of spare parts (different tunnels)

Training and education	• Introduction of new operator employees, • Training / refresher training	• Building operational competence • Safe and fast application of concepts

4.1. Technical Faults and System Failures

In the event of a fault, RU employees refer to the operational concept for the affected tunnel. Module 3 provides a tabular overview of all relevant failures, including their classification (permissible deviation, operation under minimal requirements or tunnel closure), the permissible outage time, the required measures and the responsibilities. For more complex cases, reference is made to the associated contingency planning in Module 4.

4.2. Support in Event Management

Even for external events, such as traffic accidents or fires, the operational concepts serve as a basis for decision-making. Depending on the severity of the event, various phases of event management are implemented (see Fig. 2). The operational concepts help to assess whether route clearance is possible and whether supporting measures are required.

4.3. Tunnel Renovations / Modifications Under Traffic

During planned tunnel renovations or modifications while the tunnel is in use, operational concepts provide initial guidance on the minimum required measures. Since interventions in the OSE are generally scheduled, additional measures are usually required. Table 3 shows an example of the conversion of an MV switchgear in a tunnel where there are no suitable bypass options.

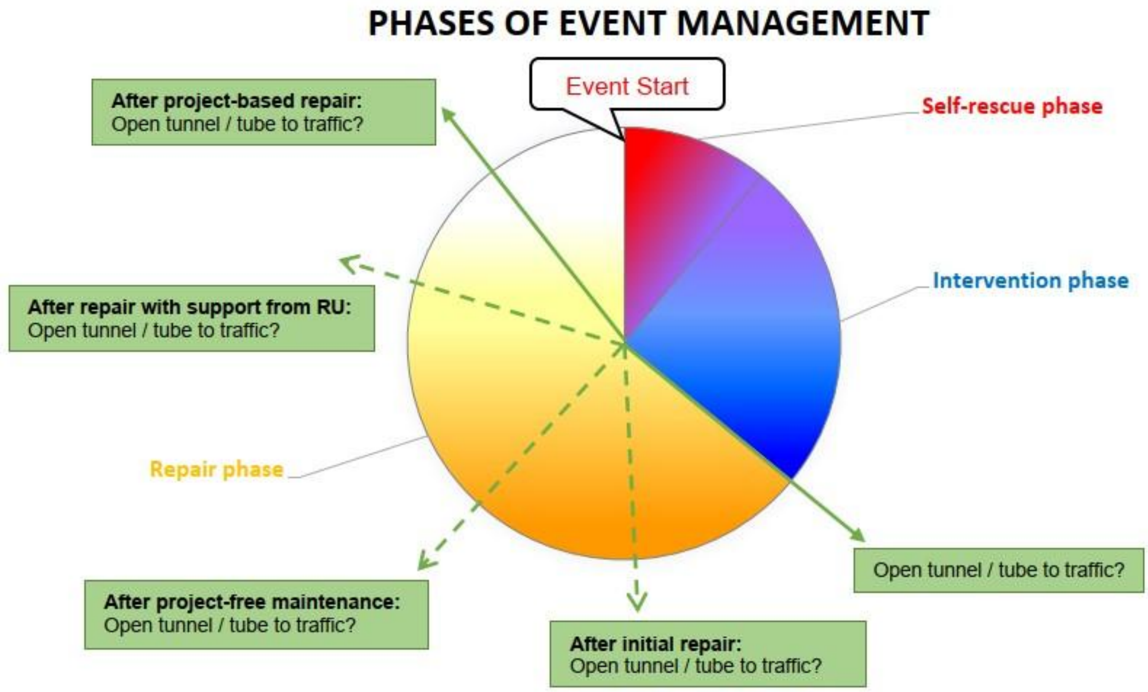

Figure 2: Operational concepts are applied in every phase when assessing route clearance. (derived from: Event Management Handbook, C+E Planing [1])

4.4. Spare Parts Inventory

Spare parts inventory is associated with high costs. Spare parts require storage space and must be procured and stored under specific climate conditions. Sometimes they also require maintenance to avoid storage damage. Therefore, it is crucial to keep on hand the components that are essential for ensuring the safe operation of tunnels and high route availability. These components can be identified in the OC. Those components that must be kept in stock are those whose failure would result in operation under minimal requirements or tunnel closure. Additionally, components must be stocked if their delivery times exceed the permissible outage time and if there are no alternatives for the failed component. Synergies between different tunnels can also be exploited to minimise overall inventory and associated costs.

4.5. Training and Education

In order to ensure that operational concepts can be applied safely and efficiently in an emergency, it is essential that RU personnel receive targeted training. OC form an integral part of initial and continuing education and are practised regularly in training sessions and learning checks.

