

# On the Regulation of Life Safety Risk

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**ABSTRACT:** The present paper takes up the issue of appropriate choice of metric for life safety and health related risks in a regulatory context addressing effects of temporal and spatial scales for their consistent quantification and comparison across societal sectors, industries and application areas. Starting point is taken in a short outline of what is considered to comprise the present best practice rationale for life safety and health risk regulation. Thereafter, based on selected principal examples from different application areas, inconsistencies in present best practice risk quantification in a regulatory context are highlighted and discussed. It is identified and explained that the principle of decision optimization and conjoint fulfillment of the marginal lifesaving principle does not render the assessment of the individual life safety risks for specific individuals relevant. Nor is the resulting absolute level of individual life safety risk subject to assessment of acceptability. It is highlighted that a major cause of inconsistency in risk quantifications and comparisons originates from the fact that present regulations partly address societal activities and partly address applied technologies; in some cases take the perspective of individuals and in other cases address the performance of applied technologies. It is furthermore shown that the typically applied averaging of individual risks over time and space may result in unintentional masking of poorly performing activities and applied technologies. Finally, a proposition is made on how the individual life safety risk may be assessed and compared consistently and uniformly over different activities and applied technologies.

## 1. INTRODUCTION

Over the last half century significant efforts have been devoted by the scientific community in the area of risk and reliability informed decision making on the development of frameworks, methods and tools in support of management of life and health related risks in society. In this the focus has been directed on the knowledge consistent quantification of risk and reliability. Comparatively little efforts have been devoted by the scientific community on the development of the regulatory framework for societal management of life safety and health risks. This in turn has resulted in risk regulations with poor consistency and inappropriate variability across

societal activities and technologies. At present even experts from different application areas within the risk and reliability profession vividly disagree on the proper interpretation of regulatory requirements, the appropriate choice of metrics as well as the corresponding choices for temporal and spatial scales for the quantification and comparison of life and health related risks. An important but unfortunate effect of this is that substantial knowledge provided by high quality risk and reliability assessments cannot be consistently utilized for improving risk management; with a consequential loss of potential for sustainable societal developments.

The present paper addresses regulation of life safety risks for societal activities and applied technology with a focus on why and how to quantify risks associated with life safety and health. Focus is here directed on the regulation of activities having at least a slight element of involuntariness such as e.g. residence, transport, nourishment and occupation. Risks for individuals arising from voluntary leisure activities such as sports, hiking, etc. may indeed also be relevant in a risk regulation context, however, are not specifically addressed in the present paper. Starting point is taken in the presentation of a general framework for life safety regulation closely following the recommendations of the Joint Committee on Structural Safety (JCSS, 2008) and the new revision of ISO 2394 General Principles on Reliability of Structures (ISO, 2015). This framework does not prescribe maximum acceptable levels of life safety risks for individuals. However, it underlines the importance of assessing the resulting absolute levels of risk as a means of monitoring whether the applied best practices are performing appropriately in cross comparisons between technologies and procedures applied across the manifold activities in society facilitated by technology. It is in this context that the metrics of life safety and health related risks are revealed: how can risks be quantified such as to accommodate the most relevant and consistent comparisons across different applied technologies and societal activities. This issue is discussed in some detail in the context of examples from different application areas. It is furthermore highlighted that different perspectives on risk regulation, whether activity or technology focussed can be relevant in different situations. Moreover, by examples it is shown that the appropriate choice of risk metric is not always obvious as risks may be assessed and/or averaged relative to different temporal and spatial scales. As this poses a fundamental problem for the overall coherency in societal safety management across different societal

sectors and industries the paper closes with a proposition for a metric of individual life safety risks which facilitates risk quantification and comparison over different societal activities as well as the applied technologies supporting these.

## 2. FRAMEWORK FOR LIFE SAFETY RISK REGULATION

### 2.1. On the objective of life safety risk regulation

Ultimately, the purpose of life safety risk regulation is to ensure that the individuals in society are safeguarded to the highest affordable level and such that no individuals engaged in societal regulated activities are exposed to excessive levels of life safety and health related risks.

By the term *affordable* reference is made to the conditions that 1) absolute safety, from first principles, is unachievable and 2) society can only afford to allocate a limited amount of resources for life safety management. The implication of these two conditions is that life safety regulation must ensure that societal resources are applied efficiently and justly for the purpose of life safety management.

