Design of an Integrated Monitoring and Fire Fighting System for Heavy Vehicles

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Abstract: Vehicle fires, especially those involving heavy-duty vehicles, like trucks and trailers, produce substantial economic and safety risks due to their relatively low but notable occurrence rates. Understanding the causes, characteristics, and consequences of these fires is essential for effective prevention and mitigation. This paper outlines the design and development of an innovative system (T-Fire) aimed at monitoring potential ignition points on heavy vehicles and extinguishing the subsequent fires. To address existing gaps in current firefighting technologies, the T-Fire system integrates IoT solutions for continuous vehicle status monitoring and employs an environmentally sustainable extinguishing agent. Furthermore, the paper discusses the requirements for a novel firefighting system tailored for trucks and heavy vehicles based on their characteristic design and operational challenges. The selection criteria for firefighting foams have prioritized environmental sustainability and effectiveness in extinguishing various fire types. The foaming agent meeting these criteria, also offers high expansion capacity, water retention, and environmental compatibility. Additionally, the paper outlines the certification procedures undertaken to ensure compliance of T-Fire system with stringent European and national regulations, to prove its commitment to safety and environmental standards, and the development of a semi-automatic production line for the system, which aims at both optimizing production standards and minimizing environmental impact. Overall, the development of this innovative fire prevention system represents a significant advancement in enhancing safety and reducing economic losses associated with vehicle fires, particularly on heavy-duty vehicles.

Keywords: Heavy Vehicle Fires; Fire Fighting System; Fire Monitoring System; Compressed Air Foam (CAF); Certification Procedure; Production Line Design;

1. Introduction

If a heavy vehicle is involved in a fire, although the likelihood of occurrence is low, this could bring to important losses in terms of life and economic costs. In 2021 in the US, vehicle fires are responsible of the 18% of fire deaths, and 10% of fire injuries, causing $2.1 billion of damage (Hall & Evarts, 2022). Almost 20000 are associated to heavy vehicle fires, with 53 deaths, and almost half billion dollars in damage (Ahrens, 2020). More than the 50% of heavy vehicle fires are generated in the engine area, with the 60% caused by mechanical failure or malfunction ("Vehicle Fires – Supporting Tables," 2020). From 2020 to 2021 in Italy there has been an increase of almost 10% of fires and explosions with 2500 fires associated to heavy vehicles ("Annuario Statistico Del Corpo Nazionale Dei Vigili Del Fuoco," 2022). Hence, the prevention and suppression of heavy vehicle fires remain crucial issues due to their significant safety and economic implications. Therefore, this paper shows the design of an integrated monitoring and firefighting system for heavy vehicles to minimize harm to individuals and mitigate economic losses, named T-Fire System. A particular focus is drawn about its features concerning the foaming agent used for extinguishing fires, the certification procedures, and also the design of the production line to realize the system (Sassanelli et al., 2021, 2022). The system has been developed by the company Item Oxygen Srl within the project T-FIRE SYSTEM in cooperation with the Systems Engineering research group of the Polytechnic University of Bari.

2. Literature review on on-board fire extinguishing systems

Commercially available fire extinguishing systems for vehicles show several common features, but also differences in their specific composition, methods of fire detection and suppression. AFEX (AFEX) and Firecom Automotive's AK0746 (FirecomAutomotive) both offer systems for engine compartments and other vehicle areas, utilizing automatic activation. AFEX (AFEX) uses a stainless-steel distribution system with conical discharge nozzles for dry chemical agents, and features a thermal sensor-based automatic detection system with a monitoring panel for acoustic/visual alerts. Similarly, Firecom's system (FirecomAutomotive) detects fire in the engine or preheater compartments, automatically activates the extinguishing agent supply through a command/control unit, and includes electronic self-control functions, reporting anomalies to a control panel to eliminate maintenance needs. Green Safety's GS-Bus

