Identification of critical Tunnels in a Road Network

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SUMMARY
Bridges and tunnels on highways and major roads are key elements of the Trans-European Road Transport Network. In order to improve the security of these infrastructures regarding man-made hazards a comprehensive overview about number and different types existing in the different European Member States is necessary. In order to get this overview a survey among road operators in Europe was conducted. The paper describes the comprehensive analysis carried out concerning relevant tunnel types in Europe and presents a method to identify possible critical tunnels in a road network. Finally an outlook of the currently executed detailed investigation of critical infrastructures on a major highway links is given.

KEYWORDS: road network, road tunnel, critical infrastructure, protection measure, infrastructure failure, man-made hazards

1 INTRODUCTION
The European road network is of major importance not only for the mobility of European citizens but also for the European economy. Even small disruptions due to traffic restrictions or failure of road network elements can lead to severe traffic interference resulting in potentially high economic costs and negative environmental impacts. Bridges and tunnels are key elements of the road network, particularly as they can act as functional bottleneck. Such infrastructure objects may therefore constitute attractive targets for man-made attacks, and attractiveness added to by their accessibility and great potential impact on human lives and economic activity.

In order to identify the most critical infrastructure objects in the European road network and to protect them with appropriate measures an overview about existing bridge and tunnel types in the different EU member states is essential. Due to different construction standards in the European countries especially before the introduction of the Eurocodes and because of different environmental conditions (e.g. climate, topography, geology) many different types of bridges and tunnels exist in the EU. The investigation concentrates on bridges and tunnels on major highways of the Trans European Road Network (TEN-T roads). Based on the results of a survey among European road operators relevant bridge and tunnel types could be identified and categorised by major construction specifications (e.g. length, material, etc.). Based on the identified relevant bridge and tunnel types a classification concerning parameters, important to assess an objects criticality, is done.

This paper presents the tunnel results of the investigations. The bridge results have been presented at the 2011 IABSE-IASS Symposium [1]. The paper describes the comprehensive analysis carried out concerning tunnel types in Europe and presents a method for the identification of possible critical tunnels in a road network. Finally an outlook and first results of the currently executed detailed investigation of critical infrastructure failure on an example TENT-T highway link is given.

2 SURVEY AMONG EUROPEAN ROAD OPERATORS
2.1 Survey questionnaire
To identify the most common tunnel types in the EU, operators of Trans European Roads (TEN-T roads) were interviewed by means of a survey. To support this, different forms were developed to gather data about tunnel types in the different EU member states (Figure 1). The forms contain a big
variety of tunnel types considered as relevant. The contacted road operators were also asked to add new types if some types existing in their road network are not included in the initial forms. Additionally the road operators were asked to categorize their tunnel stock by type, number of tubes / cells and length (Figure 1).

<table>
<thead>
<tr>
<th>Types of Tunnels</th>
</tr>
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<tbody>
<tr>
<td>System</td>
</tr>
<tr>
<td>NATM Tunnel</td>
</tr>
<tr>
<td>(bored)TBM Tunnel</td>
</tr>
<tr>
<td>Immersed Tunnel</td>
</tr>
<tr>
<td>Cut and Cover Tunnel</td>
</tr>
<tr>
<td>Partly Covered Tunnel / Gallery</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Type No.</th>
<th>1 tube</th>
<th>2 tubes</th>
<th>1 tube</th>
<th>2 tubes</th>
<th>2 cells</th>
<th>3 cells</th>
<th>1 cell</th>
<th>2 cells</th>
<th>3 cells</th>
<th>1 cell</th>
<th>2 cells</th>
<th>3 cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 500</td>
<td>43</td>
<td>14</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<td>12</td>
</tr>
<tr>
<td>500-1000</td>
<td>13</td>
<td>12</td>
<td>1</td>
<td>5</td>
<td>14</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000-2000</td>
<td>12</td>
<td>7</td>
<td>1*</td>
<td>2*</td>
<td>12*</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000-5000</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>1*</td>
<td>1*</td>
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<tr>
<td>&gt; 5000</td>
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</tbody>
</table>

Figure 1: Final Survey form for identification of relevant tunnel types (completed example for one country)

### 2.2 General survey results

For the survey 32 road operators from 19 European countries were contacted. The selection of member states was done based on availability of contact persons and TEN-T road network length. The organization of responsibility for road operation and technical infrastructure data differs between EU member states. In many countries the responsibilities for road infrastructures are still at government level whereas the network operation is in the hands of private companies. In some countries it is private operators that have technical data for the infrastructure in an area that they are responsible for. In countries with many different private road operators like e.g. France (18 companies), Spain (38 companies) and Italy (24 companies) only selected operators responsible for a considerable length of road network have been contacted for the survey.