The notion *societal regulated activities* is introduced in order to highlight that only some of the activities in society are, can and probably should be regulated. The life safety risks which may be eligible for regulation are those which arise from normal participation of individuals in the activities supporting the functions of society. The regulation of life safety and health related risks must thus address on the one side the activities in which the individuals engage, and on the other side the technologies and the organizational procedures for their implementation.

With the term *excessive levels of life safety risks* reference is made to life safety risk levels which are judged too high compared with the life safety risks which are normal for the broad range of applied technologies in society. There is substantial vagueness in this definition as both the terms *too high* and *normal* are highly

subjective. Indeed, as the life safety risk level associated with different applied technologies, as will be outlined later, depends on the efficiency of available means for risk reduction, the societal optimal levels of life safety risks vary over different activities and corresponding applied technologies. For this reason both the level of life safety risk which can be considered to be normal and too high depend on the activity and applied technology and must be assessed correspondingly. The choice of appropriate metric for the quantification of life and health related risk, with due consideration of corresponding domains with respect to activity, applied technology, time and space, forms a main focus of the present paper. However, before progressing on this issue, the underlying principles for the regulation of life safety and health related risks will first be outlined.

## 2.2. General principle for life safety and health related risk regulation

For what concerns the acceptability of decisions which imply life safety risks for individuals, the principle of marginal lifesaving costs applies as recommended by the Joint Committee on Structural Safety (JCSS, 2008) and implemented into the recently revised ISO 2394 (ISO, 2015). In Faber and Maes (2008), where premises and formats for risk regulation are considered in more detail, it is outlined how the LQI principle may be utilized consistently in the context of the ALARP framework - the presently leading best practice format for life safety risk regulation.

The philosophy underlying this framework is that decisions relating to societal activities and how applied technology best support such activities are subject to optimization. In principle the preferences represented in the optimization, i.e. objective function and possible constraints, may be freely chosen by the decision maker. However, the domain of acceptable decisions is bounded downwards by the marginal lifesaving principle. Investments into lifesaving and health improving risk reduction measures must comply with the marginal lifesaving principle such that at least a certain amount of economic resources

must be spent or committed for reducing risks. The investments, which can and should be spent to save life or to improve life expectancy at good health, may appropriately be determined through the Life Quality Index (LQI) (Nathwani et al., 1997). The principle and its application are illustrated in Figure 1. The decision alternatives indicated on the x-axis are ordered in accordance with reducing life safety risks. The feasible domain of decision alternatives is determined on the basis of pure optimization from the perspective of the decision maker and the acceptable domain of decision alternatives is limited by consideration of the marginal lifesaving principle. The decision alternative corresponding to the lower limit of the acceptable domain corresponds to one particular value of the implied life safety risk to individuals.

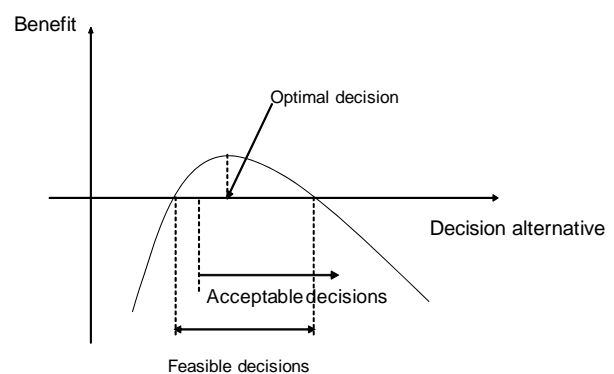


Figure 1. Illustration of the decision optimization coupled with compliance with the marginal lifesaving principle.

A property of this framework is that the resulting absolute levels of life safety and health risks for individuals depend strongly on the efficiency of the applied best practice technology and procedures for reducing risks. To assess the acceptability of such decisions in the context of regulation of activities as well as individual applied technologies all possible best practices engineering technical and organizational measures of risks reduction must be assessed with respect to their lifesaving efficiency – i.e. the marginal costs associated with saving one

additional life or improving life expectancy at good health. Note here that the lifesaving costs do not include implied costs of loss of functionality implied by risk reducing measures but only the costs of the risk reducing measures in a marginal sense.

