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Improving Risk Assessment for Transporting Dangerous Goods through European Road Tunnels: A Delphi Study

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Abstract: Managing the transportation of dangerous goods (DG) through road tunnels is of great importance since it is associated with a serious risk of accidents. The consequences of an accident involving DG, especially in the closed tunnel environment, might be more significant and even more catastrophic compared to the same accident occurring on an open road. This article presents the Greek experience regarding the application of quantitative risk assessment (QRA) methods for the transportation of DG through Greek road tunnels. The modified Delphi method, with the participation of nine experts, is employed to investigate the obstacles to successfully conforming with the mandatory European Union regulatory framework that applies to transport operations within the Trans-European road network. Recommendations are made to improve the applied QRA approach, to facilitate the cooperation between tunnel managers and emergency services, to communicate lessons learned and to enhance the training of risk assessors.

Keywords: road tunnels; dangerous goods; risk assessment; Delphi method; operation; ADR

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1. Introduction

In Greece, due to the development of the modern national road network over the last decades, there has been a significant number of road tunnels constructed and they are critical infrastructure elements [1]. In fact, since 2004 the increase in length of road tunnels operating on the national road network increased by more than 200%—the greatest increase throughout Europe [2]. The road networks, as well as the road tunnels, are used for all kinds of transportation, including commercial transportation. In this sense, transportation of dangerous goods (DG) through road tunnels is of great importance, especially since it is associated with a serious risk of accidents [3]. DG refers to goods that are subject to special transport regulations due to being flammable, explosive, radioactive, toxic, etc. [4]. The consequences of an accident involving DG, especially in the closed tunnel environment, might be more significant and even more catastrophic as compared to the same accident occurring on an open road [5,6]. An interesting finding by Bubbico et al. [7] is that, while it may be unnecessary to limit dangerous goods circulation in rail tunnels, for road tunnels this decision should be taken based on the results of tunnel specific risk assessment.

Hence, the transportation of DG through road tunnels should be determined by a clear regulatory framework in order to prevent and/or eliminate such grave consequences. The European Agreement concerning the international carriage of Dangerous goods by Road, known as the 'ADR Agreement' [8], along with European (EU) Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network [9], define the rules regarding the transportation of DG through road tunnels. The EU Directive applies to all tunnels in the Trans-European road network with a length of over 500 m, whether they are in operation, under construction, or under design. The Directive defines the entities involved in the procedures for ensuring safety in tunnels, i.e., the Administrative Authority, the Tunnel Manager (TM) and the Safety Officer. The Administrative

Authority is responsible for ensuring that all tunnel safety precautions are adhered to, holds the power to suspend or restrict the operation of a tunnel, ensures that tasks such as testing and inspecting tunnels are carried out on a regular basis and implements necessary risk reduction measures. The TM is the public or private body responsible for the daily management of each tunnel, whether it is in the design, construction, or operating stage. The TM is also responsible for recording, in an incident report, any significant event or accident occurring in a tunnel, which should then be forwarded to the Safety Officer, to the Administrative Authority and to emergency services. Finally, the Safety Officer is nominated by the TM (following approval of the Administrative Authority) and coordinates all preventive measures to ensure the safety of users and operational staff.

A study contracted by the European Commission on the implementation and effects of the EU Directive [10] was performed ten years after the Directive entered into force. Its purpose was to analyze how its member states had implemented the Directive, to assess whether it had served its purposes and to identify other economic, social and environmental effects by looking at practices applied by them. However, detailed analysis of the individual provisions of the Directive, such as the need for risk analysis for road tunnels or the necessary cooperation between emergency services and TMs, was not part of the evaluation.

In the abovementioned regulatory framework, it is stated that a risk analysis should be carried out for a given tunnel, where necessary, by a body functionally independent from the TM. The content along with the results of the risk analysis shall be included in the safety documentation submitted to the Administrative Authority [9]. Based on the results of this analysis, the competent authority shall assign the road tunnel to one of the road tunnel categories according to ADR (A, B, C, D, E), and relevant transport of DG restrictions should apply [8,11]. According to Borghetti, et al. [12] tunnel risk analysis methods aim at evaluating and managing the risk associated with a specific tunnel system regarding the consequences for the potentially exposed population. Risk analysis can be seen as a useful tool for supporting decisions when evaluating the safety of the tunnel system; it identifies those infrastructure, equipment and management procedures which guarantee greater benefits in terms of expected risk reduction as well as cost savings. Furthermore, tunnel risk analysis is an analytical method that fundamentally consists of identifying possible events, their probability of occurrence and their possible consequences.

In PIARC's technical report [13] it is stated that '*risk analysis is a key element of the risk assessment process*' for a tunnel, since it is the primary element of the risk assessment process, followed by the risk evaluation and the risk reduction elements. Moreover, a broad spectrum of qualitative or quantitative methods exists for every step of the risk assessment process. However, the Quantitative Risk Assessment Model (QRAM) is the most widely accepted method for assessing transportation of DG through tunnels and is used by several European countries, including Greece [1].

For Greece, the regulatory framework regarding the transportation of DG through road tunnels is defined by Presidential Decree (P.D.) 230/2007 [14], which was issued in conformance to EU Directive 2004/54/EC [9] and the guidelines issued by the Greek Tunnel Administrative Authority (Dioikitiki Archi Sirangon—D.A.S.) in 2011 [15]. According to the guidelines, a risk analysis using the QRAM is to be carried out in order to determine whether vehicles transporting DG are allowed to enter a tunnel that falls within the scope of P.D. 230/2007 and the EU Directive. This risk analysis is not mandatory when the tunnel is located on a route where the transportation of DG is already prohibited for other reasons or when the existing regulatory framework for the operation of the tunnel already prohibits the transportation of DG.

A body functionally independent from the TM must carry out the risk analyses regarding the transportation of DG through a given tunnel. The contents along with the results of the risk analysis are included in the Tunnel Safety File (TSF), which is then submitted to D.A.S. In the guidelines published by D.A.S., the minimum qualifications for those carrying out these risk analyses were also defined. Since using standardized methods for carrying out risk analyses for engineering projects was uncommon in Greece [16], this study aims to investigate ways to improve the QRA approach for the transportation of DG through road tunnels in Greece.

To this end, the objectives of the current research are the following:

- Determination of the obstacles arising from the need for a QRA for the transportation of DG through road tunnels in Greece to help improve the applied QRAM.
- Determination of the obstacles impeding the cooperation between the TMs and the emergency services to forge a common risk mitigation culture.
- Identification of methods of communicating the acquired experiences and lessons learned for use in future risk assessments.
- Determination of best practice risk assessor training requirements.