In the end 17 operators (53%) from 14 countries (74%) replied and provided data about their tunnels on major roads/highways including TEN-T roads. Due to the good levels of feedback to the survey the gathered data may reasonably be seen as representative for the European road network.

The survey questionnaire asked for network length (Figure 2) and number of tunnels, each subdivided in total length/number and length of/number on TEN-T-roads. The questionnaire was accompanied by the form for relevant types (Figure 1).

The total European network length covered by the survey is about 26.400 km of TEN-T roads. Due to the different answers of the countries concerning other roads (some considered motorways / highways, some also secondary roads), only the TEN-T road network length is taken into consideration and shown by country in Figure 2. The data for some countries is for the complete network (e.g. Germany, Austria, and Sweden). For other countries (e.g. Italy and France) only part of the road network is considered because the operator answering the survey is only responsible for part of the road network.
Figure 2: Length of TEN-T roads covered by the survey

2.3 Tunnel results

Stakeholders from 13 countries provided general data of overall 638 tunnels. In total 12 main tunnel types were identified as relevant in the EU (Figure 1). The tunnel types differ from one another regarding construction method/system (e.g. NATM tunnel) and cross section (e.g. 1 tube, 2 tubes).

The following figures show the distribution concerning tunnel length (Figure 3) and tunnel type (Figure 4). The analysis is presented in the following chapter 3.

Figure 3: Tunnel lengths for all countries
EUROPEAN TUNNEL TYPES

The reason for the classification regarding the parameters type and length was to identify limit values in order to determine which infrastructure - from a big stock of tunnels in a road network - are possible critical and must be investigated more in detail. From the analysis of all technical data gathered with the survey the following conclusions concerning European tunnel types may be drawn:

The most frequent tunnel types in Europe are NATM-tunnels (54%) and Cut and Cover tunnels (37%). The other tunnel types like TBM- and Immersed tunnel or Gallery are only built for special applications (e.g. river crossing, soft ground, etc.) if the standard solutions are technically not possible or if the construction method has economical advantages. This could be the case e.g. for very long tunnels in hard rock. Here the mechanised TBM tunnel could have cost advantages compared to the conventional NATM tunnel. Due to the potential extensive effects in case of damage or failure, tunnels under water (TBM (single shell) and Immersed Tunnel) are considered as sensitive and therefore as relevant concerning criticality.

Concerning tunnel length the short tunnels up to 500 m are dominant in the EU (56%). Tunnels longer than 1000 m (22%) are identified to be interesting concerning criticality. The reason why 1000 m has been chosen as a limit value is because of the regulations of the EC-tunnel directive [2]. Here a number of additional safety requirements must be investigated and considered if necessary for tunnels longer than 1000 m (e.g. ventilation system, emergency exits).

A summary of the classification of the relevant European tunnel types could be found in Table 1. The criteria for a classification concerning criticality mentioned here will be considered further in the development of a method to identify possible critical tunnels (cf. chapter 4).

Table 1: Classification of relevant European bridge and tunnel types based on all survey data collected

<table>
<thead>
<tr>
<th>Infrastructure</th>
<th>Parameter</th>
<th>Classification frequency</th>
<th>Classification criticality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel</td>
<td>Type</td>
<td>NATM and Cut &amp; Cover Tunnel</td>
<td>TBM and Immersed Tunnel</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>&lt; 500 m</td>
<td>&gt; 1.000 m</td>
</tr>
</tbody>
</table>
4 IDENTIFICATION OF CRITICAL TUNNELS

Based on the presented classification of relevant European tunnel types a method for the identification of possible critical infrastructure objects or better “for the exclusion of obvious not critical objects” has been developed. This method takes also traffic parameters into account because also a short tunnel could be critical in terms of a network perspective. The flowchart in Figure 5 gives an overview of the identification method for tunnels.