Obviously this approach will in general not lead to a uniform level of individual life safety risks over different societal activities, applied technologies, time and space. Moreover, and most importantly, it should be noticed that the individual life safety risks which result from the approach are to be interpreted in a statistical sense. The assessment of the lifesaving efficiency in accordance with the marginal lifesaving principle does not keep track of the individuals exposed to risks. The activities and applied technologies together with the persons exposed to their implied risks comprise a continuum in time and space where persons, activities and technologies in principle, subject to possible limitations imposed by regulation, are otherwise freely moving around and fatalities and loss of life years at good health may as a result dissipate, see also Figure 2.

The assessed individual risks can, however, be utilized to assess the performance of different societal activities and to monitor best practices of applied technologies in different contexts individually over time and space and on a comparative basis between activities and corresponding applied technologies. The objective here is to identify if a given best practice is improving and if it is performing in accordance with the general norm evaluated across different societal activities and applied technologies. Depending on the results of such assessments there could be different courses of action including improvements of best practices or even abandonment of a given activity or applied technology.

Disregarding the specific purpose it is critical that the comparison and/or aggregation is/are undertaken consistently. This may seem to be a relatively small obstacle of no fundamental difficulty. Nevertheless, in practice, for various

reasons as will be discussed in the subsequent section, this is indeed non-trivial and in effect presently leads to significant problems in practical life safety and health related risk management.

### 3. ISSUES IN PRESENT LIFE SAFETY REGULATION

#### 3.1. On the issue of regulatory framework

As an introductory remark it should be noted that alone with respect to choice of regulatory frameworks for life safety and health risk management in present practice there exists a significant variability across different societal sectors, industries, activities and applied technologies. As reported in e.g. (Trbojevic, 2009) and (Faber and Maes, 2008) presently applied formats for life safety and health related risk regulation encompass not only the ALARP principle, but also different interpretations of this principle as well as regulatory formats relating to collective risks, project aggregate risks in addition to different metrics of individual risks.

The implied inconsistency originating from this variability has detrimental effects for sustainable management of life and health related risks and it should be a main focus of the professions to ensure that a common uniform and consistent basis is established across all regulatory domains in society. In the following, however, whether or not the preferred framework outlined in the foregoing section is followed, the issue of possible inconsistencies originating alone from the existence of different metrics utilized for comparison of individual risks forms the focal point. These inconsistencies play an important role also if an inadequate risk regulation framework is applied.

#### 3.2. On the mechanisms of individual risks

In most cases activities in society involve life safety risk exposure to individuals as a result of several applied technologies both simultaneously and sequentially. In Figure 2 the domain of the regulatory framework is indicated in terms of broken line boxes for different activities and full

line boxes for the applied technologies supporting the activities.

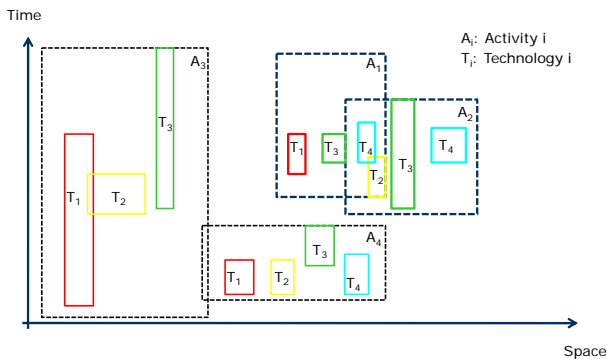


Figure 2 Illustration of a regulatory domain in terms of activities and applied technologies distributed over time and space.

For purposes of illustration, only a few different activities (could also represent specific projects), each supported or comprised by a few applied technologies, have been indicated in the figure. In practice, however, the activities and technologies are manifold and the interactions between applied technologies supporting societal activities (services) are complex. In principle it is relevant to consider regulation of life safety risk both from the perspective of applied technologies as well as the level of activities where technologies are applied jointly in given contexts.

