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ORIGINAL ARTICLE

PROCESS SAFETY PROGRESS

Lessons learned from the Barracas accident: Ammonium nitrate explosion during road transport

Xavier Baraza[1] | Jaime Giménez[2] | Alexis Pey[3] | Miriam Rubiales[4]

[1]Faculty of Economics and Business, Universitat Oberta de Catalunya, Barcelona, Spain

[2]Chemical Engineering Department, University of Barcelona, Barcelona, Spain

[3]Global SHE & Process Safety Department, Stahl Holdings BV, Waalwijk, The Netherlands

[4]Safety Process Department, Pragma Safety Solutions S.L., Barcelona, Spain

Correspondence
Xavier Baraza, Faculty of Economics and Business, Universitat Oberta de Catalunya, Avda. Tibidabo, 39-43, 08035 Barcelona, Spain.
Email: jbaraza@uoc.edu

Abstract

On March 9, 2004, a lorry transporting ammonium nitrate (AN) overturned. The load caught fire and exploded due to the self-sustaining decomposition reactions of the AN. The consequences were two deaths, five injuries, and significant material damage in the form of destruction to vehicles and the highway. This article delves into the causes of the accident through root cause analysis techniques, such as fishbone, AcciMap and events and causal factors charting, which have demonstrated that the causes were not only physicochemical but also of an organizational nature. The explosion caused a crater 18 m in diameter, which would be equivalent to one caused by 11.4 tonnes of TNT. Through the relevant models, we have established the overpressure-distance map, explaining the breakage of lorry windscreens located 100 m from the accident site, and the vibration of glass planes at a distance of some 4 km. This accident underscored the need to comply with the safety measures handed down by competent bodies: (a) avoid contamination of AN, especially with fuels; (b) prevent the AN from being exposed to heat; (c) isolate for a minimum distance of 800 m in all directions around the accident site; (d) in case of fire, flood the area from a distance and stay away from the fire.

KEYWORDS
accident, ammonium nitrate, case study, detonation, lessons learned

1 | INTRODUCTION

Ammonium nitrate (AN) is one of the world's most widely manufactured and utilized hazardous chemical products.[1] The annual AN production capacity is estimated at 63 million tonnes, which are manufactured throughout some 200 plants now in operation.[2] AN is used as a nutrient in fertilizers and an oxidizing agent in explosives.[3] Nonetheless, the physicochemical properties and heat instability inherent to AN frequently lead to undesired accidents during its storage, handling, and transport.[4–6]

A significant number of accidents take place in hazardous material transport in its various modalities (rail, road, sea, etc.). The Failure and Accidents Technical Information System (FACTS) database,[7] containing information on 26,509 accidents that had occurred until December 2020, showed that 21.5% took place during transport, and of those, 52.2% were road accidents.

This information, together with the occurrence of an important number of severe accidents in road transport, has led to a significant effort over recent decades to improve transport safety, especially in developed countries. Such accidents include the one in Los Alfaques in Tarragona (Spain) in July 1978, with 126 direct deaths and over 300 wounded by the explosion of a tanker carrying propylene with the subsequent blaze of fire,[8] or that of Kannur in the Kerala region (India) in August 2012, with the explosion and fire of a tanker truck loaded with LPG, causing 20 deaths and 7 severe injuries,[9] among others.

Despite the improvements, accidents such as these continue to happen since their complete prevention is practically impossible. This is one of the reasons why studies are conducted on the accidents that take place, as they are essentially the only source of broad-scale experimental data.[10] This article features an analysis of the explosion of a dump trailer truck that was transporting AN, which took place in the municipality of Barracas (Castellón, Spain) on March 9, 2004. The authors' aim is to carry out an in-depth study of its causes and consequences, the conclusions of which may help to prevent such accidents, and if they do happen, mitigate their consequences.

2 | PHYSICOCHEMICAL PROPERTIES AND POTENTIAL HAZARDS OF AN

AN (NH_4NO_3), with CAS number 6484-52-2, was first synthesized by German chemist Johann R. Glauber in 1659 by combining ammonium carbonate and nitric acid. He called this new compound *nitratum flammans*.[11]

Since that time, many processes have been reported in the literature on the preparation of AN.[4] Currently, the main industrial production process is the neutralization of nitric acid with liquid or gaseous ammonia, following this exothermic reaction:

$$HNO_{3(aq)} + NH_{3(g)} \rightarrow NH_4NO_{3(aq)} (\Delta H = -175\ \text{kJ/kmol})$$

Approximately 84% of the AN produced is used as fertilizer for agriculture. The rest (16%) is used to make military and commercial explosives.[12]

AN is an odorless crystalline solid that is between colorless and white, with a molecular weight of 80.04 g/mol and a density of 1725 kg/m^3 at ambient temperature. It is highly soluble in water (194 g of AN at 20°C and 405 g at 60°C in 100 g of water).[3] It is a complex substance that presents five allotropic forms with transitions among them at certain temperatures.[12] Especially relevant for the fertilizer sector is the transition at 32°C (a temperature easily reached during the summer months), in which pure AN's sensitivity to detonation increases after passing through a number of transition cycles at 32°C.[4]

AN is stable at ambient temperature and pressure. It does not burn but acts as an oxidizing agent, reinforcing and improving the combustion of combustible material. AN melt at 169.6°C, initiating a complex decomposition, although this occurs with greater intensity as of 200°C. Decomposition initially takes place endothermically (requiring heating), to then evolve toward exothermic reactions.[13] It is likely that decomposition releases significant amounts of toxic smoke that contains ammonia and nitrogen oxide fumes.[14,15] Thermally or mechanically triggered explosive reactions cannot be ruled out in extreme conditions.[4,16] AN has a number of incompatibilities that can significantly increase the risk of fire and explosion and, in many cases, even reduce the temperature at which decomposition takes place.[17]

