Deterministic Scenario Analysis:
An Approach to Improve Transport Safety of Infrastructure Projects during the Decision-Making Process

Sandra IJsselstijn MSc
Delft University of Technology, Faculty of Technology, Policy and Management, Section of Transport Policy and Logistics’ Organisation
DHV B.V., Environment and Transportation

Introduction / Problem Definition
In present risk policy, quantitative risk analyses play an important role for assessing if a system meets the safety requirements. During the last decade, several manuals like the Red Book (probabilities) [1], the Yellow Book (physical effects) [2], the Green Book (damage to people and subjects) [3], and the Purple Book (guidelines) [4] were developed for quantitative risk analyses. Although quantitative risk analyses are widely used and well embedded in decision-making processes among risks of infrastructure projects, they are not always a satisfactory approach for safety decisions in a multi-actor environment. This was shown by experiences with large infrastructure projects like the Westerschelde tunnel, the High Speed Railway connection, the Betuweroute and the development of Schiphol Airport [5]. The most important restrictions of quantitative risk analyses are:

• quantitative risk analyses are a generic technique, which means that specific and environmental features that can be important for the outcome of the risk assessment are not taken into account;
• quantitative risk analyses are not an optimal communication technique, because rescue and emergency services, involved persons, and society do not think in terms of probabilities, but in terms of effects;
• quantitative risk analyses can only be applied to a detailed system design level, because it can not handle the great deal of uncertainty in earlier design phases.

Therefore, a deterministic scenario analysis is being developed as a complementary analysis. A deterministic scenario analysis is a qualitative multi-actor approach that can be used for assessing and improving safety of infrastructure projects. In the analysis, a limited number of critical accident scenarios are designed describing accident processes of potential or actual sequences of events in time as a dependent variable, in a specific context and operating environment [6]. With these critical accident scenarios, infrastructure projects including technical systems, users and stakeholders, and rescue and emergency services can be evaluated and possible safety bottlenecks can be identified.

During the last few years, the relevance of a deterministic scenario analysis as an additional safety decision-making support tool is more and more being recognized:

• In 2003, the National Institute for Public Health and the Environment developed a risk policy-making strategy [7] that focuses on the layered structure in decision-making and the position of different types of risk analyses, including a deterministic scenario analysis, in decision-making.
• In 2003, the Ministry of Transport, Public Works and Water Management, the Ministry of the Interior and Kingdom Relation, and the Ministry of Housing, Spatial Planning and the Environment developed a policy document concerning tunnel safety [8]. This policy document focuses on a methodology containing probabilistic risk analyses as well as a deterministic scenario analysis to gain insight into the safety performance of a tunnel.
• In 2004, the Parliamentary Inquiry Committee Duivesteijn [9] identified several phases of policy decision-making processes with deficiencies in risk assessment procedures. New policy-making support procedures and notions for multi-level decision-making are needed, because of the multi-actor context.
**Scope / Research Approach**

The goal of this PhD. research is the development of a deterministic scenario analysis in order to improve transport safety of infrastructure projects during the decision-making process. Therefore, three more specific research questions containing a number of sub questions have to be answered:

How should the scenarios of a deterministic scenario analysis be defined scientifically?
- Which types of scenarios can be distinguished?
- In which fields are scenarios applied?
- How are scenarios in different fields of application defined?
- Which definition(s) of scenarios is (are) useful for a deterministic scenario analysis?

How should a deterministic scenario analysis be positioned in the decision-making process of infrastructure projects?
- Which moments and levels of decision-making concerning infrastructure projects can be distinguished?
- Which stakeholders are involved at these different moments and levels of decision-making?
- How are risk analyses positioned in the decision-making process of infrastructure projects?

How should a deterministic scenario analysis be worked out to become practically feasible?
- Which steps in the methodology of a deterministic scenario analysis can be distinguished?
- Which stakeholders should be involved in a deterministic scenario analysis?
- How can critical accident scenarios be designed?
- How can transport safety of infrastructure projects be assessed with help of critical accident scenarios?

During the research, these questions may change and/or other questions may be added because of new and better understandings concerning deterministic scenario analyses.