This complex problem was addressed through an extensive, though non-exhaustive, literature review and with the application of the modified Delphi method with the input of nine experts, in order to systematically acquire represent expert opinion through two series of questionnaires [17]. This approach aims to provide all stakeholders with critical information in order to improve the applied QRA approach.

2. Literature Review

An extensive literature search of various databases such as www.heal-link.gr, www.scopus.com, www.sciencedirect.com, www.jstor.org, www.tandfonline.com, (accessed on 6 October 2021), etc. by using keywords such as 'risk analysis', 'road tunnels', 'hazardous materials' and 'dangerous goods', recovered a number of studies. These studies aimed at determining the factors contributing to accidents involving DG [18,19], proposing new approaches for the evaluation of acceptable risk in road tunnels [20,21], reviewing the existing methods for the risk assessment of road tunnels [1,2,5,22,23] and proposing extensions or modifications to existing risk assessment approaches [24–26]. Only one study was found regarding a non-European country's implementation issues with ADR in DG transportation [6].

Research work carried out based on real accident data on the motorway network in China, by Shen and Wei [18] and Xing et al. [19], focused on the risk factors for transporting DG. As the safety of road transport of DG in China is poor, and the losses caused by accidents are substantial, they examined the factors that led more frequently to different categories of accidents—i.e., damaged property only, number of evacuations, injuries and fatalities—and incorporated various statistical models.

Abrahamsen, et al. [20] presented a practical layered approach for the evaluation of acceptable risk in road tunnels, so that the available time and energy resources are spent more efficiently considering the existing differentiations of road tunnels. Their proposed approach consisted of three levels of criteria ranging from purely qualitative (simple) to quantitative (complex), with the third level requiring much more documentation than the first two. This approach ensured a much more efficient allocation of available resources than the prevailing regime, where it was common to evaluate the acceptability of risk in road tunnels using quantitative acceptance criteria. The use of quantitative acceptance criteria requires extensive analyses and documentation for all types of tunnels, rendering this extensive analysis redundant when there are tunnels presenting no special features, or where the environmental surroundings of the tunnel might not affect the safety of road users.

In the same spirit, Lundin and Antonsson [21] presented a comprehensive and flexible approach for categorizing road tunnels according to ADR by applying transit restrictions on the vehicles transporting DG based on risk analysis. This approach assists the decision maker with risk framing, so that they can do a relevant characterization of the risk before the risk analysis method is chosen. With this method, an appropriate tunnel category can be derived by the competent authority with less resources and skills compared to making a complete quantitative risk assessment (QRA).

One of the main topics of discussion in the literature revolves around the selection of the appropriate risk assessment approach for the road tunnel in question. Based on the characteristics of each specific tunnel, one can select among a qualitative, a quantitative or a combination of qualitative and quantitative approach [13]. Based on the literature, it seems that the QRA approach has prevailed in the European area [1,2]. Nevertheless, factors which cannot be quantified ought to be taken into account [2]. Through a comparative review of the risk assessment methods used within the EU, Ntzeremes and Kirytopoulos [2] uncovered the deficiencies and limitations of the proposed methods. Important parameters for the safe operation of tunnel systems, such as traffic load, trapped users' behavior, emergency response of tunnel personnel, the behavior of the fire and environmental conditions, are ignored by most risk assessment methods.

What is more, Toretta et al. [22], through their study, reviewed the decision support systems (DSS) that have been designed to assist decision makers with the problem regarding alternative routes for the transportation of DG. They compared existing DSS, concluding that they are quite advanced but improvable and that the transportation of DG crosses different scientific fields, such as risk management, transportation of goods and territorial planning. In addition, Turkmen et al. [27] developed a DSS based on the Analytical Hierarchy Process to help decision makers choose between alternative routes for DG transportation through tunnels.

Three studies proposing extensions or modifications to existing risk assessment approaches were examined. The first by Su et al. [24] referred to developing a tunnel operation risk model based on data such as traffic accidents, running speed, acceleration and deceleration of vehicles as recorded in over thirty cases of expressway tunnels operating in China. The second by Weerheijm et al. [26] aimed at improving the previously developed QRAM by TNO in the Netherlands. They extended this model to combine the dispersion of a flammable cloud with its probability of ignition and the resulting physical effects such as overpressure. Similarly, Caliendo and De Guglielmo [25] extended the DG-QRAM developed jointly by PIARC and the Organisation for Economic Co-operation and Development (OECD), by introducing additional scenarios related to hydrogen.

Only one study was found regarding the implementation issues of ADR in DG transportation in a non-European country [6]. Çelebi created a systems dynamic model to analyze the impact of the ADR regulatory issues on performance of the DG transportation system in Turkey. One of the findings of the research is that the additional benefits in terms of avoided accident costs are far below the additional operational costs. Although this finding may be misleading, since potential operational efficiency benefits of ADR standards were neglected in Çelebi's study [6], it was concluded that the aggregated effect of ADR standards on the sector might be much higher in the long term.

Things become even more complicated if the difficult to define human factor [12] is considered. The human factor comes into play at both an organizational level, when the tunnel safety officer is responsible for taking actions the moment an accident occurs inside the tunnel, as well as at the level of the tunnel user–driver, when the latter should follow the guidelines of those in charge in order to safely escape [28]. Noteworthily, the human factor is the most unpredictable risk factor even during tunnel construction, regardless of the fact that normally all health and safety regulations are generally adhered to in such megaproject sites and workers undergo systematic safety training [29].

The modern road network constructed in Greece during the last two decades is part of one of the nine core network corridors of the Trans-European Transport Network (TEN-T) named the Orient/East-Mediterranean Corridor [30]. The central motorways crossing the mainland along with the road authorities responsible for the operation of each motorway/road section, the total length of the motorway in operation as of 2019 and the number of tunnels, per road, with a length of over 500 m are presented in Table 1.

Table 1. Motorways in Greece (adapted from [31]).