Due to these properties, three different accidental scenarios can arise involving AN and AN-based products.[16] Although the probability of occurrence is very low, there is a risk of detonation for technical-grade AN (containing over 28% nitrogen), simple fertilizers, and possibly, compounds containing significant amounts of AN.[18,19] Another hazardous situation is the simple decomposition of AN normally associated with a situation of exposure to an external fire.[20,21] Last, in the case of some AN-based fertilizers (for example, NPK-type fertilizers), situations of self-sustaining decomposition have been identified in storage facilities and maritime transport, generating ammonia and nitrogen oxide emissions.[14,15,22]

3 | AN DETONATION MECHANISM

The explosive properties of AN have been thoroughly studied over the years. From a theoretical point of view, pure AN is an explosive, as it can give rise to a rapid exothermic reaction with the release of a significant amount of gasses at high temperature. In 1869, Marcelin Berthelot put forth the following explosive decomposition reaction for AN[23,24]:

$$NH_4NO_3 \rightarrow N_2 + 2H_2O + \frac{1}{2}O_2 (\Delta H = 1480\ \text{kJ/kg})$$

Common explosives release an amount of energy ranging between 2500 and 6000 kJ/kg. Therefore, the 1480 kJ/kg released by AN indicates that it is a moderately powerful explosive.[12]

The key parameters that can influence the detonability of AN are[25]:

- AN content,[19,26]
- combustible material content, expressed in equivalent carbon,[27]
- the pH of an aqueous solution,[17]
- particle size,[28]
- the crystalline structure of the grain (particle) and its superficial state,[29]
- the bulk density of the product,[28]
- the degradation associated with the shift from the crystalline transition point to 32°C,[4]
- and degradation related to water content (moisture).[30]

However, none of these data enable definitive conclusions to be drawn on the detonability of AN.[25]

The mixture of AN with combustible or other noncompatible products facilitates its detonation.[31,32] For example, in combination with aluminum dust, it makes up ammonal, a highly explosive mixture.[33,34]

Another element that can trigger the detonation of AN is the presence of an external fire that involves contamination due to fusion with organic materials and very high heat stress that facilitates exothermic decomposition.[20,21]

TABLE 1 Ammonium nitrate transport accidents

Accident (country, year)	Description	Causes	Damages
Australia, 1974	The electrical wiring of the tractor-trailer hauling AN was faulty and caused a fire, which resulted in an explosion.	Technical failure	3 dead
Australia, 1996	Trailer carrying AN overturned when it swerved to avoid collision with another vehicle.	Human error	1 injured
Canada, 1998	Lorry and trailer drove off the road, causing fire and an ensuing explosion of AN.	Human error	3 injured
Spain, 2004 (Barracas)	Lorry transporting AN collides with another vehicle, igniting a fire that causes an explosion.	Human error	2 dead 5 injured
Romania, 2004 (Mihăileşti)	Lorry transporting AN overturns in heavy rain, igniting a fire that causes an explosion.	Natural causes	17 dead 12 injured
United States, 2005	Lorry transporting (explosives grade) AN overturns and spills its payload on the road, where it mixes with fuel. No fire or explosion takes place.	Human error	1 injured
Mexico, 2007 (Monclova)	Lorry carrying AN caught fire following a road accident, and the fire caused an explosion.	Unknown	28 dead >150 injured
United States, 2008	Collision of lorry carrying AN against the guardrail, causing it to overturn on the road. No fire or explosion takes place.	Human error	1 injured
Australia, 2009	Lorry carrying AN drove off the road, overturning and causing a spill. No fire or explosion takes place.	Unknown	1 injured
Australia, 2014	Lorry carrying AN overturns and explodes on a highway bridge while the police, emergency medical services and fire brigade were in the area.	Unknown	8 injured

Abbreviation: AN, ammonium nitrate.

The sensitivity to shock wave detonation increases with temperature, the presence of fuels, reactive substances, and the presence of hollow spaces and bubbles in the substance.[35] The temperature of AN increases upon exposure to a large fire. The thermal decomposition mechanism of AN subjected to heating has been extensively studied.[16,36,37] This situation, along with the absence of sufficient prevention resources, can lead to a mass explosion of the product, as occurred in the accident analyzed in this article. A violent shock from a projectile or sufficiently powerful pressure wave can also trigger the detonation of AN.[25]

4 | ACCIDENTS INVOLVING AN IN ROAD TRANSPORT

Throughout history, there have been many accidents involving AN that have resulted in explosions with severe consequences.[5,12] These include the accident that occurred in Oppau, Germany, in 1921, resulting in 561 dead, 1952 injured and the evacuation of over 7500 local residents,[38] and the more recent example of the explosion in the Port of Beirut (Lebanon) on August 4, 2020, with the explosion of 2750 tonnes of AN, 202 dead, and over 6000 injured.[36,39] There have been many others, such as that of Port Neal (Iowa, United States, 1994, 4 dead, 18 injured),[40] Toulouse (France, 2001, 32 dead, 2442 injured),[41] West (Texas, United States, 2013, 15 dead, 200 injured)[21,42] and Tianjin (China, 2015, 173 dead, 28 missing and 797 injured),[43,44] to mention just a handful of cases. Further, AN has been involved in another type of accident that does not result in an explosion, in which the phenomenon of self-sustaining thermal decomposition has taken place. Also, AN compound NPK fertilizers (mixtures of AN with ammonium phosphate and KCl) in the right composition can be subject to slow deflagration (also called cigar-burning, although no fire can be seen). However, it is capable of burning through a large heap. Confinement and pressure increase accelerates the burning rate. This applies to the accidents of Nantes (France, 1987, 24 injured and over 20,000 evacuated)[20] or Escombreras Valley (Cartagena, Spain, 2002, 170,000 persons confined),[14] among others.

