

# Risk assessment of dangerous goods in road tunnels

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*Abstract:* - An evaluation of the impact due to vehicles transporting dangerous goods on the risk level in road tunnels is presented. Unidirectional tunnels having characteristics in compliance with the European Directive 2004/54 EC were more especially investigated. Different percentages of dangerous goods vehicles (DGVs) considered as part of freight vehicles were analysed. The results expressed in terms of social risk, as F/N curves, or expected value (EV) show that the risk level increases in a linear way with the percentage of DGVs. However longer tunnels present both higher gradients and major risk levels. These results can help us in getting an understanding whether the circulation through tunnels of DGVs should be free, limited to specific time periods (e.g., by night), or forbidden.

*Key-Words:* - Quantitative risk analysis, road tunnels, heavy vehicles, dangerous goods

## 1 Introduction

According to Eurostat [1] the volume of freight carried on Europe's roads increases continuously. An evaluation of about 39 million freight vehicles circulating on the roads of the EU-28 at the end of 2013 has been estimated, with a rate of 77.8 utility vehicles per 1000 inhabitants.

Among the aforementioned vehicles, dangerous goods vehicles (DGVs) have a relevant importance for safety both on roads and in tunnels. Their circulation is governed, from 1957, by European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) [2]. In the light of this agreement, each *Contracting Party* can apply restrictions to the passage of vehicles carrying dangerous goods through tunnels by means of assigning the road tunnel to one of the tunnel categories (from *A* to *E*). Category *A* indicates tunnels with no restriction for the carriage of dangerous goods; while, on the contrary, category *E* specifies tunnels with restrictions to all type of dangerous goods. The tunnel category, which is based on the consideration that in tunnels the severe accidents can be caused by explosion, release of toxic gas (or volatile toxic liquid) and fire, must be made by competent authority. However, it has to be stressed that, at moment, many countries (e.g., including also Italy) have great difficult to apply restrictions for orographic features, political or social implications, as well as for management

problems of tunnels belonging to border roads. Therefore, in lack of the specified category, a tunnel has to be considered free to passage of all type of vehicles. This includes also those carrying dangerous goods, with the legal responsibility of their circulation which is attributed to the Tunnel Management Agency (TMA). For this reason, TMAs need tools for making more appropriate decisions about to limit or forbid that DGVs pass through a tunnel. In this respect, a quantitative risk analysis (QRA) is suitable.

The European Parliament and Council in 2004 adopted the European Directive 54/EC [3]. In this Directive, in which minimum safety requirements are reported, is also specified that for tunnels opened to dangerous goods a risk analysis should be carried out to establish if additional safety measures should be implemented. The Italian Ministry of Infrastructure and Transports also adopted the aforementioned Directive [4], and subsequently the Italian Management Agency of National Roads and Motorway (ANAS) [5], has published guidelines including a risk analysis method.

Most risk analyses are based on an average value of the percentage of dangerous goods vehicles (DGVs) considered as part of freight vehicles. Indeed, dangerous goods flow is not constant but can vary depending on the type of road (e.g., a road serving nuclear, chemical or petrochemical plants is interested by a higher number of DGVs than a common road) and during the day (e.g., peak

dangerous goods volumes are expected more especially in the mornings and/or evenings compared to night ones). Therefore, in some cases, making a risk analysis of tunnel based only on the average value of DGVs might be not justified. Taking into account that dangerous goods flow can vary with the type of road or during day is within the main scope of this paper.

Different risk analysis models are used in various countries (see [6] for a summary). In Europe, for the risk analysis of DGVs only (i.e., it is not strictly for vehicles that does not carriage dangerous goods) is widely used the DG-QRAM (Dangerous Goods-Quantitative Risk Model) proposed jointly by PIARC (Permanent International Association of Road Congress) and OECD (Organization for Economic Co-operation and Developed) with associated software developed by INERIS [7].

Applications of the DG-QRAM can be found in: Ronchi et al. [8], Zulauf [9], Zhou et al. [10], Knoflacher and Plaffenbichler [11], Petelin et al. [12], Kyritopoulos et al. [13] and Steiger et al. [14], Caliendo and De Guglielmo [15] and [16], Saccomanno and Haastrup [17], Hall et al. [18], Parson Brincherhoff Quade & Douglas [19], Diernhofer et al. [20], Caliendo and De Guglielmo [21], and recently Benekos and Diamantidis [22].