Protection System (GreenSafety) and Firetrace Automatic Fire Suppression Systems (Firetrace) also focus on automatic activation without human intervention. Green Safety's system (GreenSafety) includes an electronic unit that manages thermal sensors and controls the extinguishing system. Firetrace systems (Firetrace) utilize heat- and flame-sensitive detector pipes that act as both detection and suppressant devices, expelling extinguishing agents quickly when the hottest part of the pipe breaks. Domino Technology's Safety Automotive System (DominoTechnology) and FirePro's VELEX (FirePro-Velex) both provide real-time monitoring and intervention capabilities. Domino's system (DominoTechnology) is suitable for various vehicles and includes a health monitoring system with an interface for real-time anomaly detection, allowing the driver to intervene promptly. FirePro's VELEX (FirePro-Velex) is a dual fire detection and extinction system that can be self- or manually actuated, using a hybrid technology involving a premixed liquid extinguishing agent and a condensed aerosol generator. The Fogmaker (Fogmaker) is notable for not requiring an operator or electricity for activation; it uses high-pressure water spray for fire suppression in engine compartments, featuring a hydro-pneumatic detection circuit made of thermosensitive material pipes. Falcon Fire Extinguishing System (Falcon) and Reacton's certified systems (Reacton) both focus on limiting damage and providing broad applicability. Falcon (Falcon) offers a smart, economical solution for various equipment, including electrical equipment and vehicles, aiming to limit damage at the ignition source and prevent fire spread. Reacton's systems (Reacton) are designed for heavy vehicles and harsh conditions, suitable for confined spaces and various vehicle types, including heavy equipment and buses. Main features of on-board fire extinguishing systems are briefly summarised in Table 1.

Overall, these fire extinguishing systems emphasize automatic activation, comprehensive coverage, and real-time monitoring to ensure effective fire suppression and enhanced safety in vehicle applications. The following paragraph is devoted to describing the specific T-Fire system, highlighting its novelties.

Table 1. List of on-board fire extinguishing systems commercially available

Product	Extinguishing Agent	Typology
AFEX	Dry and liquid	CAF
GS-BUS PROTECTION SYSTEM	Aerosol and Powder	/
SAFETY AUTOMOTIVE SYSTEM	Aerosol	CAF
FOGMAKER	Water mist	Hydro-pneumatic
FIRECOM AUTOMOTIVE	Aerosol	Condensed aerosol
FALCON	Dust, Gas, Water	ILP
FIRETRACE	CO_2	ILP/DLP
REACTON	Dry and liquid	CAF
VELEX	Aerosol	FPC®

Abbreviations: CAF (Compressed Air Foam), ILP (Indirect system Low Pressure), DLP (Direct system Low Pressure), FPC® (Fire Pro Compound)

3. Features and specifications of the T-Fire System

The implementation of the T-Fire system in heavy vehicles requires minimal structural alterations, thanks to its plug-and-play design. The design and placement of the T-Fire System enables fast intervention of the drivers to extinguish the ignition fire that may develop on the heavy vehicle. The entire system is placed inside a toolbox commonly installed on board of heavy vehicles, which makes the system extremely versatile and easy to use (Figure 1).

Additionally, the T-Fire system incorporates a diagnostic process for ignition fire detection through monitoring physical parameters of the tyres. It is adaptable to unconfined environments and utilizes an environmentally sustainable extinguishing agent, namely Compressed Air Foam (CAF), renowned for its reliability in such spaces (Junjunan et al., 2022). The following section is devoted to show the monitoring system of the T-Fire, as well as the analysis related to the foaming agent employed.

Figure 1. T-Fire extinguishing system (left) and its location on the vehicle (right)

3.1. Monitoring System

The onboard diagnostic system includes two main components: the detection block and the monitoring block. Within the detection block, there are selective Temperature Pressure Monitoring System (TPMS) wireless sensors installed on the tyres, along with temperature sensors situated in the engine compartment and optionally in the refrigeration unit (Figure 1).
The monitoring system incorporates smart tyre sensors, an intelligent vehicle terminal, and a cloud-based smart tyre management platform. These sensors, positioned on the inner part of the tyre, measure tyre temperature, tyre pressure, vehicle instantaneous velocity and geolocalisation. The collected data are then transmitted to the intelligent vehicle terminal (tablet or PC), installed in the cabin, which performs various data analytics (descriptive, predictive, prescriptive) *via* dedicated Artificial Intelligence.
Since the driving behaviour mainly affect the overheating of some vehicle components, such as tyres (Barreno et al., 2024; Júnior et al., 2017; Romera et al., 2016), a precise set of physical parameters have been established as key performance indicators to be measured about driving behaviour with the aim of preventing fire ignitions on heavy vehicles:

- Speed, since a high average travel speed reduces the time available for the tyre to cool, favouring heat increase and consequent overheating.
- Acceleration, as abrupt and sudden acceleration generates a sudden spike in tyre temperature, due to the increased friction between the tyre and the road surface.
- Braking, since frequent, intense or abrupt braking puts the tyre under severe mechanical stress, generating excessive heat production that can lead to overheating and, in extreme cases, tyre breakage.
- Steering, because cornering at excessive speed or with sharp turns can lead to uneven wear of the tread and a localized increase in temperature, especially in the lateral area of the tyre.