The previously mentioned historical analysis has revealed that, of the 26,509 accidents listed in the FACTS database, 2972 accidents (11.2%) took place during road transport; of the total number of road accidents, 31 involved AN. Table 1 lists the information on accidents with victims (injuries or deaths) that have occurred during road transport of (solid) AN taken up in the FACTS database.[7]

Of all the foregoing records, the accidents of Mihăileşti in the region of Buzău (Romania, May 24, 2004) and Monclova in the region of Coahuila (Mexico, September 4, 2007) both occurred during road transport of AN, are especially noteworthy for the number of fatalities.

In the Mihăileşti accident,[5,45] a lorry transporting 20 tonnes of AN in sacks drove off the road and overturned. This ignited a fire in

FIGURE 1 Lorry overturned in the roadside ditch, with fire burning under the dump trailer[50]

the driver's cab, which then surrounded the entire lorry. One hour later, the load exploded. Firefighters had attempted to cool the fire, but they did not have enough time. There was not enough time to block the roads or order an evacuation before the explosion. The result of the accident was 17 dead and 12 injured.[7]

In the Monclova accident,[5,6] a lorry carrying between 22 and 25 tonnes of AN collided with a pick-up truck on the highway. The collision resulted in a fire. Drivers, firefighters and journalists gathered around the accident to watch and help. Forty minutes after the accident, the AN exploded. A nearby city was impacted by shrapnel from the explosion. The result of the accident was 28 dead and 150 injured.[7]

Although it is not as serious as those mentioned, it should be noted for its similarity to the Barracas accident, the one that occurred in Angellala-Creek, an explosion of AN in contact with fuel after a previous time of fire. No fatalities were reported and the number of injured was 8.[7] The conclusions of this work would be easily extrapolated to this accident.

Both accidents have characteristics that are similar to the one analyzed in this article. This adds to the interest in learning from these types of accidents by carrying out detailed case studies.

5 | CASE STUDY: THE ACCIDENT OF BARRACAS, CASTELLÓN (SPAIN)

The accident took place on March 9, 2004, at 12:20 p.m., at kilometer 56 of highway N-234, between Sagunto and Burgos, in the vicinity of the Barracas municipality (Castellón, Spain). The media thoroughly covered the accident. The results were two persons dead, five injured, and major physical damage to the highway and to other vehicles.[46,47]

The lorry, which belonged to the Viesga company, was towing a dump trailer with a capacity of 40 tonnes. It was transporting 25 tonnes of AN fertilizer (33.5% N), loaded at the Fertiberia factory in Sagunto. Formulations featuring high nitrogen content have a high explosion risk,[48] and the EU Fertilizing Products Regulation[49] stipulates that fertilizers with AN, as of 28% nitrogen content, must be submitted to EC tests for detonability, equivalent to those of ANs with high nitrogen content. The EC test is insufficient to determine the detonability of a massive amount of AN subjected to fire. The mechanism to protect AN from detonation gets lost at higher temperatures. That mechanism is the hardness of the prills and the absence of defects in the prill. In addition, there is the endothermic-exothermic balance of the thermal decomposition that can be disturbed. Other studies to consider would be the Slow cook-off test, the UN gap test, and The fragment impact test (MIL-STD-2105B standard).[37]

The accident happened when the lorry was overtaking another vehicle and entered the left lane of the highway. An oncoming lorry tried to avoid the collision but still collided with the lorry hauling the AN. Both ran off the road and caught fire. The fire affected the front section of the lorry and spread to the lower part of the trailer, in which the AN was loaded (Figure 1). Several drivers stopped to aid the accident victims.

Approximately 25 min after the collision and after being exposed to the high temperatures of the fire, the AN exploded. This situation was accelerated by the mixture with diesel fuel, a combination thoroughly described in the literature.[4,5,16,17] Mention can be made of the aluminum present in the alloy composition of the dump trailer, which can act as a booster of AN explosions.[51]

The explosion was audible within a radius of 30 km. It made a crater on the roadway some 18 m in diameter and 3 m deep[50] and blew

FIGURE 2 Crater caused and guardrails blown off by the explosion[50]

off 100 m of guardrail (Figure 2). The expansive wave damaged the windows of over a dozen lorries within a radius of up to 100 m. Windows rattled 4 km from the accident site. The lorry and its payload were completely blown apart. In the words of one witness, "We had to take cover under the lorries because stones and pieces of iron began to fall out of the sky." A forest fire with 15 different sources began due to the projection of burning shrapnel.[46]

The accident caused two fatalities and injuries to five persons. The mortal victims were the driver of the lorry involved in the accident and another lorry driver who had stopped to offer assistance. He was struck by one of the fragments projected from the explosion. The injured were the driver of the other lorry involved in the collision, and four others who had stopped to help with the accident.