However, the abovementioned studies focused more especially on some parameters that may influence the risk level in road tunnels. A wider assessment that contemporaneously take into account the variability of the percentage of DGVs (which is related to type of road and/or peak hourly flow), ventilation system, and tunnel length does not appear to have been sufficiently well investigated. Thus this paper focuses on these factors all at the same time.

The present paper is organized as follows: the next two sections contain descriptions both of the used software (DG-QRAM) and the types of implemented tunnels. These tunnel types are derived from two of the tunnel categories of EU Directive, based on two key parameters: average annual daily traffic (AADT) per lane and tunnel length (L).

The results of computer simulation are then presented in comparison with the limit of ALARP region. Finally, conclusion and further developed are indicated.

## 2 Methodology description

A quantitative risk analysis (QRA) is generally based on a probabilistic approach that involves the identification of hazards, the estimation of probability and consequences of the risk. QRA

involves, according to this probabilistic approach, event trees, fault trees and consequences estimation models. The main output of this analysis is an evaluation of social risk resulting from exposure to a hazardous event both for tunnel users and surrounding population. Two are the ways to represent the social risk: a quantitative way in term of expected value and a graphical way with F/N curves in a bi-logarithm chart. In particular, the expected value or EV is the average number of fatalities per year while, in the form of F/N curves, F represent the cumulative frequency that the number of fatalities is equal to or greater than a given number N. Each F/N curve, that is obtained for a studied risk scenario, needs to be compared with threshold values for understanding whether the risk may be tolerable or not. In Italy, the Italian Ministry of Infrastructure and Transports [4], in adopting the aforementioned Directive, has indicated a region of the bi-logarithm chart called ALARP (as low as reasonably practicable) where the acceptability of risk depends on a benefit/ cost analysis.

The software used in this study, as said, is DG-QRAM. It considers 13 accident scenarios since a comprehensive assessment of the quantitative risk analysis, on the transport of goods through tunnels, needs simplifications. Two scenarios are concerning fire due to heavy goods vehicles with no dangerous goods characterized by HRR of 20 and 100 MW. The remaining scenarios consider fires, explosions or releases due to heavy vehicles carrying tank, bulk or cylinders of: liquefied petroleum gas (LPG), motor spirit, chlorine, ammonia, acrolein, liquefied refrigerated CO<sub>2</sub>.

DG-QRAM takes into account: accident frequencies; consequences of incidents, escape and sheltering effects; and effects of hazards (such as heat and smoke) on people. A wide range of information has also to be introduced as input: geometry, traffic, ventilation system, drainage, emergency escape, density of population, etc. The results for each scenario are reported both in terms of social risk by means of F/N curves and also in term of expected value (EV).

## 3 Studied tunnels

In the light of EU minimum safety requirements for road tunnels (reported in EU Directive and, with additional details in the Italian Decree), two types of unidirectional road tunnels, at design stage, are analysed in this study. *Type I* and *type II* point out, as summarized in the following table 1, two categories of tunnels widespread used in Italian

rural roads: length greater than 1 km, no emergency lane, and high daily traffic per lane.

Application for tunnel with length less of 1km, respect of which the mechanical ventilation is not explicitly required, are not reported because of the well known limitation of DG-QRAM in giving reliable risk evaluations in this specific

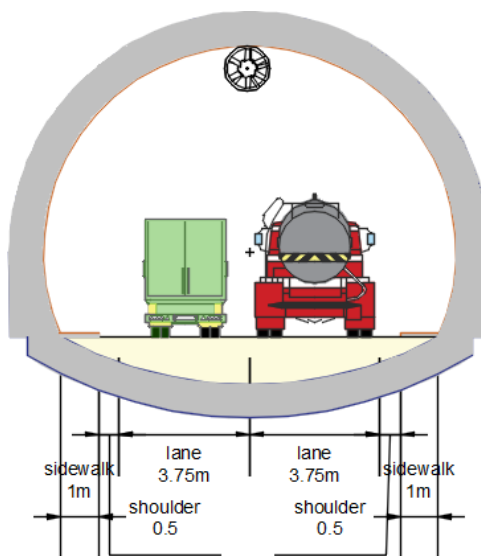
circumstance (see [21] for more details about DG-QRAM limitations).