Motorway/Road Section	Total Motorway Length in km	Number of Tunnels over 500 m Long	Road Authority	Motorway Code
Attica Tollway	70.00	5	Attiki Odos S.A.	A6
Egnatia Odos	887.20	67	Egnatia Odos S.A.	A2
ATHE [1]/ Metamorfosi (Attica)–Skarfia (Fthiotida)	172.50	12	Nea Odos S.A.	A1
Ionia Odos/Antirrio–Ioannina	196.00			A5
Schimatari (ATHE [1])–Halkida	8.50			A11
Central Peloponnese/ Korinthos–Tripoli–Kalamata	205.00	10	Moreas S.A.	A7
Lefktro–Sparti				A71
ATHE [1]/Malliakos–Kleidi	263.70	8	Aegean Motorway S.A.	A1
Athens–Patra	202.30	17	Olympia Odos S.A.	A8
Patra–Pyrgos–Tsakona				A5
Central Greece Motorway	136.50	3	Kentriki Odos S.A.	A3
Total:	**2145.30**	**122**		

[1] ATHE: Athens—Thessaloniki—Evzonoi.

Sixty percent of the overall length of Greek motorways was constructed as Public-Private Partnerships (PPP) while the remaining 40% corresponds to the Egnatia Odos Motorway and its perpendicular axes, which were constructed through a series of public works contracts awarded by the client organization Egnatia Odos S.A. (EOSA). EOSA is a government owned company, responsible for the design, construction, operation and maintenance of said motorway and its perpendicular axes [32]. The concessionaires of the PPPs (Attiki Odos S.A., Nea Odos S.A, Moreas S.A., Aegean Motorway S.A., Olympia Odos S.A. & Kentriki Odos S.A.) and EOSA are currently the Administrative Authorities and TMs responsible for the operation of all road tunnels in Greece, except for one which is under the responsibility of the local road authority (Prefecture of Central Greece). According to data from D.A.S., there are 68 road tunnels in Greece that fall within the scope of P.D. 230/2007, 51 of which were in operation as of 2019 (Table 2).

Skarvelakis [16] examined the application of the DG-QRAM in the Driskos tunnel of the Egnatia Odos Motorway in Greece, to contribute to the efforts being made at that time by D.A.S. for the adoption of the quantitative approach for the risk assessment of road tunnels in Greece. One of the results of this study was that the use of standardized methods for carrying out risk analyses for engineering projects was uncommon in Greece, which makes it difficult for the decision maker to use risk analysis since those involved in these decisions need to be experienced and properly educated.

Soon after, in 2011, D.A.S. [15] published guidelines for carrying out risk analyses regarding the transportation of DG through road tunnels in Greece and prescribed the methodology used for these analyses at a national level. To date, no evaluation of the implementation results of these guidelines has been made.

Furthermore, Benekos and Diamantidis [1] provide an overview and a brief discussion of the existing prescriptive and risk based methods for the risk assessment of a typical tunnel, one that does not deviate from the minimum infrastructure requirements of European Directive 2004/54/EC, based on traffic and accident data from Greek motorways. The resulting risk from the application of each method were compared. Their study resulted in a proposed integrated framework for the optimal selection of safety measures based on risk reduction and socioeconomic considerations.

All of the above makes risk analysis regarding the transportation of DG through road tunnels a complex research topic [22], and it shows that it is necessary for the risk assessors to collect many and various data, such as data regarding the accidents that have occurred inside road tunnels. The issue of lack of data for transport models has been proven to be quite common, increasing the need for a statistical database that can be useful in obtaining better estimates [6].

Table 2. Road tunnels within the scope of P.D. 23/2007 in operation in Greece as of 2019.

Motorway/Road Section	Number of Tunnels	Total Tube Length (m)	TM
Attica Tollway (excluding the Metamorfosi–Elefsina section)	1	1670	Attiki Odos S.A.
Egnatia Odos	17	51,673	Egnatia Odos S.A.
Perpendicular Axes of Egnatia Odos	3	2738	Egnatia Odos S.A.
ATHE [1] section Metamorfosi (Attica)–Skarfia (Fthiotida)	2	6276	Nea Odos S.A.
Ionia Odos (Antirrio–Egnatia)	4	27,668	Nea Odos S.A.
Central Peloponnese (Korinthos–Tripoli–Kalamata)	5	8966	Moreas S.A.
Mesologgi–Agrinio–Lamia	1	1360	Prefecture of Central Greece
ATHE [1] section Malliakos–Kleidi	3	21,391	Aegean Motorway S.A
Athens–Patra (Elefsina–Korinthos–Patra)	11	20,147	Olympia Odos S.A.
Patra–Pyrgos–Tsakona	2	2959	Olympia Odos S.A.
Central Greece Motorway	2	2423	Kentriki Odos S.A.
Total:	**51**	**147,361**	

[1] ATHE: Athens–Thessaloniki–Evzonoi.

In summary, the literature review revealed studies that provide recommendations for using new risk assessment methods for the transportation of DG through road tunnels [20,21] or for reviewing and/or extending the existing methods for risk assessment of road tunnels [1,2,5,22–26]. Since only one study confronts the implementation issues of ADR in the DG transportation sector in Turkey, a non-European country [6], the current paper intends to fill this gap by investigating the specific issues arising from the implementation of the EU Directive in Greece, a member state of the EU.

3. Materials and Methods

3.1. Research Framework

Initially, a significant though non-exhaustive literature review was carried out to: determine the gap in the literature, choose the research method (Delphi method), develop the initial questionnaire and also to provide background information for the final recommendations. The second step of this Delphi study was finding a suitable team of experts to participate, which was then followed by the Delphi method first round questionnaire. Afterwards, the first round results were analyzed and the questions where consensus among the experts was not achieved were chosen for the second round questionnaire. The analysis of the first and second round results led to determining the risk assessment issues in need of improvement and, finally, recommendations were made based on the literature and experts' opinions. The sequence of the abovementioned activities for the current research methodology is shown in Figure 1.