Several media outlets criticized the time it took first responders (police, fire brigade, and ambulances) to arrive on the scene. The first to arrive was a physician, who got there 30 min after the accident. The fire brigade took nearly 1 h to arrive.[52]

A few days later, on March 18, 2004, there was another accident involving AN on the same highway (N-234), with one dead and three injured. On that occasion, there was no impact on the payload, as the temperature conditions, fuel, and combustion mix that caused the Barracas explosion were not repeated. In that case, the AN was being shipped in sacks, not in bulk form.[53]

6 | ANALYSIS OF THE CAUSES OF THE ACCIDENT

One of the most important aims of accident investigation is the analysis of the causes. In this way, root-cause analyses can be helpful. The goal of such an analysis is to reach the root causes of the accident, in the understanding that if they are eliminated, the paths that lead to the accident are also done away with. Three of these techniques have been used in this study: the Ishikawa or fishbone diagram,[54] events and causal factors charting analysis (ECFC/A),[55] and AcciMap.[56]

In a fishbone diagram, the accident is laid out along a graphic fishbone, from which it takes its name. Each of the main causes is a fishbone branching off the backbone, which leads to the accident at the head. Within each of the main causes, there are small bones that stand for the causes that contribute to that main cause. As shown in Figure 3, one factor is that the fire was the immediate cause of the explosion, which was the final accident in this case, and another is the succession of causes leading to the final accident. Among them, as shown in Figure 3, are the physicochemical causes, as well as those of a purely organizational nature. When applying the fishbone technique, it is shown that the basic causes of the accident tend to correspond to what is known as the five Ms (methods, machinery, management, materials, manpower), four Ps (place, procedures, people, policies) and/or four Ss (surroundings, suppliers, systems, skills). Indeed, in the case being studied, several of these causes can be clearly identified, observing that those related to methods, management, procedures, policies, etc., have significant weight in the development of the accident.

The fishbone technique provides a relatively comprehensive snapshot of the accident, including the immediate physical causes, as well as all the organizational factors that contribute to it happening or increase its severity.

Another root-cause analysis technique that can help understand the development of the accident is the ECFC/A. In this technique, the chain of events leading to the final accident is sought, as well as the conditions in which these emerge. Figure 4 shows the ECFC analysis for the case at hand.

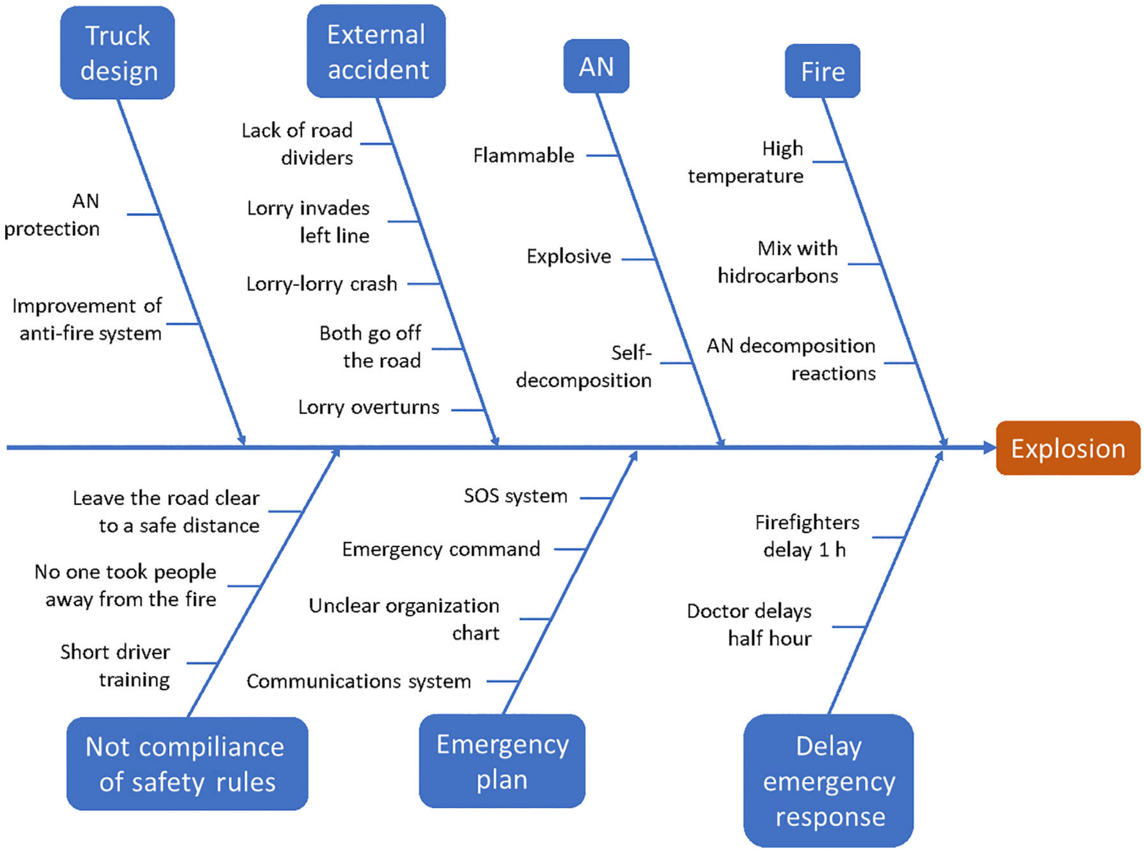

FIGURE 3 Fishbone diagram of the accident. ADR, agreement of dangerous by road; AN, ammonium nitrate; SOS, safety operational system.