In addition to the data of table 1, it has to stress that the presence of longitudinal system for ventilation is supposed to be provide by jet fans on the ceiling with the following characteristics: 1 m of diameter, air flow rate of 28 m<sup>3</sup>/s and thrust of 1200 N.

Table. 1 Tunnel description according to EU Directive

Tunnel category, according to Directive 54/2004/CE, with traffic per lane > 2000 veh./day	1000 < Length ≤ 3000m	Length > 3000m
	Type I	Type II
Traffic	5000 veh./day per lane (Average Annual Daily Traffic = 10000 veh./day)	
Percentage of heavy vehicles (HGVs)	20 %	
Percentage of dangerous good vehicles respect to HGVs	1%; 6%; 12%; 18%; 24%	
Length	2 km	4 km
Longitudinal slope	1 %	
Emergency exits	At every 500m	
Lighting systems	Normal, safety and evacuation lighting systems	
Mechanical ventilation system	Longitudinal ventilation system provides by 8 jet fans on the ceiling	Longitudinal ventilation system provides by 13 jet fans on the ceiling
Monitoring system	CCTV	CCTV and automatic fire detection
Traffic signals	Before the entrances	Before the entrances and inside the tunnel

Cross section [not in scale]



Furthermore, table 1 also shows the percentage of vehicles transporting dangerous good.

Starting from the average Italian value [23] of 1%, the impact on risk is evaluated for the following percentages: 6%, 12%, 18% till a maximum of 24% (corresponding, for traffic of 5000 veh./day per lane, to 20 vehicles per hour, i.e. about a quarter of all heavy vehicles).

#### 4 Analysis of results

In this paragraph the results of DG-QRAM software application are reported in function of the type of tunnels and percentage of dangerous goods vehicles (DGVs).

According to the above mentioned Italian Decree, the F/N curves are drawn in the bi-logarithm chart with the upper and lower thresholds of risk. In particular, the limit of tolerable risk is under  $10^{-4}$  for  $N=1$  and  $10^{-6}$  for  $N=100$  while limit of intolerable risk is over  $10^{-1}$  for  $N=1$  and  $10^{-3}$  for  $N=100$ .

Figure 1 shows that, with reference to the *type I*, all the F/N curves are in the ALARP region.

In particular, the lower F/N curve corresponding to 1% of DGVs; the higher one is related to 24% of DGVs. In other words, the risk level increases with the percentage of DGVs.