**DTV** = Average daily traffic volume of whole cross-section (both directions, all lanes)

**HGV** = Heavy goods vehicles > 3.5 t (Percentage of DTV)

**Figure 5: Flowchart for the identification of possible critical tunnels**
The method applied is that of a „rough filter“ which should help to identify a limited number of possible critical objects from a large amount of tunnels. The method considers 4 important criteria (influence factors):

- Criterion 1: Traffic volume
- Criterion 2: Damage potential
- Criterion 3: Economic impact
- Criterion 4: Probability

The criteria are checked in a top-down procedure, beginning with the 1st (basic) criterion for importance of an object (Figure 5). If an object fulfils one of the criteria the object is retained for further study, the subsequent criteria need not be checked. The method considers different steps: Step 1A consists of a basic check regarding the defined criteria. Only if the result of Step 1A is „yes“, the object specific relevance of the criterion is checked in Step 1B. Some possible criteria of object specific relevance are mentioned in the flowchart (Figure 5). More relevant criteria must be defined object specific by an engineer, who has knowledge of the infrastructure, i.e. someone who is responsible for the operation of a certain tunnel stock. If the result of Step 1B is also „yes“ the infrastructure is possibly critical and must be investigated in more detail in Step 2 which is not part of the method described in the flowchart. A possible method for Step 2 is described in sub-chapter 4.5. The method for the identification of possible critical infrastructures (Step 1A, 1B) has already been evaluated with the available tunnel data from Germany, Austria, Italy, Denmark and Great Britain gathered with the survey (cf. chapter 3). The criteria threshold values (e.g. for traffic volume) must be adjusted according to the infrastructure stock and particularities of different EU member states. Unified criteria for whole Europe are very hard to define.

4.1 Criterion 1: Traffic volume

Traffic volume is a basic criterion. All infrastructures with a very high traffic volume (DTV - average daily traffic volume) are considered to be very important for the road connection and should be checked in detail. The same should be done with infrastructure which has a high heavy goods vehicle (HGV) volume. In order to identify only infrastructure with a high absolute number of HGV vehicles this check is included in Step 1B.

The 2nd traffic volume criterion is used to identify objects, which have a relatively high traffic volume (DTV) and additionally a high HGV percentage. Objects satisfying Step 1A („yes“) should be directly investigated more in detail in Step 2. Due to the „and“ combination of the two parameters a Step 1B is not necessary for this 2nd traffic volume criterion.

The threshold value for criterion 1 must be chosen according to the traffic load of the investigated road network. This value could be very different in the EU member states. For example in Germany with a very high DTV on many highways a threshold value of 100,000 vehicles per day (both directions) and a HGV percentage of 20% could be feasible. For the 2nd traffic volume criterion 50,000 vehicles per day and a HGV percentage more than 15% have been proved to be realistic for Germany and some other EU member states.

4.2 Criterion 2: Damage potential

All long tunnels with bi-directional traffic (only one tube) should be investigated more in detail due to the possible negative impact on the road network if the tunnel is not available (no redundancy via a 2nd tube). The threshold value for a long tunnel could be set to 1000 m which comes from the EG Tunnel Directive [2]. Tunnels under water (river or completely in soft ground underground water) or directly under sensitive buildings are considered to be possibly critical and should be investigated more in detail. All immersed tunnels and TBM driven tunnels will fall under this criterion. With Step 1B tunnels crossing very small rivers, very deep under buildings or with a very low traffic volume (e.g. less than 10,000 vehicles/day) are excluded from a detailed investigation in Step 2. These tunnels could be considered as not critical concerning criterion 2 and will be checked further with criterion 3.
4.3 Criterion 3: Economic impact

Tunnels that are very hard to rebuild (i.e. have a long re-construction time) are considered to be potentially critical. If for this infrastructure operation or part operation (more than about 50% of the previous DTV) could be easily resumed with a provisional construction, this is considered as object specific not critical (Step 1B) and Step 2 need not to be executed. An example is a tunnel with 2 tubes: if one tube is blocked, traffic could still flow through the 2nd tube.

Due to the often missing information about reconstruction costs and the problem to define a threshold value for costs, this criterion has not been chosen for the estimation of economic impact. Reconstruction time has been chosen instead. The threshold value for a long reconstruction time could be e.g. more than one year. Reconstruction time means in this context only the time for construction works and does not include damage assessment, tender procedure, awarding and design works. Especially the necessary time for tender procedure and awarding differs from country to country. For the estimation of the reconstruction time of tunnels the construction time of the initial tunnel construction could be used.