To answer these questions, three types of research will be done: literature review, interviews and case studies. Case studies will be the most important type of research and will be provided by DHV and Delft University of Technology. Case studies create opportunities to test the instructions for using a deterministic scenario analysis. By testing the instructions, the practical utility of the instrument can be improved. Case studies containing a deterministic scenario analysis for the (re)design of infrastructure projects will be preferred. However, if necessary, also case studies containing parts of a deterministic scenario analysis or concerning other projects than infrastructure projects (for example industrial parks or shopping malls) will be done.

This PhD. research results in a dissertation that will include instructions for using a deterministic scenario analysis. These instructions will not only describe the methodology of a deterministic scenario analysis (how to design critical accident scenarios), but also at which moment in the decision-making process of infrastructure projects the analysis should be applied and which stakeholders should be involved.

The structure of the dissertation will be as follows:

Chapter 1: Introduction
Chapter 2: Deterministic scenario analysis (history, differences with probabilistic risk analyses, etc)
Chapter 3: Scenarios (definitions, applications, etc)
Chapter 4: Position of deterministic scenario analyses in decision-making processes of infrastructure projects
Chapter 5: Instructions for using a deterministic scenario analysis
Chapter 6: Conclusion
Relevance (Scientific / Societal)
This PhD. research delivers scientific expertise on:

- the further development of the distinction between two types of decision-making: scenario-based (how) versus frequency-based (how often).
- the further development of the distinction between four types of uncertainty in decision-making processes: data uncertainty, method uncertainty, decision-making uncertainty and scenario uncertainty.
- the development of critical accident scenarios that make intervention on accident processes and causality possible.

This PhD. research delivers societal arguments on:

- safer infrastructure projects because of the possibility to take radical safety measures ‘high and early’ in the decision-making process. Because of the ‘high and early’ application of a deterministic scenario analysis, it is possible to take radical safety measures if necessary. When the analysis is applied ‘late and low’ in the decision-making process, many of these radical changes can not be taken anymore.
- less infrastructure projects exceeding the budget because of expensive safety measures ‘late and low’ in the decision-making process. The ‘high and early’ application of a deterministic scenario analysis prevents stakeholders from dealing with expensive safety measures with a limited scope, ‘late and low’ in the decision-making process [10]. Because of the ‘high and early’ application, a good insight in the system can be gained and (relatively cheap) measures can be discussed immediately in the decision-making process.
- a communication technique that stimulates the commitment of stakeholders of infrastructure projects. Infrastructure projects are characterized by many stakeholders with different views on safety that can lead to conflicting interests. In that case, a deterministic scenario analysis can serve as a communication technique. By taking all relevant safety aspects of the infrastructure project into account in the decision-making process, the commitment of stakeholders can be stimulated [11].

Results
During the last two years, much literature has been studied concerning the history of safety thinking, the differences between probabilistic risk analyses and deterministic scenario analyses, different ways of dealing with risks, and different types of uncertainty in decision-making processes. Besides the literature review, also several case studies including (parts of) a deterministic scenario analysis have been done. This paper shows some of the results.

History of safety thinking
In the past, various ‘schools of safety thinking’ have been developed representing different ways of safety thinking. McIntyre [12] distinguishes three ‘schools of safety’:

Transportation Tort Law School
The Railroad Safety Appliance Act (1893) is the starting point of the ‘Transportation Tort Law School’ and the historical origin of patterns in transportation safety thinking. It requires railroad cars to be safely equipped to decrease the number of accidents involving railway workers. The Railroad Safety Appliance Act brought immediate and striking improvement by reducing the accident rate to railway workers and passengers, but had also another influence. Railway organizations discovered the positive effects of safety on their business, which increased the improvements in safety. The knowledge that the safety of their employees and passengers paid dividends was a milestone in safety thinking. Lorenzo Coffin, the first lawyer of rail transportation safety, deserved full appreciation in the U.S. transportation safety history, because of his opinion that ‘safety was everyone’s business’ and his work in drafting the Railroad Safety Appliance Act. Coffin’s efforts resulted in the tradition of governmental intervention to regulate the safety of transportation.
This also influenced other forms of transportation and Coffin was followed by people like Ralph Nader in the automobile industry and Mary Schiavo in the aviation sector. From this development, an engineering design approach emerged focusing on certification and standardization of technical designs and products [13].

Reliability Engineering School
The ‘Reliability Engineering School’ is based on the problems of maintenance, repairs and failures during the Second World War. These problems fuelled the development of techniques in probabilistic risk assessment. The drive to understand the likelihood of failures, led to the application of probabilistic risk assessment in many high-risk industries [13].