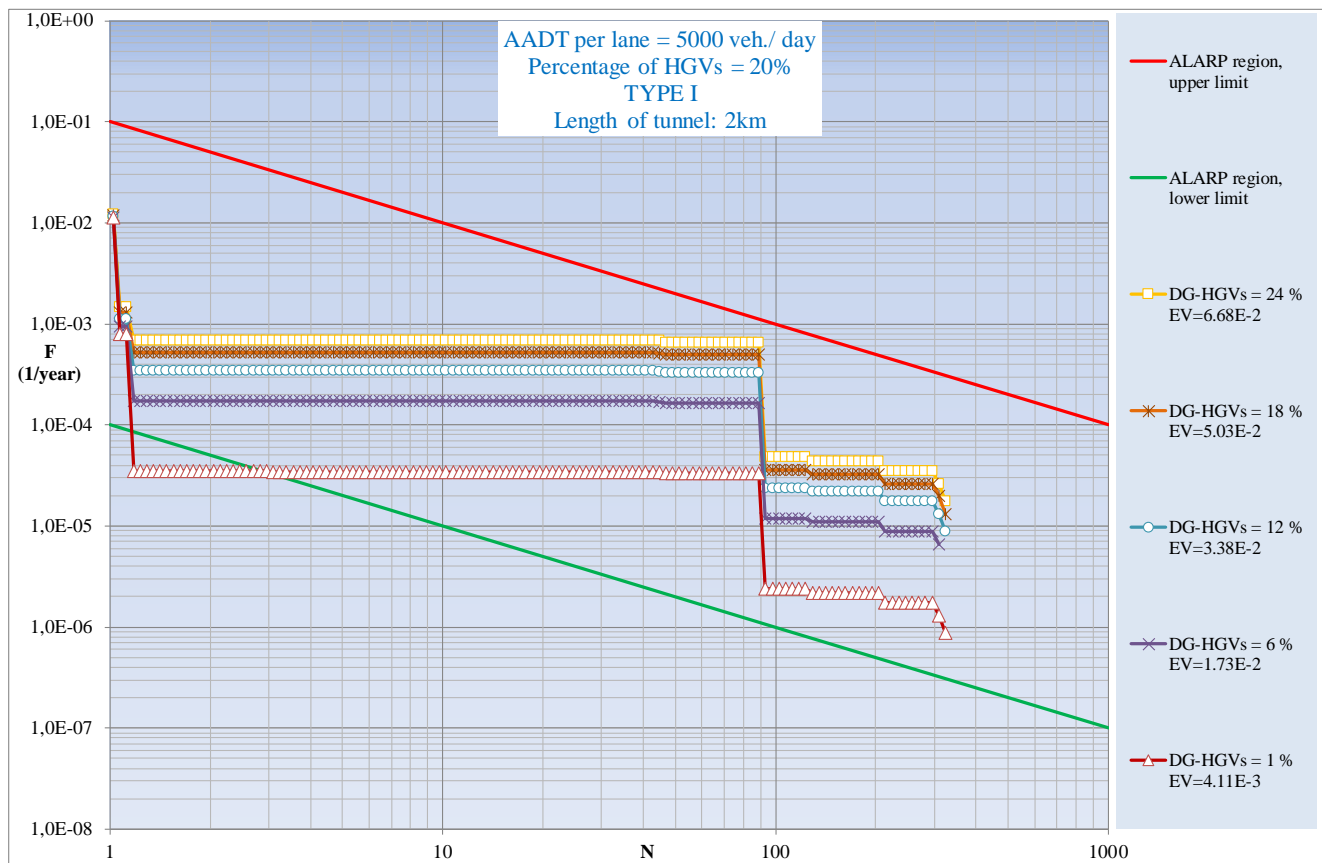


Fig.1 F/N curves of aggregated scenarios for unidirectional tunnel with length of 2 km (DG-HGVs as percentage of HGVs)

However, it appears to be interesting to note that the results, in term of expected value of risk (EV), from 1% to 6% of DGVs, show an increase of about 75%: from  $4.11E^{-3}$  to  $1.73E^{-2}$ .

If the number of these vehicles continue to increase, the corresponding increase in term of EV tend to reduce till 30 % between 18 and 24 % of DGVs: from  $5.03E^{-3}$  to  $6.68E^{-2}$ . This result might to be explain by considering that, from a certain number

onwards of vehicles transporting dangerous goods, the effect on the level of risk, already high, has a less substantial increase in value.

Similar findings are illustrated in figure 2.

In fact, for a tunnel with length of 4 km an increase of influence on EV of about 65% is found from 1% to 6% of DGVs (EV=  $7.79E^{-3}$  and EV  $2.28E^{-2}$ , respectively). Then EV tends to increase with a minor gradient passing from 18 to 24% of DGVs,

(e.g., +24% passing from  $EV = 6.03E^{-2}$  to  $EV = 7.79E^{-2}$ , respectively).

Also for the type II, all the F/N curves are also in the ALARP region.

This means that a reduction of the risk level should be justified by a benefit/ cost analysis. In this respect, low cost measures might consist in the fact that the Tunnel Management Agency permits, for instance, that DGVs pass through the tunnel only during night or on an alternative route.

Figure 3 shows the relationships obtained between the EV values and the percentage of DGVs for the two tunnel lengths investigated.

One can see that the risk level increases in a linear way with the percentage of DGVs. However longer tunnels present both higher gradients and major risk levels.