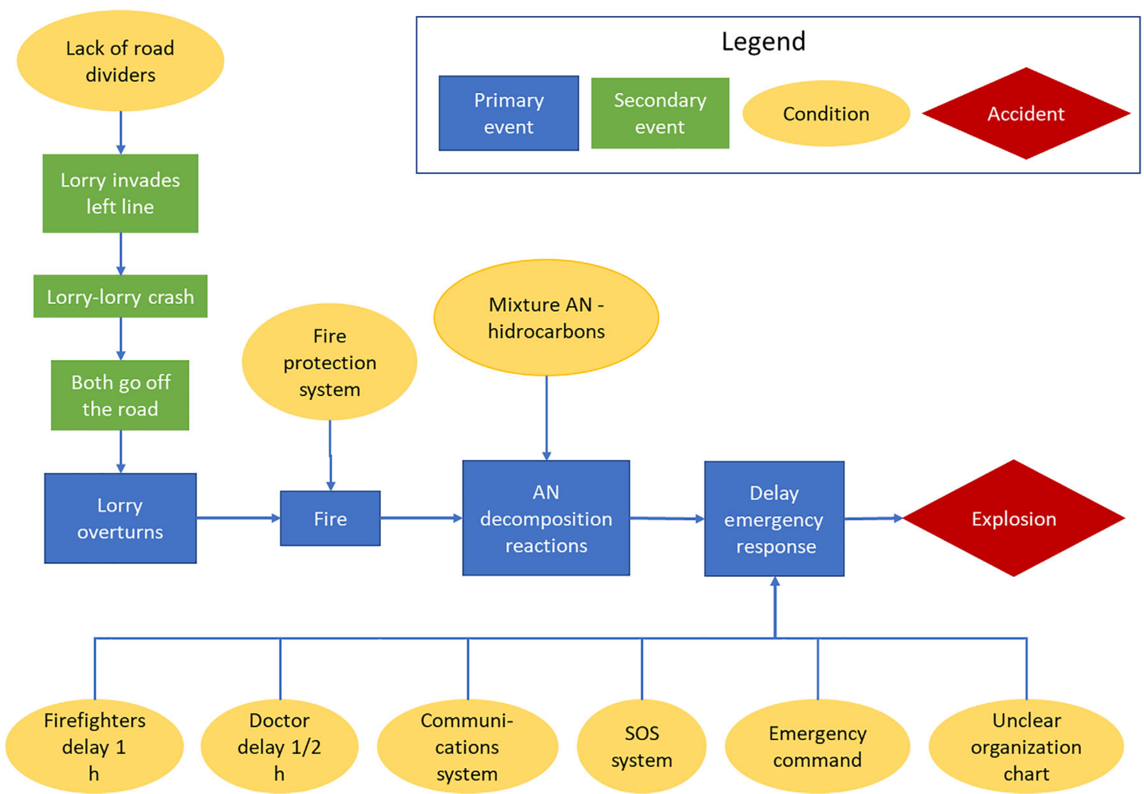

FIGURE 4 ECFC analysis scheme for the accident under study. AN, ammonium nitrate; SOS, safety operational system.