The fundamental thought of the Reliability Engineering School is that safety is achieved through reliability, and reliability is further reinforced by redundancy. However, the tragic Swiss Air 111 accident in September 1998 off the coast of Halifax, a ‘high reliability’ airline with an impeccable safety record, underscores the challenge of understanding ‘the dynamics of accident causation’ outlined in the text Human Error by James Reason. As Reason [14] has pointed out, the major failing of probabilistic risk assessment was revealed in its focus on hardware failures and its inability to accommodate human failures. This resulted in a new science of human reliability analysis. With this new science, the reliability concept has expanded from the technical aspects into the organizational aspects of systems [13].

System Safety Engineering School
No discussion of the ‘Systems Safety Engineering School’ can be conducted without reference to Willie Hammer’s authoritative text, Handbook of System and Product Safety. According to Hammer [15], it is a misconception to assume that by eliminating failures, a product will be safe. He recognized that there are also other causes of accidents: dangerous characteristics of the product, human action, extraordinary environmental factors, or combinations of these. Roland & Moriarty [16] reinforced Hammer’s view by pointing out that a failure is when something functions in a way in which it was not intended. However, a failure can occur without loss and accidents have happened without failure. That is why system safety engineering focuses on hazards (what can go wrong) instead of failures (what can fail).

The main objective of system safety engineering is to identify hazards, and through design, try to prevent them from causing harm or try to reduce the risks to acceptable levels. This is based on the principle that “the most effective means to avoid accidents during system operation is by eliminating or reducing hazards and dangers during design and development” [12]. This is also shown in the following figure [Petrella 1975 in 16].

In addition to the Transportation Tort Law School, the Reliability Engineering School and the System Safety Engineering School, Stoop [13] describes a fourth ‘school of safety thinking’:
Safety Deficiency and System Change

In 1984, Charles Perrow introduced the concept of ‘Normal Accidents’ [17]. With this concept, he changed the perspective from operator error into a system safety deficiency. Risks inherent to the design of a system would become the normal outcome of the system performance. Systems with complex interactions and tight couplings are more likely to have a ‘system accident’ than other systems. Given these system characteristics, multiple and unexpected interactions of failures are inevitable.

In this school, separating the mission and efforts of accident investigations from the allocation of blame and interests of major stakeholders is crucial. The focus is on safety critical characteristics in the structure, culture, contents and context of the system with respect to its safety critical performance. This school no longer focuses on ‘deviation’ from a normative performance, but refers to ‘system deficiencies’. [13]

After discussing the different ‘schools of safety thinking’, it becomes clear that probabilistic risk analyses have their origin in the Reliability Engineering School while deterministic scenario analyses originates from the System Safety Engineering School.

Differences between probabilistic risk analyses and deterministic scenario analyses

The most important difference between probabilistic risk analyses and deterministic scenario analyses is the goal of both analyses. Probabilistic risk analyses are aimed at calculating the individual risk and the societal risk to establish if a system meets the safety performance level [18]. The quantification of these risks allows decision-makers to compare risks at different locations and risks of different activities, and to set standards for the acceptability of risks [19]. Deterministic scenario analyses are aimed at analyzing accident processes to search for possibilities to control these processes.

Other important differences between quantitative risk analyses and deterministic scenario analyses are shown in the table below.

<table>
<thead>
<tr>
<th>Probabilistic risk analyses</th>
<th>Deterministic scenario analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>The goal is calculating the individual and the societal risk to establish if the system meets the safety performance level</td>
<td>The goal is analyzing accident processes to search for possibilities to control these processes</td>
</tr>
<tr>
<td>The probability of a scenario is smaller than 1</td>
<td>The probability of a scenario is equal to 1</td>
</tr>
<tr>
<td>As many as possible scenarios are examined superficially</td>
<td>A limited number of critical scenarios is examined in detail</td>
</tr>
<tr>
<td>The effects of a scenario are calculated (mainly quantitative)</td>
<td>The effects of a scenario are described (mainly qualitative)</td>
</tr>
<tr>
<td>The result is the individual risk and the societal risk or F/N-curve</td>
<td>The result exists of descriptions and images of the accident processes</td>
</tr>
<tr>
<td>The result can be used to optimise the technical process</td>
<td>The result can be used to optimise the operational process</td>
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</table>

Different ways of dealing with risks

Slovic et al. [20] distinguish two fundamental decision-making processes in which human beings comprehend risk: the ‘analytic system’ and the ‘experiential system’. The ‘analytic system’ uses algorithms and normative rules, such as probability theory, formal logic and risk assessment, and is characterized by ‘risk as analysis’. The ‘experiential system’ is intuitive, fast, mostly automated, and not very accessible to conscious awareness. This system is characterized by ‘risk as feelings’ and focuses on affect. “Affect means the specific quality of ‘goodness’ or ‘badness’ (1) experienced as a feeling state (with or without consciousness) and (2) demarcating a positive or negative quality of a stimulus.”