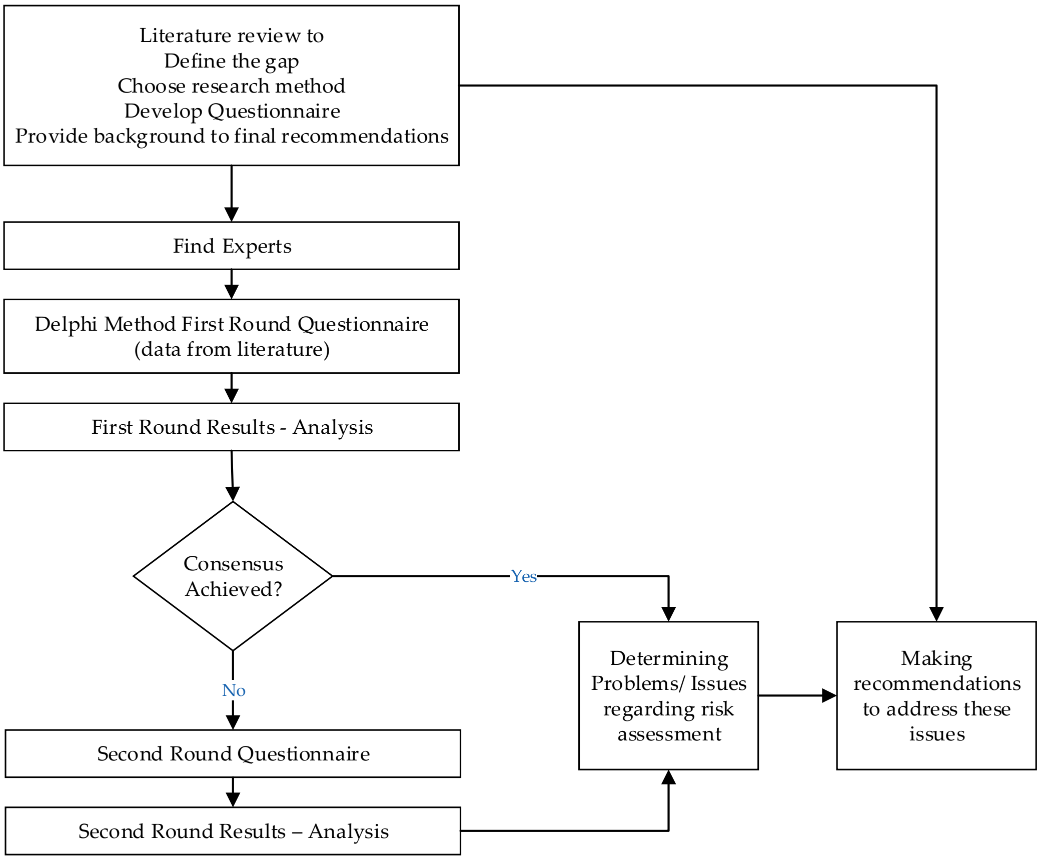

Figure 1. Current research framework.

3.2. Modified Delphi Method

After an in depth review of existing research approaches such as quantitative, qualitative, mixed-methods or arts based and community based participatory [33], the modified Delphi method was selected for collecting the data. The Delphi method was developed in the 1950s and can be applied when consensus among experts upon a specific topic is sought [34]. This method is useful when there is a need to handle complex problems that require more judgmental analysis, to study or define areas where there is considerable uncertainty or lack of agreed knowledge and to highlight topics of concern [17]. The Delphi method is considered a flexible research approach and has evolved to produce variations, such as the modified Delphi Method [34]. Despite the various types of the Delphi method, the following defining characteristics of the method can be systematically found [17,34]:

- Repetition: Any Delphi study consists of at least two subsequent rounds of data collection from a single sample of experts. The opinion of the experts is provided through a series of questionnaires.
- Anonymity and controlled feedback: Experts remain anonymous throughout the study and after each round the moderator provides experts with controlled opinion feedback using a summary of the results of the previous round. This process continues until a certain level of agreement has been obtained or a pre-specified number of rounds has been completed.
- Statistical group response: The individual opinions of all experts participating in the final round are analyzed and conclusions are drawn.

Usually, the first round in the Delphi method consists of general, open ended questions regarding the topic in question, making this the qualitative phase of the method. One or two rounds of questionnaires follow [33], where statements using closed ended questions based on the first round are presented and experts are then asked to express their level of agreement on a Likert scale [34], making this the quantitative phase of the method [33]. The difference in the modified version is that the first round consists of a structured list of items arising from the literature or previous studies [17,30,33].

3.3. Data Collection and Description

The modified Delphi method, consisting of two consecutive rounds of questionnaires, was selected to collect the necessary data for the current study. The search for the appropriate group of experts to participate in the study began by communicating through e-mail with Greek road authorities, D.A.S., the Greek Tunneling Society (GTS) and two engineers who were approached through the LinkedIn social network. In this e-mail, a short and clear text regarding the aim of the current study was stated, which invited those involved with the risk analysis regarding the transportation of DG through road tunnels to participate. This procedure resulted in collecting 10 responses, of which nine were positive for participating in the study and one was negative, since they viewed themselves as unsuitable for participation.

3.3.1. Data Collection: First Round of Modified Delphi Study

The first round questionnaire was constructed using Microsoft Forms and was divided into four (4) sections consisting of thirty-one (31) questions. The first eight (8) questions were related to demographic data (e.g., age, sex, educational background, etc.) while the rest were based on the literature [3]. These sections were organized as follows:

1. General Data: This section contained demographic questions, fields for contact details and questions about the professional experience of the respondents regarding risk analysis in Greece and/or abroad. It consisted of eleven (11) questions, i.e., four (4) open ended, five (5) closed ended and two (2) list questions. The main aim of this section was to record the participants' level of risk analysis expertise and, in combination with four of the questions in the second section, to verify their selection for participation in the Delphi study.
2. Basic Data about road tunnel risk analyses: This section investigated the role of each participant in the risk assessment process, their professional expertise, whether they had participated in these analyses before or after the publication of the D.A.S. guidelines and whether the abovementioned guidelines had a positive impact on the procedure for conducting these analyses were investigated. Furthermore, they were asked to select among possible obstacles (based on the literature) and/or add extra ones derived from their experience. There were eight (8) questions, i.e., one (1) closed ended, one (1) semi-closed, four (4) list questions and two (2) rating scale questions.
3. Organizational Data about road tunnel risk analyses: The questions in this section were devised in order to investigate whether a database containing relevant tunnel characteristics exists, if it is available to all those involved in the risk analyses and how many people participate in the QRAM. Additionally, the respondents were asked if D.A.S. had assigned tunnel risk analyses to external consultants. Finally, questions were posed in an attempt to investigate the existence of procedures for communicating acquired experience to future risk assessors. This section consisted of nine (9) questions, i.e., seven (7) closed ended, one (1) list question and one (1) open ended.
4. Possible issues arising following publication of the D.A.S. guidelines in 2011: In this final section there were three (3) questions. The first was a list question investigating possible ways to overcome potential obstacles. The second was a closed ended question to determine whether a specific training system for those conducting risk analyses could improve these procedures. Finally, the last open ended question was posed to extract the reasons that led them to their previous response.