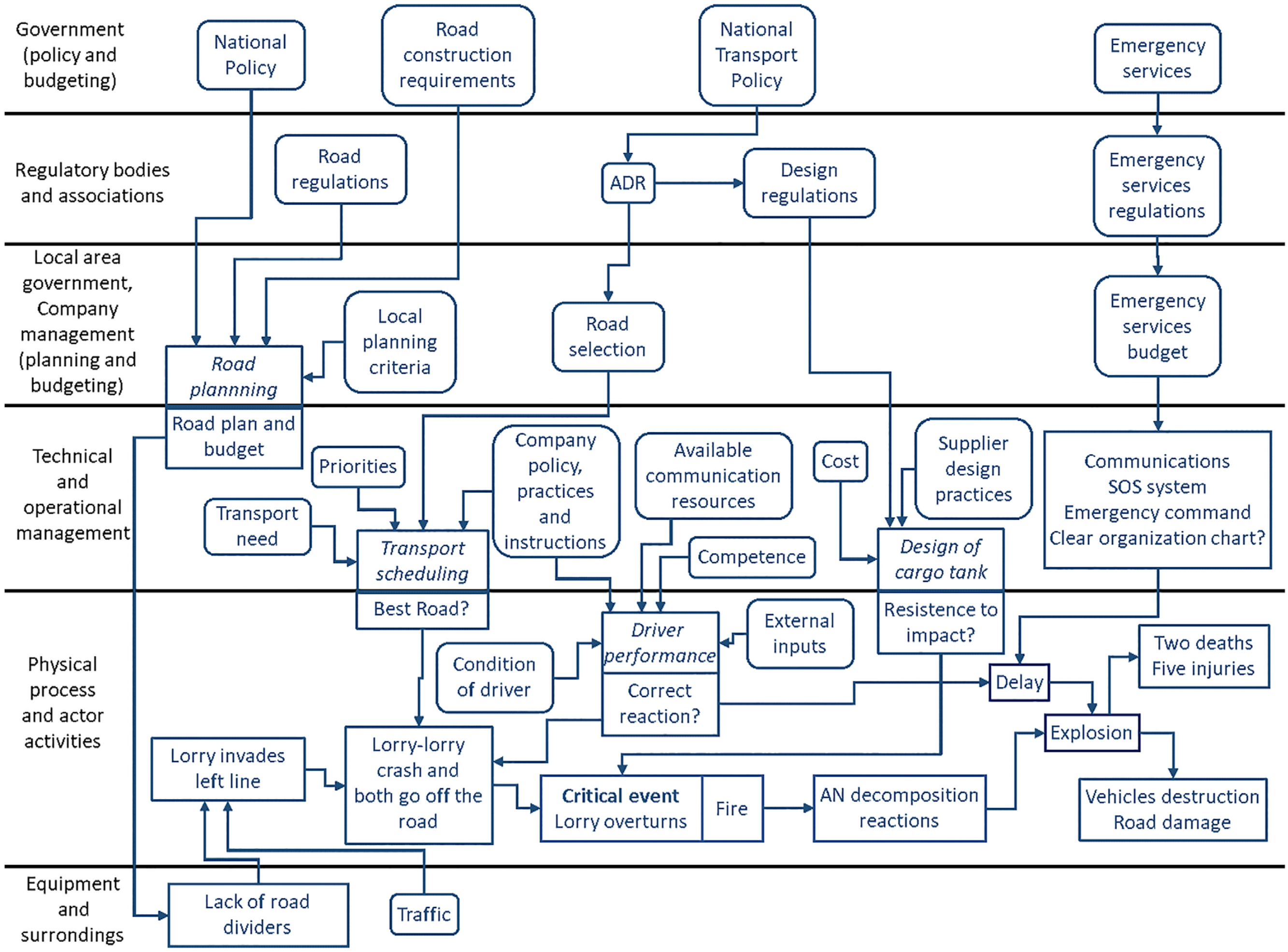

FIGURE 5 AcciMap of the studied accident. ADR, agreement of dangerous by road; SOS, safety operational system.

As shown in Figure 4, the main chain of events leading up to the final accident began with the overturning of the lorry and the ensuing fire. This triggered the self-sustaining decomposition reactions of AN that, as they were not stopped in time, led to the final explosion. Additionally, in order for that chain of events to be possible, there had to be a number of secondary conditions and/or events that triggered each of the events. For example, it can be observed that the delay in the emergency responders' action was due to a number of failures, chiefly at the organizational level.

As with the fishbone technique, the ECFC method shows that the physicochemical causes were not the only ones that led to the accident; organizational and design factors also played a major role. Thus, a more rigorous analysis of the sociotechnical system is needed. This analysis can be done by using several root-cause analysis methods, which can relate organizational causes with the final accident. In this way, AcciMap is a well-known methodology that allows to establish this kind of relationships. AcciMap runs at six different levels: (a) Government (policy and budgeting), (b) Regulatory bodies and associations, (c) Local area government—Company management (planning and budgeting), (d) Technical and operational management, (e) Physical process and actor activities and (f) Equipment and surroundings.

With this way of working, it is possible to reach the initial causes of the accident, which can sometimes be initial errors in the design or organization of a certain activity. Likewise, this methodology allows finding the interrelationships between all the possible causes until reaching the final accident, showing a complete map of the accident. Figure 5 shows the application of this method to the studied accident.

As can be seen, the fact of having designed a road without lane dividers has favored the accident. That decision comes from the policies set by the corresponding ministry and also from regional planning.

Likewise, Figure 5 shows that if we want the driver to have a correct reaction, he must have adequate competence and training, he must work in the best possible conditions, and company policies must facilitate his work. Otherwise, it will be easier for him to make a mistake, or he cannot avoid being affected by the mistake of other drivers. On the other hand, the postaccident reaction, assuming that the driver does not die or is seriously injured, will also depend on the factors that have just been mentioned and on the communication resources that he has at hand in order to notify the accident as soon as possible to emergency services and make the right decisions himself. If this is not the case, precious time will be lost, or inappropriate decisions will be taken that can aggravate the consequences of the accident. In the case at hand, after the lorry crashed, overturned, and caught fire, although it was a while until the explosion happened, the appropriate measures had not been taken and the emergency services had still not arrived.

It is also clear that the emergency services must be well organized and have the necessary means and capacity to be able to act as soon as possible to alleviate the consequences of the accident, as pointed out also in Figure 5. Any dysfunction in the organization of the emergency services can lead to disorderly or late action that worsens the consequences of the accident, as shown in the case studied.

Finally, it should be said that the three root-cause analysis methods used show the importance of going into the organizational and technical aspects to try to find the ultimate causes of the accident.

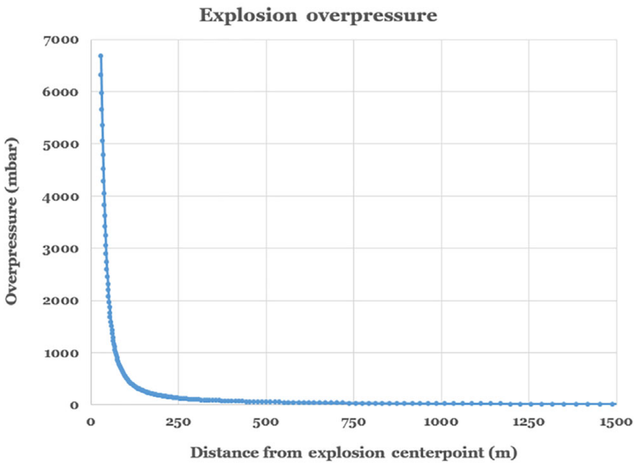

FIGURE 6 Explosion overpressure versus distance

7 | EFFECTS OF THE EXPLOSION: PRESSURE WAVE AND FRAGMENT PROJECTION

As previously stated, the explosion caused a crater of 18 m wide and 3 m deep.[50] As often happens in these cases, differences began to emerge among the various media organizations reporting on the accident.[46,47] Analysis of the crater size enables investigators to estimate the energy of the explosion, although the shape and size depend on a number of factors related to the type of soil (density, composition, resistance, water content, moisture, layers), as well as factors stemming from the AN itself (mass, type, geometry, and position of the explosive charge).[36]

Equation (1) correlates the explosion with the cratering effect, based on a study by Kinney and Graham.[57] In this equation, D stands for the diameter of the crater (m), and W_{TNT} is the equivalent mass in TNT (kg).

$$D = 0.8 \cdot (W_{TNT})^{1/3} \qquad (1)$$

The correlation has been developed from the analysis of some 200 accidental explosions. Given the variability of the explosions, the estimate of the crater diameter could vary by up to 30%. Kinney and Graham[57] also established that the depth of the crater could equal up to one-third of its diameter.