The dimensions of the boxes in the figure indicate the extents in time and space over which activities and applied technologies expose individuals in society to risks. Moreover, their relative positions in the time-space domain indicate that activities and applied technologies may be distributed and overlapping. It should be noted that individuals in society in general move through the different activities in a somewhat uncontrolled and unregulated manner. The mutual interaction over time and space between persons, activities and applied technologies comprises the continuum generating the life safety risks. Finally, in the context of regulation it is realized that even though any individual activity (or project) as well as the application of

any technology is either limited in time and/or space, the principal possibility of the existence of many similar activities and identical or similar applied technologies in comparable contexts, together with the fact that individuals may move in time and space following tracks exposing them continuously to the same type of activities and the same applied technologies, implies that all activities and applied technologies in a regulatory context fundamentally must be considered as permanent over time and overall present in space unless the regulation specifically prohibits this.

As outlined in the foregoing section, the absolute levels of risks for individuals resulting from the optimization and application of the marginal lifesaving principle are different for different activities and for different technologies in their specific context; i.e. the domain in terms of activity, time, space, duration and extent. It is, however, also as highlighted earlier, relevant to be able to compare individual risks to facilitate sustainable management of life safety and health related risks. Considering the principal multitude of different contributions of life safety risks indicated in Figure 2, it is apparent that a scheme for the consistent and uniform quantification of individual risks, i.e. a generally applicable metric, is called for, independent of activity and applied technology.

Before going into the discussion of appropriate choices for such a metric, it is instructive first to consider the characteristics of a selection of typical societal activities, i.e. the contexts in which different applied technologies contribute to individual risks and how the present best practices of risk regulation in important cases lead to inconsistencies in the risk quantifications and comparisons.

### 3.3. Inconsistencies in the quantification of individual risk in present practice

Initially, the focus is here directed on differences in best practices for the quantification of individual risk in different societal activities through examples relating to the activities occupation, residence and transportation.

Thereafter inconsistencies arising from effects of averaging of individual life safety risks over time and space are addressed and discussed by consideration of activities related to transportation and occupation.

### 3.3.1. *Differences in risk metrics for the regulation of different societal activities*

In occupational risk management individual life safety risks are most often quantified in terms of the Fatal Accident Rate (FAR) defined as the expected value of the number of fatalities per 100 million working hours for persons in a given occupation. For what concerns residential safety for individuals risk management is regulated through structural codes most of which do not specifically address risks to individuals but rather prescribe a maximum level of acceptable probability of structural failure; in some cases with an annual reference period and in other cases with a reference period corresponding to the anticipated service life of the structure. In addition to structural codes, also Land Use Planning (LUP) is utilized to ensure appropriate risk management with respect to exposures of residents to natural hazards as well as to accidents associated with industrial and/or transportation related activities. In LUP individual risks are typically quantified in terms of fatalities per year with due possibilities for interpretations of associated time and spatial scales. Finally, quantification of individual life safety risks related to traffic activities typically address the Fatal Accident Rate defined for the domain of traffic safety in terms of the expected value of the number of fatalities per 100 million person kilometers.

From the aforementioned examples it is realized that prevailing differences in present practice with respect to choice of metrics for individual risks do not facilitate for assessing whether the performances of risk management in principally different societal activities are comparable. Moreover, in the mentioned examples relating to regulation of societal activities (occupation and transport) there is a tendency in best practices to address or focus on

the life safety risks for specific individuals (or statistical individuals with assumed behavioral characteristics) rather than on statistical individuals. However, as already mentioned, the personalized perspective to life safety risk is not relevant for the application of the marginal lifesaving cost principle. The variability exhibited from the foregoing few selected examples of present practice risk regulation underline the necessity of establishing a new metric for individual risk which is applicable across different domains of regulation and which facilitates consistent comparison between activities and applied technologies.

### 3.3.2. *Time-space averaging effect*

Whereas the foregoing discussion has indicated that there are significant differences in utilized approaches and perspectives for the quantification of life safety risks in different societal activities there are also significant sources of inconsistencies in the quantification of risk contributions from the different applied technologies supporting the activities. An important source of such inconsistencies originates from averaging effects over time and space.