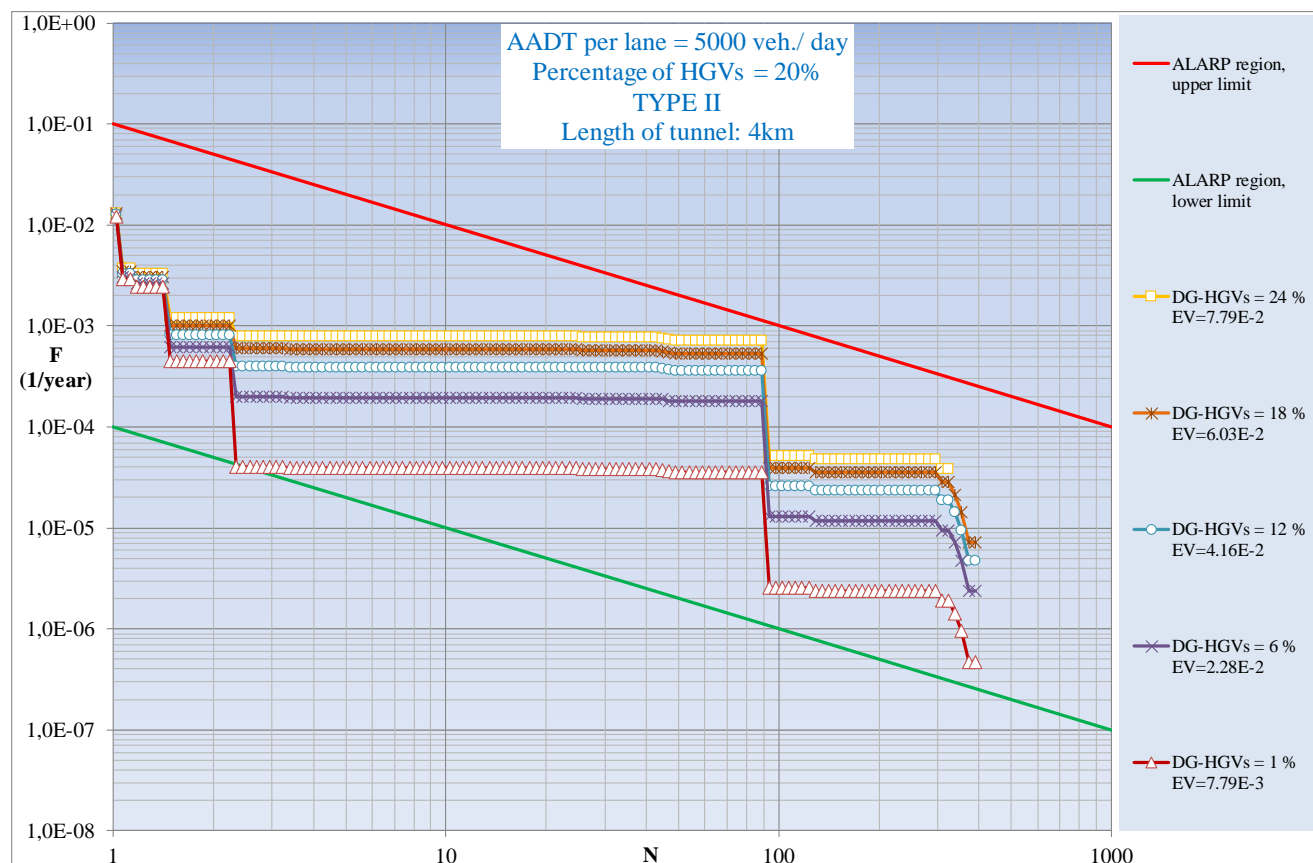


Fig.2 F/N curves of aggregated scenarios for unidirectional tunnel with length of 4 km (DG-HGVs as percentage of HGVs)

## 4 Conclusions

A quantitative risk analysis of unidirectional road tunnels for certain combinations of tunnel length and percentage of dangerous goods vehicles (DGVs) was performed.

The results in terms of social risk, as expressed by the F/N curves, show as the risk level increases with the percentage of DGVs.

However, the F/N curves were found to be still in the ALARP region for the cases investigated. Therefore, a reduction of the risk level should be justified by a benefit/ cost analysis. In this respect, low cost measures might consist in the fact that the

Tunnel Management Agency permits that the DGVs pass through the tunnel only during night.

Linear correlations between the expected value EV and the percentage of DGVs were also found. In other words, EV increases in a linear way with the percentage of DGVs. However longer tunnels present both higher gradients and major risk levels. This article presents the first interesting results concerning the open question on the transport of dangerous goods through tunnels.