4.4 Criterion 4: Probability

For the probability of attack only the symbolic value is considered as relevant. Only objects (mainly valid for bridges) internationally known should be considered as relevant. Tunnels with a symbolic value are considered as very rare. There is no Step 1B for infrastructures with a symbolic value, because it is a yes / no decision. The accessibility of the structure has not been chosen as relevant for this criterion, because most of the road infrastructure is easy accessible and is therefore a simple target for people with malicious intent. This was also result of the survey.

4.5 Procedure for a detailed examination (Step 2)

The steps for a detailed investigation of an objects criticality in a risk assessment could be as follows:

1. Determination of decisive scenarios for the tunnel (e.g. explosion and fire scenario)
2. Determination of the scenario probabilities (tools: fault- and event tree analysis)
3. Calculation of the direct consequences due to the chosen scenario
   a. Structural damage (tools: fire simulation, explosion impact calculation)
   b. Fatalities (tools: CFD models, pedestrian movement models)
4. Calculation of the indirect consequences due to the scenarios
   a. Network related effects of infrastructure failure (tool: traffic flow simulations)
   b. User costs due to additional travel time
   c. Other socio-economic consequences (e.g. environmental costs)
5. Calculation of the risk

The result of the risk calculation for different objects allows a comparison of objects and a possible ranking of tunnels according to criticality. If the level of acceptable risk could be defined (which is often a problem) the result of the risk calculation could be checked against this threshold value and allows a direct conclusions about the criticality of a single tunnel.

5 EXAMPLE TEN-T LINK

The method described in the previous chapter has been applied to an example TEN-T highway link based on the technical infrastructure data gathered with the survey. The Brenner Highway link (E45) from Munich (Germany) via Innsbruck (Austria) to Modena (Italy) crosses the Alps and has many bridges and tunnels (Figure 6). Concerning tunnels the majority of tunnels are short (<500 m) on the Brenner link. There are only 4 long tunnels between 500 and 1000 m on the Italian A22. Nearly all tunnels were built as NATM tunnel or gallery.
For the Brenner highway connection from Munich to Modena (E45) the results of Step 1A are as follows:

11 (of 22) tunnels must be investigated more in detail in Step 1B and/or Step 2:

- 4 tunnels due to Criterion 1
- 1 tunnel due to Criterion 3
- 6 tunnels due to Criterion 4

This shows that the method for the identification of possible critical tunnels could considerably reduce the number of tunnels to be investigated more in detail. The 6 tunnels with symbolic value (according to the local operator) have no international symbolic value and should therefore not be considered to be possible critical. Tunnels with a high symbolic value are generally considered to be very rare. The 4 tunnels due to Criterion 1 met the 2nd traffic volume criterion and could therefore be investigated directly with Step 2 of the method (detailed investigation). Thus there are 4 tunnels remaining which should be investigated more in detail in Step 2 of the method and one tunnel in Step 1B.

The application of Step 2 of the method for 2 example tunnels on the E45 is currently under examination. Results will be presented at the symposium.

6 CONCLUSIONS AND OUTLOOK

A large number of technical tunnel data has been gathered with the help of a survey among European road operators. The available data stock could be considered as representative for Europe because more than half of the European member states participated in the survey. Based on the technical data available the most relevant European tunnel types have been identified and classified. For the 12 relevant tunnel types the overall tunnel length and the construction method (e.g. NATM tunnel) have been identified as relevant for classification. Tunnel classification is subdivided into frequency and criticality.

Based on the presented classification of relevant European tunnel types a method for the identification of possible critical infrastructure has been developed and tested with example data from the survey. The proposed method to identify critical tunnels could be applied to every road network. It should help owners and operators to filter their tunnel stock and by this to focus on the decisive infrastructure of their road network. The method could be also helpful for the national implementation of the European directive 2008/114/EC [3]. The identified possible critical tunnels (Step 1A) must be investigated more in detail with the help of further object specific expert knowledge (Step 1B) or finally with a detailed risk assessment (Step 2). Depending on the outcome of this detailed analysis, the calculated risk and the conclusions concerning criticality, additional measures to improve the tunnels security could be implemented by the operator. The risk reducing influence or “effectiveness” of additional security measures could be investigated with the proposed procedure for detailed investigation (risk assessment) as well. The detailed investigation of 2 example tunnels with Step 2 of the method presented in this paper is currently under progress and will be finished end of 2011. Results of the detailed risk assessment will be presented at the symposium.
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