By using the crater diameter, the equivalent mass of TNT that exploded can be determined.[36,42] Following this correlation, an 18 m crater would be caused by the explosion of an equivalent TNT mass of 11.4 tonnes.

According to references, the relative effectiveness of AN compared with TNT is between 0.32[35,58,59] and 0.42.[60,61] By applying a conservative criterion, a higher value of 42% has been applied. Relative effectiveness indicates the amount of TNT that is equivalent to 1 kg of explosive (the higher the relative effectiveness, the more powerful the explosive). In this case, 1 kg of AN has the same demolition power as 0.42 kg of TNT. Considering this statistic and the previously mentioned conclusion that a crater 18 m in diameter would be caused by an amount of TNT equivalent to 11.4 tonnes, the mass of AN in this accident could be estimated at 27.1 tonnes. This weight is close to the declared payload of 25 tonnes of AN fertilizer and also matches witnesses' statements regarding the total disintegration of the lorry and the AN load it was transporting.[46,47] The largest fragment recovered from the lorry was some 30 cm long. It was found at a distance of 500 m from the accident site.[50]

The effects associated with the wave and peak overpressure were established by applying the TNT equivalent method. TNT is a widely used conventional explosive, and its effects have been studied in depth. Therefore, quite a lot is known regarding the ratio between the TNT mass that explodes and the overpressure and impulse of the wave generated as a function of the distance from the source of the explosion. As already stated, the TNT equivalent method makes it possible to calculate the effects of any explosive substance by comparison of the energy generated with the energy that would be released by an equivalent amount of TNT that produced the same effects.[35,62]

Figure 6 shows the results of the wave and peak overpressure, respectively, applying the TNT equivalent method according to the equivalence criteria described above. The EFFECTS consequence analysis software from Gexcon has been used to determine the consequences. Other commercial software are available, IMESAFR having an AN module[63]; however, risk results for overpressure are equivalent to the TNT model used, and as frequencies are not reviewed in this paper, the consequence results displayed next are considered to be reliable according to the current state of the knowledge.

The results shown in Figure 6 confirm the explosion's capacity to damage the windows of lorries at 100 m distance, as at that distance, the estimated wave overpressure would have had an approximate magnitude of 500 mbar. Assuming that glass can be broken at pressures of 10 mbar,[64] this could have been expected up to a distance of 1600 m from the center of the explosion. Along these lines, the sonic boom from the overpressure, which can rattle windows, is expected at an overpressure of around 2.7 mbar.[65] Calculations render a

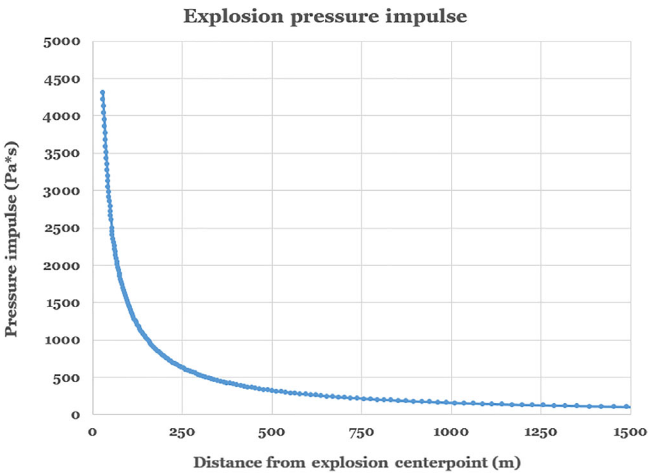

FIGURE 7 Explosion pressure impulse versus distance

distance of 3825 m for this value, approximately equivalent to the 4 km reported by witnesses following the accident.

As is common for these types of calculations, wave overpressure diminishes rapidly with distance. The peak explosion pressure impulse curve can also be depicted.[66] Figure 7 shows the calculation results of the pressure impulse.

The combination of maximum pressure impulse and explosion overpressure meant that the Barracas accident had the maximum potential for damage, according to the damage iso-curves expected for structures,[67] which consider the partial demolition of structures. At 100 m, the applicable iso-curve would enter the range of major damage to structures, and at 181 m, the lowest level implies minor structural damage.

Additionally, as concerns the fragment projectiles, it would be trivial to justify the observed effects in light of the energy released in the explosion according to the equivalences and results described in the foregoing paragraphs. Although it is true that the fragment projection models are highly reliable in terms of results, it is also true that the determination of the entry variables into these models entails a high degree of uncertainty. Therefore, it is necessary to determine the characteristics of the fragments, such as their mass, shape, and aerodynamic coefficients. It is also necessary to define the amount of energy transferred to each fragment, its initial velocity, projection angle, and rotation during projection. By taking into account the available energy released in this accident, the fragment projection calculations could easily justify the effects observed, but it would be more of an exercise of entry parameter adjustment to reach certain already-known results than an objective evaluation of them for comparison against observed facts.