3.3.2. Data Collection: Second Round of the Delphi Study

After collecting and analyzing the completed first round questionnaires, six (6) questions were chosen to be investigated further. The second round questionnaire was prepared in a MS-Word file and was sent to the group of experts via e-mail. The first page contained information about the professional identities of the participating experts without revealing their identities. On the following pages, the results of the chosen questions of the first round and the new second round questions were presented.

Instructions for answering these new questions were given and the completed second round questionnaires were collected via e-mail. The second round questions were mainly open ended or a combination of open ended and list questions, so that the experts could express their opinion more freely and a more in depth investigation could be achieved. It should also be noted, that although usually a Delphi method is used in order to obtain consensus among the experts, Delphi can also be used to find out on which aspects of a topic experts disagree, since it may be just as worthwhile [34].

4. Results

4.1. First-Round Results

Table 3 presents the results of the first round of the modified Delphi study. The results of the first four questions, which are related to personal details, are not presented in order to respect the respondents' anonymity. The results of the first section's questions (Q. 5–11) and four of the questions in the second section (Q.12,13,15,16) were used to verify the selection of the Delphi group of experts. As a result, all nine (9) experts participating in the first round were deemed particularly experienced in the field of risk analysis. Most of them had at least six years of professional experience in this field, three of them had, in fact, more than 10 years professional experience and two of them had also participated in risk analysis for road tunnels abroad. Experts with less professional experience were also accepted, taking into consideration their availability and their interest in participating in the study [17]. Other criteria that were used for justifying the use of all nine participants' answers were their level of expertise in the broader spectrum of risk management. Five of them were experts in the field of risk analysis, one held a Ph.D. Degree, another was experienced through their professional involvement, one was the technical support director of the D.A.S. and the last one had relevant knowledge at a graduate level. The final criteria were their relevant positions (Table 3, Q. 13) such as tunnel safety officer, TSF supervisor, QRAM user, or risk analyst, and they had various engineering backgrounds so that the key viewpoints on the topic could be represented [17]. However, it should be noted that 8 of the 9 experts possess roles on behalf of the various TMs and only one was on behalf of the D.A.S. (Table 3, Q. 12). Finally, a significant finding is that only one of the nine experts had participated in training seminars on the use of the QRAM (Table 3, Q. 14), a qualification that is mandatory for carrying out tunnel risk analyses [15].

The majority of the experts agree that the contribution of the D.A.S. guidelines to the facilitation of the QRAM (Table 3, Q17) is very positive. In fact, the responses to question 18 show that the requirements of the input data to the QRAM are mostly upheld. On the other hand, the fact that five out of the nine experts were unaware of the existence of a database including all Greek tunnel characteristics is quite disquieting (Table 3, Q. 20,21). The most common difficulties found had to do with collecting the necessary data for the risk analysis, difficulties in the cooperation between emergency services and TMs and lack of skilled personnel (Table 3, Q. 19). These results were further investigated during the second round using three additional questions.

Most of the respondents were unaware of if D.A.S. has assigned risk analyses to external consultants instead of the relevant TM (Table 3, Q. 22), except for the risk analyst and technical support director from D.A.S. who state they have not. Moreover, all experts agreed that road tunnels have been assigned multiple categories according to ADR during the operational stage (Table 3, Q. 25). Both issues were investigated further in the second round.

Table 3. First-round results.

No	First Round Questions (Q)	Results	
Q	1. General Data	Options	No. of Resp.
5	Educational Degree:	Electrical—Electronic Engineering	5
		Civil Engineering	2
		Chemical Engineering	1
		Mechanical Engineering	1
6	Have you participated in risk analysis regarding the transportation of DG through road tunnels?	Yes	7
		No	2
7	(For those answering Yes in Q. 6) Regarding road tunnels in Greece and/or abroad?	In Greece	5
		In Greece and abroad	2
8	(For those answering Yes in Q. 6) How many years of professional experience in carrying out risk analyses regarding the transportation of DG through road tunnels do you have?	1–3 years	1
		3–6 years	1
		6–10 years	2
		10–15 years	2
		Over 15 years	1
9	Have you participated in risk analyses regarding projects other than road tunnels?	Yes	1
		No	8
10	(For those answering Yes in Q. 9) Regarding projects in Greece and/or abroad?	In Greece	1
11	(For those answering Yes in Q. 9) How many years of professional experience in carrying out risk analyses do you have in total?	Over 15 years	1
	2. Basic Data about the risk analysis for road tunnels	Options	No. of Resp.
12	Regarding road tunnels in Greece, did you participate in these analyses on behalf of:	TM	8
		Technical Support for D.A.S.	1
13	Regarding road tunnels in Greece, your role in these analyses was:(each respondent may have multiple roles)	Tunnel Safety Officer	4
		Conducting the risk analysis	2
		QRAM User	3
		Expert in the Field	3
		Inspection Entity	1
14	Have you participated in training seminars in the use of QRAM organized by PIARC, OECD, INERIS?	Yes	1
		No	8
15 *	**What is your level of expertise in the broader spectrum of risk analysis and/or risk management?**	Graduate	1
		Expert	5
		Ph.D.	1
		Empirical	1
		D.A.S. Technical support director	1
16	Have you participated in these analyses before and/or after the publication of the D.A.S. guidelines?	After	6
		Before and after	3
Q	2. Basic Data about the risk analysis for road tunnels (cont.)	Options	No. of Resp.
17	How much easier has the publication of the D.A.S. guidelines made the conducting of these analyses?	Not at all	0
		Very little	0
		Average	1
		Quite easier	7
		Significantly	1
18a	To what degree is the tunnel's Environment taken into consideration in the QRA after the publication of the D.A.S. Guideline?	Not at all	0
		Very little	1
		Average	4
		Quite often	3
		Significantly	1
18b	To what degree is the tunnel's Length taken into consideration in the QRA after the publication of the D.A.S. Guideline?	Not at all	2
		Very little	0
		Average	3
		Quite often	3
		Significantly	1
18c	To what degree is the tunnel's traffic volume and HGV presence taken into consideration in the QRA after the publication of the D.A.S. Guideline?	Not at all	0
		Very little	0
		Average	3
		Quite often	5
		Significantly	1
18d	To what degree is the tunnel's uni-directional or bi-directional traffic into consideration in the QRA after the publication of the D.A.S. Guideline?	Not at all	0
		Very little	0
		Average	2
		Quite often	4
		Significantly	3