Consider as an example the activity roadway tunnel transportation (or equivalently a specific roadway tunnel project). The roadway/tunnel system may be subdivided into segments over which the risk is largely constant and based on statistical assessments of roadway/tunnel accident data or by means of risk models (or combinations hereof) it is possible to assess the life safety risk for different segments of the roadway/tunnel system individually. For a given traffic situation the life safety risk might vary between the different segments due to the physical characteristics of roadway/tunnel system segments. Assume that the life safety risk is constant and small over the entire length of the tunnel except for one small segment in the middle of the tunnel where the life safety risk is significantly higher due to e.g. a crossing roadway. The differences in the levels of individual life safety risks for the principally

different segments of the tunnel system may be ascribed to differences in the lifesaving efficiency in the different applied technologies. Disregarding the choice of metric for the individual life safety risk; if the individual life safety risks are averaged over the entire length of the tunnel system, i.e. considering the contributions from both segments, the resulting averaged individual risks may compare well with the level of individual life safety risks for a typical comparable segment of the open roadway system outside of the tunnel. If, however, the individual life safety risk levels are assessed individually for the different segments the middle segment may turn out to perform significantly worse than a typical comparable segment of the open roadway system.

As another example consider an ageing offshore steel jacket type oil and gas production facility. Whereas the life safety risks for individuals living and/or working on such a facility in the largest part of its service life are governed by operational risks related to working tasks and procedures, towards the end of the intended service life of the facility, deterioration processes, such as corrosion and fatigue, eventually affects the integrity and reduces the reliability of the structural system. Consequently, the contribution of structural deterioration and subsequent failure to life safety risks increase towards the end the service life of the structure. Assume further that all possible risk reducing measures have been assessed in accordance with the marginal life safety principle and those which are efficient have been implemented and the resulting life safety risk levels towards the end of the service life of the structure turn out to be significantly higher than those for the initial phases of the service life of the structure. Averaging the total service life, individual life safety risks for personnel working and/or living on the facility over the entire service life of the structure may lead to life safety risk levels which are low compared with other generally accepted applied technologies and would indicate that applied technologies in the context are

performing well. If instead the applied technologies are assessed for the very end of the service life in isolation, the picture would be different.

From such considerations it appears not to be relevant and appropriate to assess the performance of societal activities and the applied technologies supporting these in terms of the life safety risks for individuals as quantified on the bases of averages of risks over time and space. It should also be remembered that the individual risk levels resulting from decision optimization subject to the fulfillment of the marginal lifesaving costs principle both can and should address relevant applied technologies individually as well as in the interaction with other technologies in the context of activities (or projects). From this perspective and bearing in mind that the purpose of assessing the absolute level of individual life safety risks is not to judge the acceptability of the activity or the applied technology, averaging is indeed irrelevant.

#### 4. PROPOSITION FOR A LIFE SAFETY RISK FOR INDIVIDUALS METRIC

Since the concern of life safety risk assessment and regulation is focused on avoidance of loss of lives and life years at good health, it is natural to direct the focus on a metric which relates directly to the activities and applied technologies which potentially cause the loss of lives and also duly accounts for the exposures of individuals. Moreover, since dying is a natural consequence of living it appears reasonable and relevant to use a metric which can be compared to the life safety risks all individuals are subject to in general, such as provided by fatality rates available from demographical studies, i.e. cohort life tables.

Based on these considerations, it is suggested to apply a life safety risk metric defined as the ratio between the expected value of the number of lost lives per annum caused by a given type of activity (or project) or applied technology  $n_F$  to the expected value of the total number of person years per annum during which individuals are

exposed  $N_L$  (to the considered activity or applied technology), i.e.  $\gamma_{LR}$  is defined as:

$$\gamma_{LR} = \frac{n_F}{N_L} \quad (1)$$

This metric may be realized to be equivalent to the commonly applied metric utilized for assessing the fatality rate of technical components given operational conditions. In Annex 1 this relationship is highlighted and also the link to the concept of Individual Risk, i.e. the risk for an individual with a known track in time and space is addressed.