New employees receive comprehensive training on operational concepts during their induction. This training covers not only the contents of Modules 1 to 5, but also the underlying systematics, the distribution of roles between RU, ELG and ELA staff, and the processes for technical faults and events.

The training is based on a standardised presentation format developed by RU VII and IG BeSt and includes basics and objectives of operational concepts, distinction from other concepts (e.g. emergency management), definitions and abbreviations, operational modes and accepted residual risks, interfaces to action plans and event management as well as practice-oriented exercises. Using real-life scenarios such as transformer, lighting or ventilation system failure, trainees practise applying the concepts.

They learn how to identify the fault in Module 3, to check measures and responsibilities and to initiate defined actions. These exercises foster understanding of and the routine in handling the concepts, thereby preparing staff for emergency situations.

Table 3: Application of operational concepts to planned renovations/modifications to BSA

Example: Uetliberg Tunnel	Operational Concept Measures	Measures for Conversion
The MS system is converted during operation and there is no bypass option. **<u>Colour code</u>** **Green**: Not required for a planned conversion measure as everyone has already been informed. **Black:** Measures that apply in both cases. **Blue:** Additional measures for planned	MS system failure: • Information from the police, head of operations GE VII, national road maintenance, fire brigade • Information from ASTRA operations manager • Closure of one lane using a traffic management system/tunnel traffic control (TVR) • Closure of the lane with scissor barriers and lane closure signage	Planned conversion of the MS system: • Testing of ventilation functions (longitudinal ventilation) • Informing the public to avoid the tunnel • Traffic is restricted to a single lane. • Use of emergency power generators for lighting, escape route signage, fire and flow measurement sensors,

interventions in the BSA	• Speed reduction to 60 km/h on open lane • Traffic control, e.g. with mobile traffic lights (to prevent congestion in the tunnel). • Connection of emergency power generators → Establishment of minimum functions (e.g. lighting) → Traffic metering with TVR → Manual ventilation control (longitudinal ventilation). → Use of mobile jet fans in the event of power failures	ventilation control and jet fans. • Yellow flashing lights and a reduced maximum speed limit • Permanent traffic monitoring and congestion avoidance in the tunnel by trained personnel • Preset permanent operation of longitudinal ventilation in the direction of travel, with manual control of steel fans by the area unit in the event of a fire. • Fire brigade on standby with emergency vehicles on site

5. WHAT MUST THE PLANNER OF OPERATIONAL CONCEPTS CONSIDER?

Operational concepts are primarily intended as a working and support tool for RU staff. As RU in Switzerland are not organised uniformly, their responsibilities and communication paths differ. Each RU also has its own processes for tunnel monitoring and fault message handling, as well as different RU requirements for implementing technical BSA solutions.

Therefore, operational concepts must address RU-specific processes and characteristics and cannot simply be transferred from one RU to another. They can only be created through close collaboration between the RU, the FEDRO and the planning office. All measures must be coordinated with the RU's capabilities. This includes personnel resources, material resources and distance between the operations centre/control centre and the tunnel.

A crucial aspect is the phased/stepwise development of OC, as these directly influence planning, tendering and the inventory of spare parts. During the planning phases, redundancy concepts, failure strategies, monitoring strategies and bypass options must be closely coordinated with the consequences and necessary measures for operating under minimum requirements or tunnel closure. The failure of a single component must not result in operation under minimal requirements or tunnel closure if the tunnel has high availability requirements.

OC must be developed during detail design (SIA Phase 32). All failures requiring measures must be monitored, and appropriate fault notifications must be sent to the operations control centre. Depending on the importance of the system and the measure, fault notifications can be prioritised. Considering the OC, the costs of spare parts, which must be tendered in the next project phase (SIA Phase 41), can be determined in this phase. Therefore, must be finalised by SIA Phase 41 at the latest.

6. SUMMARY AND CONCLUSION

Returning to the questions raised at the beginning of the abstract: Such events cannot be planned for and confront RU staff unexpectedly during daily business. What should be done? Six years ago, staff of the RU VI and VII had to answer these questions independently, hoping that all of their decisions to handle the event are correct.

Today the answer is simple: Use the OC!

Operational concepts for road tunnels enable RU staff to assess situations during system failures or external events (e.g. accidents or fires) quickly and accurately, make immediate decisions and involve the right people. Measures to maintain safe tunnel operation and high route availability are defined and coordinated with FEDRO. The remaining residual risks are known to and accepted by FEDRO. And most importantly: Operational concepts have repeatedly alleviated pressure on RU staff in situations like those described above.

- Situation assessment during events has become much easier!
- Reporting lines and responsibilities are now clearly defined!
- Everyone can now fully focus on their role and tasks in event management!

That is why a RU VII employee concluded: **'Operational concepts are the best thing FEDRO has provided us with in recent years!'**

7. REFERENCES

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