8 | LESSONS LEARNED: PREVENTION, CONTROL, AND MITIGATION

AN and AN-based fertilizers have UN numbers 1942 and 2067, respectively. In both cases, they are classified as oxidizing agents and included in Division 5.1 for transport, according to the requirements and tests defined in the *UN Manual of Tests and Criteria*.[68] For transport, the *Agreement Concerning the International Carriage of Dangerous Goods by Road* (also known as ADR)[69] is applicable for the packaging and labeling of this substance. Furthermore, the companies involved in the transport of fertilizers classified as hazardous must appoint a *Dangerous Goods Safety Advisor* (DGSA).[70] Within the ADR framework, AN and Class 5.1 AN-based fertilizers are considered dangerous goods with severe consequences requiring additional safety measures, such as safety plans.[69,71]

In this regard, prevention measures are overly known, and many countries have regulations in this regard.[4,49,59,70–72] Considering this fact, it is clear that the current state of knowledge would allow avoiding AN accidents at large when properly applied and ensured. Being aware of potential deviations, the scenarios that can arise, and how to prevent and react to them shall be addressed at companies producing and transporting AN from higher management to first-line operators and drivers. All personnel involved in industrial activities involving AN must have the golden safety rules for safe conditions clear. Inspections from regulators would then duly ensure the application of the regulations.

The analysis of the accident concludes that it is likely the explosion resulted from the presence of an external fire (the fire affecting the lorry itself), which had an impact on the AN bulk fertilizer being transported, and the AN being contaminated by fuel. Based on this analysis, a number of measures can be established to prevent such accidents. The following general measures are listed for the transport of AN and AN-based fertilizers[3,69,73]:

- Take care to prevent spillages in loading/unloading areas and during transport in general.
- Avoid contamination of the product, especially by non-compatible materials. Prevent contamination by combustible matter.
- Prevent contact with water, as AN is highly hygroscopic.
- Care should also be taken to prevent the load from being thermally affected by exhaust pipes and catalytic converters.
- Vehicles should not enter storage areas or park in them.
- Loads must be kept under control throughout the journey, and care taken when the vehicle is parked. Vehicles should not be left with the engine running.

For bulk products (as was the case in the Barracas accident), the following apply:

- The load-carrying compartment should be constructed of impervious, not-readily combustible materials.
- Ensure that the vehicle is clean and dry. Vehicles should be adequately cleaned between (before) each operation.
- An undamaged sheet should be used to cover the whole of the cargo-carrying compartment adequately. The sheet should be of a suitable material (e.g., coated synthetic fiber).

Furthermore, special attention should be given to[3]: marking and labeling, provision of TREMCARDS, training, and safety provisions.

In case of a transport accident involving AN, the protection and mitigation measures to be taken will be the following[3,71,74–76]:

- In case of spillage (solid product), the spill must be isolated inside a radius of at least 25 m in all directions. Keep combustible materials at a distance.
- If a fire is detected, the site of the fire must be isolated for at least 800 m in all directions. The evacuation of this area should be considered.

In the event of a fire that could be affecting the AN load, the main goal must be to extinguish the fire and prevent the explosion of the load. In this regard:

- Use water. Do not use dry chemicals or foams.
- Flood the fire area with water from a distance. Use unmanned hose holders to the greatest possible extent.
- Cool containers with flooding quantities of water. Continue cooling until well after the fire is out.
- For a massive fire that cannot be controlled, withdraw from the area and let the fire burn. Always stay away from tankers engulfed in fire.

Firefighting personnel must wear positive pressure self-contained breathing apparatus and chemical protective clothing.[74]

9 | CONCLUSIONS

Road transport of chemical products continues to be a (perhaps inevitable) source of accidents. This case was compounded by the presence of AN, the danger of which has been clearly demonstrated. The overturning of the lorry and ensuing fire led to the hydrocarbon fuel-AN mixture expediting the self-sustaining decomposition of AN until reaching explosion.

Analysis of the accident, using root-cause techniques such as fishbone, ECFC, or AcciMap, has shown that, in addition to the physicochemical factors discussed in the foregoing paragraph, there concurred a number of organizational causes that contributed to the accident, such as the long response time by emergency services and the absence of emergency plans.

Modeling of the accident has enabled corroboration of the damage observed at the accident site. The crater caused (18 m) by the explosion would be equivalent to one caused by 11.4 tonnes. of TNT. Based on this amount and using the pertinent models, the overpressure-distance maps show that there was overpressure of 500 mbar at a distance of 100 m from the accident. This explains the breakage of windows of lorries parked at that distance. In fact, given that overpressure of 10 mbar is enough to break glass, in the case of Barracas, it would have been plausible at a distance of up to 1600 m. In the same vein, overpressure of around 2.7 mbar is enough to cause glass to rattle. According to the models, this value would still be reached at a distance of 3825 m, which coincides with the 4 km reported by witnesses in the area.

Last, the lessons learned could be summed up in the need to respect the prevention and protection measures approved by the competent authorities. These could be summarized as (a) avoid contamination of AN, especially with fuels; (b) keep the AN load from being exposed to heat; therefore, the load-carrying compartment should be constructed of impervious, not-readily combustible materials; (c) use an adequate sheet to cover the whole of the cargo-carrying compartment; (d) in case of an accident, the site must be isolated for at least 800 m in all directions, and the evacuation of this area should be considered; (e) in case of fire, flood the area from a distance and remain far from the AN load engulfed in fire.

AUTHOR CONTRIBUTIONS

Xavier Baraza: Conceptualization (lead); data curation (equal); formal analysis (equal); investigation (lead); methodology (equal); supervision (lead); validation (lead); writing – original draft (lead); writing – review and editing (lead). **Jaime Giménez:** Conceptualization (equal); formal analysis (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **Alexis Pey:** Data curation (equal); formal analysis (equal); methodology (equal); software (lead); writing – original draft (equal); writing – review and editing (equal). **Miriam Rubiales:** Methodology (equal); software (equal); writing – original draft (equal); writing – review and editing (equal).

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ORCID

Xavier Baraza https://orcid.org/0000-0003-2647-2041

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