Table 3. *Cont.*

No	First Round Questions (Q)	Results	
19 *	**Have you come across any of the following issues during the risk analysis process?**	Difficulty in collecting Data	4
		Difficulty in cooperation between emergency services and TM	3
		Lack of skilled personnel	3
		None of the above	2
		Other: Modelling of flame traps	1
	3. Organizational Data about road tunnel risk analyses	Options	No. of Resp.
20	Is there a database where all the Greek tunnels and their relevant characteristics are recorded?	Yes	3
		No	1
		Don't know	5
21	(For those answering Yes in Q. 20) Is this database open access for all involved entities?	Yes	3
		No	0
22 *	**Has D.A.S. assigned risk analyses to external consultants instead of the relevant TM?**	Yes	0
		No	2
		Don't Know	7
23 *	**(For those answering Yes in Q. 22) What was the reason for this happening?**	-	
24	How many people participate in the QRA process?	1–4	6
		5–10	2
		Don't know	1
Q	3. Organizational Data about road tunnel risk analyses (cont.)	Options	No. of Resp.
25 *	**Has it occurred for a road tunnel to be assigned to multiple ADR categories during the operation?**	Yes	9
		No	0
26	Have accidents involving DG occurred in the road tunnels since 2011?	Yes	6
		No	2
		Don't know	1
27 *	**Do procedures exist for communicating the acquired experience to future risk analyses?**	Yes	3
		No	5
		Don't Know	1
28 *	**(For those answering Yes in Q. 27) In which of the following ways is the acquired experience communicated?**	Relevant conventions and seminars	1
		Frequent transmission of the relevant data from the TM to D.A.S.	2
		Other: At an internal level per TM	1
		Other: Collection of incident data	1
		Other: Following the mandatory 6 years update of the TSF and the re-conducting of the risk analysis	1
	4. Possible Issues arising since the publication of the D.A.S. guidelines in 2011	Options	No. of Resp.
29	In case you come across issues during the risk analysis procedure, which of the following ways can be used for tackling these issues?	Communication with D.A.S.	6
		Communication between D.A.S. and the relevant European Institutions	1
		Other: Experience of researcher	1
		Haven't come across such an issue	1
30	Do you believe that a specific training system for those conducting the risk analysis could improve these procedures?	Yes	9
		No	0
31	(For those answering Yes in Q. 30) Please elaborate the reason that led to your previous response.	Knowledge and Experience on the use of QRAM	
		Experience and Expertise on conducting the risk analyses	
		D.A.S.'s requirement for the risk analysis to be conducted only by those who have participated in training seminars on the use of QRAM should be replaced by a more structured approach	
		Improvement of the risk analysis approach	

* Bold text indicates the issue was investigated further in round two of the Delphi study.

Only three of the experts gave a positive response regarding if procedures for communicating the acquired experience to future risk assessors exist (Table 3, Q. 27). The three who responded positively were then asked to choose one or more among such possible procedures (derived from the literature) or to note additional ones (Table 3, Q. 28). A second round question attempted to achieve consensus on such an important issue related to the long term viability of the adopted risk assessment methods.

4.2. Second-Round Results

The results of questions 19, 22, 23, 25, 27 and 28 (Table 3) were investigated further in a second questionnaire that was sent to all nine of the participating experts. Six of them responded, two did not give a response and one responded by saying they preferred not to participate further in the study.

4.2.1. Difficulties Encountered by the Experts during the Risk Analysis Process

As was previously found (Table 3, Q. 19) the main difficulties the experts have encountered during the process of risk analysis were the following:

- Difficulty in collecting the necessary data for the risk analysis.
- Difficulties in the cooperation between emergency services and TMs.
- Lack of skilled personnel.

In the second round, the experts were asked to provide an opinion about how these obstacles could be overcome. Tables 4 and 5 present a brief overview of the results, showing that the employment of the Delphi method contributed to further elaboration of the first round results and provided the authors with extra qualitative data.

Table 4. Expert recommendations to address the existing difficulties in data collection.

<table>
<tr><th>Type of Difficult to Collect Data</th><th>Way to Address the Problem</th></tr>
<tr><td rowspan="3">Traffic data about vehicles carrying DG (type and composition)</td><td>Keeping systematic records at tunnel-wise key locations every one or two years. Methods for automatic detection, recording and analysis of the characteristic orange colored [1] labels on the vehicles carrying DG.</td></tr>
<tr><td>Precise forecasting based on real transportation data to and from industrial areas, large cities, etc.</td></tr>
<tr><td>Cooperation between TMs and companies transporting DG.</td></tr>
<tr><td>Wind data</td><td>Installation of meteorological stations for keeping records of wind data at locations near the tunnel.</td></tr>
<tr><td>Total traffic data and HGV [2] ratio</td><td>Keeping relevant records for a representative time period e.g., one year.</td></tr>
<tr><td>Accident rate (ratio between the number of incidents and the total vehicle mileage)</td><td>Systems and procedures for recording and calculating traffic volumes and incidents based on the data in the possession of TMs</td></tr>
</table>

[1] Special labels showing the dangerous substance's UN number and risk classification [8]. [2] HGV: Heavy Goods Vehicle.

Table 5. Reasons for difficulties in cooperation between emergency services and TMs.

Cooperation Difficulties	Reasons
A single emergency plan is not always achievable but is necessary for successful handling of an emergency event	Each emergency service operates according to their own plan due to different internal protocols.
In contrast to other European countries, where the Fire Brigade takes charge in case of a tunnel fire and heads the ventilation and smoke extraction procedures as well as extinguishes the fire, the Greek Fire Brigade is not in position to take charge of the ventilation and smoke extraction procedures.	The Fire Brigade staff are not suitably trained in order to know how the ventilation and smoke extraction systems of a tunnel operate.

More specifically, Table 4 presents the recommendations made by experts in the second round to address the existing difficulties in data collection regarding the vital traffic, accident and wind data for the execution of comprehensive tunnel QRAs. Although the cooperation between emergency services and TMs was considered favorable, some problems were detected that were investigated further in the second round. Details of the encountered problems along with the reasons behind them, as perceived by the experts, are presented in Table 5.

The third aspect found in the first round as an obstacle to proper implementation of the QRAM was the lack of skilled personnel (Table 3, Q. 19). In the second round, the experts concluded that those involved with the risk analyses should be trained to meet the following minimum qualifications:

- Knowledge and professional experience regarding the safety systems, electromechanical equipment, ventilation equipment and smoke extraction systems of tunnels.
- Risk management knowledge at an advanced level.
- Knowledge of the ADR Agreement and the relevant national and European legislature at an advanced level.
- Adequate knowledge of fluid mechanics.
- General knowledge regarding the operation of tunnels.
- Traffic data calculation knowledge at a basic level.
- Statistical knowledge at a basic level.