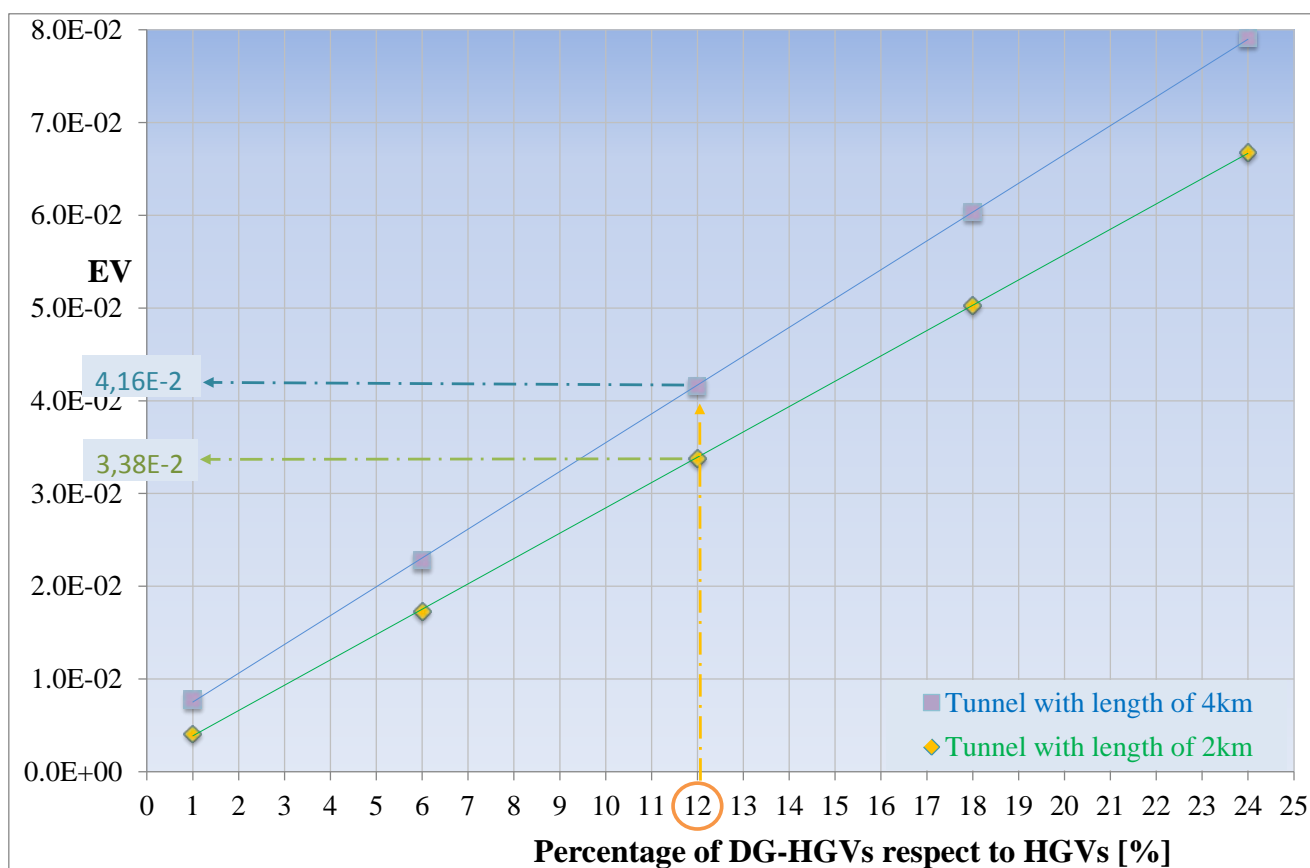


Fig.3. Straight lines representatives of the increasing trend of EV with the percentage of DG-HGVs

One possible extension of the present content, in addition to the percentage of DGVs and tunnel length, might be investigating also on different combinations both of the annual average daily traffic (AADT) and the percentage of heavy goods vehicles (HGVs).

Therefore, further research should be addressed towards studies for making these developments possible.

Moreover, it is to be said that certain improvements of the DG-QRAM software are also necessary. In fact, as already showed in [21], some additional provisions of EU Directive with the aim to improve safety in tunnels cannot be modelled (e.g., the presence of lay-bys, emergency stations, different types of emergency signs, etc.) Furthermore, it has not an interface with the more recent version of Microsoft Office. In this respect, however, it is to be mentioned that within the Technical Committee D.5- Road Tunnel Operations of PIARC is active a Task Group with the intent to update the current version of the DG-QRAM software.

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