As an illustration on the application of this metric consider the example addressing individual life safety risks generated by a tunnel system from Section 3.3.2. Assume that the annual traffic through the tunnel is equal to 10 million persons traveling at an average speed of 50 km/h. The total length of the tunnel is 1 km and the length of the mid segment is 100 m. Per year it has been assessed that the expected value of lost lives in total is 0.1 per year of which the contribution from the mid segment constitutes 50%. Based on this information the total number of man years spent in the tunnel system per year is calculated as 22.83, the corresponding numbers for the mid and edge segments are 2.28 and 20.55 respectively. Given that the total expected number of fatalities for the entire tunnel is 0.1 per year and that 50% of this originates from the mid segment the life safety risks for the total tunnel, the mid segment and the edge segments equal  $4.38 \times 10^{-3}$ ,  $2.19 \times 10^{-2}$  and  $2.43 \times 10^{-3}$  per year, respectively. These numbers are readily compared with mortality rates from cohort life tables and also facilitate comparison of life safety risks at the level of the technologies (tunnel segments) applied to facilitate the activity (or service) provided by the tunnel system.

The advantage of this metric is that it is applicable to in principle all societal domains of life safety risk regulation, and that it treats the situations in which specific individuals and statistical individuals are exposed to risks without distinction. Moreover, it is consistent in

the sense that modeled risks may be easily compared to losses actually experienced. If it is observed that the metric for a special activity or technology is relatively high, one should consider this as a signal to start investigations for risk reduction. The group of exposed persons of course needs to be sufficiently homogeneous, as it is not allowed to mix mildly and heavily exposed persons. The mild group would hide the seriously affected group. For instance, an averaged individual risk number for the total building industry would be misleading as some of the activities could be much more dangerous than others.

## 5. CONCLUSIONS

The present paper addresses life safety risk from the perspective of regulation of societal activities and projects as well as the applied technologies supporting these. It is identified and explained that the principle of decision optimization and conjoint fulfillment of the marginal lifesaving principle does not render the assessment of the individual life safety risks for specific individuals or statistical individuals with assumed behavioral characteristics relevant. Nor is the resulting absolute level of individual risk subject to assessment of acceptability. It is highlighted that a major cause of inconsistency in risk quantifications and comparisons originates from the fact that present regulations partly address societal activities and partly address applied technologies, in some cases take the perspective of the individual and in other cases address the performance of applied technologies. It is furthermore highlighted that typically applied averaging of life safety risks to individuals over time and space may result in unintentional masking of poorly performing activities and applied technologies. Finally, a proposition is made on how the individual life safety risk may be assessed and compared consistently and uniformly over different activities and applied technologies such as structural safety, land use planning and traffic safety.



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## ANNEX 1.

Consider a system, activity or technology having an annual failure probability  $p(F)$ . A person who is permanently exposed to this activity may have a conditional probability of being killed, given failure, equal to  $P(D|F)$ . The annual probability of dying for the considered person (often referred to as the individual risk  $IR$ ) is then equal to the product  $p(F)P(D|F)$ . If  $N$  persons are in a similar position the expected annual number of fatalities is  $n_F = N p(F)P(D|F)$ . As the metric  $\gamma_{LR}$  according to Equation (1) is defined as  $n_F / N$  (assuming permanent exposure), we find, as already announced in the main text:

$$\gamma_{LR} = \frac{n_F}{N} = \frac{N p(F)P(D|F)}{N} = p(F)P(D|F)$$

Of course, in reality as in the tunnel example, a given person or a group of persons may not be permanently exposed, but only a part  $\mu$  of the time. The probability of a person dying

according to this shorter exposure then reduces to:

$$IR = \mu p(F)P(D|F)$$

For the special case of a given group of individuals exposed identically by the same technology the value of  $\gamma_{LR}$ , however, does not change in the case of non-permanent exposure: as in Equation (1) the denominator (total number of exposed man years per year) is also affected:

$$\gamma_{LR} = \frac{n_F}{N_L} = \frac{\mu N p(F)P(D|F)}{\mu N} = p(F)P(D|F)$$

So, if for this special case we want to assess the technology or activity on the basis of  $\gamma_{LR}$  by comparison to other activities, the introduction of the relative exposure duration  $\mu$  does not change the basis of comparison. On the other hand, for  $IR$  (which addresses one given individual with a known track in time-space) the relative use  $\mu$  makes a change. When assessing the severity of the threat, we then should keep in mind that a person has part in many activities, which cumulate contributions to the individual risk. In the end, the resulting total  $IR$  depends on the behavior of individuals, which differs from person to person and about which we have little or no control. The conclusion is that setting criteria on the basis of  $IR$  for a relative short exposure to a single activity or technology could to some extent be relevant but can only be done in a pragmatic way.