4.2.2. Assigning Risk Analysis to an External Consultant

According to the national and EU regulatory frameworks, the required risk analysis for each tunnel should be carried out independently from the TM body by an external consultant. In round one, seven of the experts were unaware if D.A.S. has assigned risk analyses to independent consultants (Table 3, Q. 22). To clarify this issue in a relevant second round question, the experts verified that there is a lack of consultancy firms with experience in conducting risk analyses in Greece. The view that there may be several consultant firms that can undertake such a task, but that few meet the D.A.S. requirements, was also expressed. According to two of the experts, this fact can lead to a distortion of the competition, or the absence of competition can make the conducting of these analyses difficult since a monopoly situation may arise. Furthermore, one of the experts mentioned that only two or three consulting firms with the adequate experience are operating in the Greek market. It is worth mentioning that EOSA has undertaken the task of carrying out several risk analyses, with their own experienced engineers, that were partly accepted by D.A.S. as they were not carried out independently of the TM.

4.2.3. Factors Contributing to Multiple ADR Categorization during Operation

As was presented in the first round results, all experts agreed that it was common for a tunnel to be assigned to multiple ADR categories during operation (Table 3, Q. 25). During the second round it was found that the factors that contribute to this multiple categorizations during operation are:

- Significant change in traffic incidents.
- Significant variation of traffic data (Annual Average Daily Traffic (AADT), ratio of Heavy Goods Vehicles (HGV), ratio of HGV transporting DG and seasonal traffic).
- Significant variation in DG vehicles' transit, and/or DG composition.
- Change in the tunnel safety equipment: construction of new equipment, partial or total failure of the tunnel safety system.
- Change of the national or European directives and guidelines.

4.2.4. Procedures for Communicating the Acquired Experience to Future Risk Assessors

As was found from the first-round questionnaire, only three of the experts expressed the view that procedures for communicating the acquired experience regarding risk analyses to future ones exist, whereas the rest of them either expressed the opinion that such procedures do not exist or that they did not know of any (Table 3, Q. 27). In the first round those who responded that such procedures exist were then asked to choose one or more among such possible procedures as derived from the literature review, or to note additional ones (Table 3, Q. 28). In order to further investigate this issue, in the second round questionnaire the experts were given a summary of the relevant first round responses about the proposed procedures and were then asked to select the procedures they agree with or also to propose additional ones. Eventually, this resulted in all the experts agreeing that these procedures exist, and they are the following:

- Relevant conventions and seminars.
- At an internal level per TM.
- Following the mandatory six year update of the TSF and reconducting of the risk analysis.
- Transmission of the relevant data from the TM to D.A.S.
- Development of a national tunnel database

It should be noted that in this case, the application of the modified Delphi method contributed to the achievement of a consensus among the experts. Even though only three of them would acknowledge the existence of these procedures in the first round, in the second round they all agreed that these procedures exist, thus making it possible to further investigate possible improvements to these procedures.

5. Discussion

The literature review and the use of the modified Delphi method highlighted the needed improvement in risk assessment, licensing and operation procedures regarding the tunnels of the Greek road network. Based on the results of this Delphi study, recommendations are made to improve the applied QRA approach, to facilitate the cooperation between TMs and emergency services, to communicate acquired experience and lessons learned and to enhance the training of risk assessors.

5.1. Improvement of the Applied QRA Approach

A more flexible approach for categorizing the tunnels according to ADR and selecting the appropriate method for carrying out tunnel risk analyses is proposed based on the studies of Lundin & Antonsson [21] and Abrahamsen et al. [20], as well as on the views expressed by one of the experts (Section 4.2.3). The proposed approach for the evaluation of acceptable risk in road tunnels by Abrahamsen et al. [20] consists of three levels of criteria based on the differentiations among the tunnels, and afterwards the suitable risk analysis approach can be applied based on the characteristics and the importance of the tunnel as derived by Lundin & Antonsson [21]. With this approach, an appropriate tunnel category can be derived with less required resources and expertise as compared to carrying out a complete QRA. At the same time, a much more efficient allocation of the available resources is achieved for tunnels with no special features [35] or in environmental surroundings that do not affect the safety of road users, because the quantitative acceptance criteria, which require extensive analyses and documentation, are rendered redundant in these tunnels. The necessary data for applying the abovementioned approach could be derived from a national database, as proposed by one of the experts (Section 4.2.4), consisting of records of the safety characteristics of the road tunnels. This database should record both the static (invariable) characteristics of the tunnel (e.g., geometry, infrastructure, equipment) and the dynamic variables, such as the Annual Average Daily Traffic (AADT), the ratio of Heavy Goods Vehicles (HGV) and the ratio of HGV transporting DG (HGV-DG), the latter being updated periodically by the TMs. In addition, the necessary data can be found in a simplified registry for the tunnels that do not deviate from the minimum requirements (according to the regulatory framework [9,14]), based on which, a first assessment can be made on whether the conditions in the tunnel allow for the safe passage of the HGV-DG or a further investigation with the application of QRAM is needed.

5.2. Facilitating the Cooperation between TMs and Emergency Services

The results from the second round displayed that, apart from the limited availability of emergency vehicles and emergency personnel, cooperation problems between emergency services and the TMs can occur in an emergency situation. This is because of variances in internal protocols between different local emergency services along the length of a motorway under the responsibility of one TM with multiple tunnels. Moreover, one of the experts expressed the view that the police departments do not keep full records of incidents and hence accidents are being under-recorded. What is more, according to another expert the periodic training of the emergency services' personnel on the tunnel safety systems does not occur in a systematic way and depends on the existing cooperation between the TM and the emergency service department. Thus, in some cases, the fire brigade personnel lack the necessary knowledge of how each tunnel's ventilation and smoke extraction systems work. Finally, although according to P.D. 230/2007 the emergency plans have to be jointly created by the emergency services and the TM, this does not occur systematically.

Therefore, to facilitate the cooperation between TMs and emergency services, a common culture between them should be forged like in the case of the DG transport stakeholders where improved communication and understanding between them has shown to push the transport system towards safer DG transport [4]. This could be achieved by continuing their cooperation, as the regulatory framework prescribes, through meetings, sharing plans [4], seminars, and/or more training drills, which of course assumes that the emergency services are sufficiently staffed.