However, like Slovic et al. state, “it can not be assumed that human beings can understand the meaning of and properly act upon even the simplest of numbers such as amounts of money or numbers of lives at risk, unless these numbers are infused with affect”. Hendrickx [21] proved that risk assessments are based on both frequency information and scenario information. People prefer one of these types of information depending on their position in the decision-making process. In practice, people more often apply causal reasoning than statistical reasoning. However, this does not mean that frequency information has become redundant. Frequency information can be used for establishing priorities within the problems that were found [22].
Nowadays, it is more and more recognized that the analytic (probabilistic) system and the experiential (deterministic) system are complementary ways in which human beings comprehend risk. Finucane et al. [23] have characterized the interaction between the analytic system and the experiential system as ‘the dance of affect and reason’. “While human beings may be able to do the right thing without analysis, it is unlikely that we can employ analytic thinking rationally without guidance from affect.” [20]

**Different types of uncertainty in decision-making processes**

Different types of risk analyses are the result of different types of information needed during decision-making processes [7]. Decision-making processes deal with different environments and different types of uncertainty. The National Institute for Public Health and the Environment (RIVM) defines several classes of decision-making contexts that, in their turn, define different types of risk analyses. The following table shows the positioning of various risk analysis methodologies [24].

<table>
<thead>
<tr>
<th>Knowledge about likelihood</th>
<th>high</th>
<th>low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge about effects</td>
<td>Conventional design:</td>
<td>Precaution:</td>
</tr>
<tr>
<td></td>
<td>Quantitative Risk Analyses</td>
<td>Simulation / Modelling</td>
</tr>
<tr>
<td></td>
<td>Data uncertainty</td>
<td>Method uncertainty</td>
</tr>
<tr>
<td>low</td>
<td>Multi-actor decision-making:</td>
<td>Scenariuncertainty</td>
</tr>
<tr>
<td></td>
<td>Fuzzy Logic / What-If analysis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Decision-making uncertainty</td>
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</table>

Depending on the level of knowledge about likelihoods and effects, other methods for decision-making are needed. When people have a lot of knowledge about the likelihood and effects of an accident, they can use quantitative risk analyses to calculate the risks. However, data uncertainty, the result of assumptions and estimations made when not all of the quantitative information needed is available, can make quantitative risk analyses unreliable. When people do have little knowledge about the likelihood and effects of an accident, a deterministic scenario analysis is the best method for gaining insight into the risks. With a deterministic scenario analysis, the nature of uncertainty moves from data uncertainty to scenario uncertainty. Designing a wrong or incomplete set of critical accident scenarios can result in a less safe system, because of one or more undiscovered safety bottlenecks. So, the quality of the analysis depends strongly on the set of designed scenarios.

**Case studies**

The following case studies including (parts of) a deterministic scenario analysis have been done:

- a study in the safety impact of the proposed changes of the safety regime of the Willemsspoortunnel in Rotterdam [25].
- a study in the risk of a collision between a high-speed railway train and a conventional freight or passenger train at four switches [26].
- a quick scan scenario analysis concerning the security of the high-speed railway connection [27].
- a scenario analysis concerning the security of a part of the high-speed railway connection [28].
- a quick scan scenario analysis to distinguish different design alternatives of the Trekvliettracé in The Hague [29].

**Future research**

In the next years, hopefully some more case studies including (parts of) a deterministic scenario analysis will be provided by DHV and Delft University of Technology. However, the case studies that have been done will be analyzed to develop instructions for using a deterministic scenario analysis. These instructions will describe the methodology of a deterministic scenario analysis (how to design critical accident scenarios). Besides the methodology, also the position of deterministic scenario analyses in the decision-making process of infrastructure projects will be determined.
References