5.3. Communicating Acquired Experience to Future Risk Assessors

The second round of the Delphi study provided final agreement between experts that best practice procedures are in force but should be enhanced to facilitate the transference of lessons learned to future risk assessors. They concluded that this can be achieved through relevant conventions or seminars, on an internal TM level, during the required six year updates and by systematic transference of relevant data from the TMs to D.A.S.

One such opportunity for knowledge transfer is the upcoming World Tunnel Congress that will be held in Athens in 2023. One of the experts notes that the development of internal TM expertise is necessary since it is important for the TM's staff to be familiar with auditing procedures and risk analysis methods. This expertise is necessary to properly select the parameters to be used as input data in the QRAM regardless of the fact that the body responsible for carrying out the QRA is independent of the TM.

As far as the updating of the TSF and the re-conducting of the risk analysis every 6 years is concerned, the experts have conflicting opinions. Two believe that this is adequate since a time period of 6 years is the maximum time period to secure forecasts regarding traffic conditions. On the other hand, two of the experts note that in case an important change in the existing conditions or the tunnel characteristics does not occur, there is no use for the above procedure happening every 6 years. In addition, one recommends setting specific quantitative criteria for updating these analyses (e.g., differentiation in traffic data when the forecast is overcome by 30%, there is a significant accident rate increase, differentiation in the traffic volume of DG or modifications to the tunnel safety equipment).

Embracing the opportunity to recommend a procedure for communicating the acquired experience on risk analysis to future assessors, two of the experts made the following recommendations. According to the first, the previously proposed national database of static and variable characteristics should also record the quantitative results of the risk analyses carried out using the QRAM for each tunnel. From this database, a simplified registry could be created consisting of tunnel characteristics such as length, traffic volume and ratio of HGV-DG, to help determine whether deviations among similar tunnels are observed. This simplified registry would be for the tunnels that do not deviate from the minimum requirements (according to the regulatory framework [9,14]), based on which a first assessment can be made on whether the conditions in the tunnel allow for the safe passage of the HGV-DG or a further investigation with the application of QRAM is needed. In the same spirit, the other expert expressed the view that an electronic registry of the TSFs for every road tunnel in the Greek network could be kept under the care of D.A.S., and this registry should be open access for all TMs.

5.4. Enhancing the Training of Risk Assessors

In order to enhance the training of the risk assessors, according to the experts, they should be trained for broad and specialized qualifications. They should be educated regarding tunnel safety systems, risk management methods and the applicable national and European regulations. In addition, they must have adequate knowledge of fluid mechanics and basic knowledge of statistics.

Adequate knowledge of fluid mechanics is deemed necessary for understanding how smoke behaves during a tunnel fire [36], a critical element taken into consideration during the application of QRA [37]. Furthermore, according to the study of Petelin et al. [38], the QRAM requires data on volumetric air flow along the tunnel section in case the tunnel has longitude ventilation. In the case of a tunnel having transverse ventilation, it is also required to determine the air flow extracted from and blown into the section. Consequently, this understanding will influence the decision-making regarding the type and sizing of the ventilation system to be installed, its operation in an emergency and the response procedures that will be developed to allow TMs and emergency services to safely manage the incident.

It is proposed that the body that could undertake the task of training risk assessors should be the Greek Tunneling Society (GTS), which is the established and official representative of Greece in the International Tunneling Association (ITA-IATES). This recommendation is made since some of the main objectives of the GTS are the following [39]:

- To inform the Greek engineering community (individuals, companies, public sectors etc.) about the key advantages of underground structures and development.
- To record and communicate technical information, knowledge, and experience about Tunneling and Underground structures.
- To work with the responsible state authorities for drawing up regulations, specifications, recommendations etc.

Additionally, since the GTS was established, it has organized scientific events (seminars, lectures and technical visits to underground projects and tunnels) and was also recently selected to host the 2023 World Tunnel Congress in Athens, making GTS suitable to undertake the task of training the risk assessors.

6. Conclusions

The transportation of DG through European road tunnels is determined by a clear regulatory framework that applies to transport operations within the Trans-European road network, in order to prevent and/or eliminate the grave consequences of an accident involving DG, especially in the closed tunnel environment. An innovation of this study is that it applies the modified Delphi method, with the participation of nine experts, to investigate the obstacles to successful conformation to this framework, focusing on the EU Directive provisions for tunnel risk analyses and the cooperation between TMs and emergency services which have not been previously evaluated [10]. In addition, this paper contributes to the evaluation of the implementation of the national D.A.S. guidelines for carrying out the risk analyses regarding the transportation of DG through road tunnels in Greece ten years after their enforcement.

The major obstacles that were found according to the Greek experts have to do with the collection of the necessary data for the risk analysis, the inconsistently systematic cooperation between emergency services and TMs and the lack of skilled personnel. In order to address these issues, the current research resulted in recommendations useful for those involved in QRAs for the operation of road tunnels in Greece.

In summary, the following recommendations are made to improve the applied QRA approach, to facilitate the cooperation between TMs and emergency services, to communicate lessons learned and to enhance the training of risk assessors. First a national database of records of the safety characteristics of road tunnels and a simplified registry for the tunnels that do not deviate from the minimum requirements should be developed. Based on these records, preliminary assessments can be made regarding if the conditions in the tunnel allow the safe passage of HGV- DG or if further investigation with the application of QRAM is needed. The development of this database and/or an electronic TSF registry is a key tool for the transference of experience, best practices and lessons learned to future risk assessors, and should be therefore developed and maintained by D.A.S. and be open access for all TMs. The research results showed that it is necessary for a common safety culture between TMs and emergency services to be developed by providing constant feedback through seminars, meetings and more frequent training drills. Finally, it is proposed that the GTS undertakes the task to train risk assessors so that they meet the list of qualifications the experts noted to be necessary for conducting these analyses.

The limitations of this study are that even though implementation issues of the EU Directive are investigated, the authors reached out only to Greek experts and the view of their European colleagues is not reflected. Moreover, three of the experts that participated in the first round of the modified Delphi study did not participate in the second one, showing the limitation of the Delphi study because of respondent fatigue.

Future research could investigate whether enough consulting firms with experience in conducting QRA exist at a European level, versus the lack of them in Greece, and also could investigate possible obstacles regarding the implementation of other individual provisions of the EU Directive in other European countries. As investigated previously for the design and construction phases [40–42], research into how the personality attributes of key players—like first responders, risk assessors, TM's and safety officers—affect risk assessments for the tunnel operation phase could provide additional valuable insights to improving the safety of transportation of DG through tunnels.

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