Therefore, combining the physical measurements performed by the T-Fire system sensors (tyre temperature, tyre pressure, vehicle instantaneous velocity and geolocalisation) and the subsequent estimation of some derived values (instantaneous acceleration or deceleration, frequency of braking per minute), allowed the design of a novel smart scoring system which evaluates the impact of each parameter on the risk of tyre overheating and fire ignition. Precise steps have been defined to design and to calculate the T-Fire scoring system:

- Definition of the optimal/acceptable/severe ranges of the values for of each parameter, by using appropriate S-curves for quantitative risk analysis.
- Normalization of values in a scale 0-100% with the following (equation 1)

$$DI = D_{LO} + \frac{(D_{HI} - D_{LO})}{(DP_{HI} - DP_{LO})}(P - DP_{LOW}) \qquad (1)$$

  D_I is the Danger Index related to the value of the measured parameter P; DP_{HI} and DP_{LO} are the Danger-Point values which correspond to the lower and upper extremes, respectively, of the risk range (optimal, acceptable, severe) where the parameter measurement falls; D_{HI} is the Danger Index (%) corresponding to DP_{HI}; D_{LO} is the Danger Index (%) corresponding to DP_{LO}.
- Association of the T-Fire score per each measured parameter (Table 2), based on the linear correlation between Danger index (DI) and T-Fire Score (TS); in the T-Fire Score scale, 0 corresponds to the minimum safe driving score and 10 to the maximum safe driving score.

Table 2. Limit values of risk intervals for Danger Index (DI) and T-Fire Score (TS)

	Optimal		Acceptable		Severe	
	D_{LO}	D_{HI}	D_{LO}	D_{HI}	D_{LO}	D_{HI}
DI	0	20	21	60	61	100
TS	10.0	8.0	7.9	4.0	3.9	0.0

- Definition of weight of each parameter (from 0 to 1) to compute the final score, named General T-Fire Score (GTFS), which is the weighted average of the TS associated to each parameter (equation 2). xi is the weight of each parameter in the summation.

$$GTFS = \sum_{i=1}^{n}(TS_i \cdot x_i) \qquad (2)$$

As regards the temporal frequency for the score calculation, the data collected by the sensors on the heavy vehicle are not acquired simultaneously, but at different time intervals. Generally, an average value of the measurements performed in a time interval of about 2 minutes for each parameter is calculated, thereby ensuring a regular pace for the calculation of the T-Fire Score. In the event of abnormal and risky physical parameter values, the information system alerts the vehicle through the onboard tablet or PC of the central operating system. Empirical tests of the T-Fire Scores are ongoing to evaluate the efficacy of this innovative scoring model to prevent dangerous events on heavy vehicles while driving.

3.2 Fire Extinguishing Foam

Foams, commonly used in firefighting systems for their effective fire suppression and low water content, come in various types based on their expansion factor and reaction to carbon (Yılmaz-Atay & Wilk-Jakubowski, 2022). There are two main types based on their reaction to carbon: class A and class B foams. Class A foam penetrates solid materials to suppress fires quickly, while class B foam forms a film over burning liquids to prevent vapor production and ignition. Legislation dictates that foaming liquids must meet specific standards, such as EN 1568-4 (2018) set of standards for class B fires and NFPA 18:2017 for class A fires.

The fire extinguishing foam selected for the T-Fire System is a foam concentrate containing synthetic hydrocarbon foaming agents and stabilizers, including patented components such as 2-(2-butoxyethoxy)ethanol, ethane-1,2-diol, 1-dodecanol, and 1-tetradecanol. These constituents allow the production of foam with high expansion capacity and excellent water retention, even in large volumes. This foam, which is manufactured specifically for situations requiring minimal environmental impact without compromising performance, combines non-fluorinated surfactants with a foaming agent base to create a vapor-sealing foam blanket for rapid control and extinguishing.

The selected foam is compliant with standards EN 1568-4 (2018) and NFPA 18:2017 for wetting agents and is obtained from a class B foaming liquids devoid of fluorinated compounds. With an expansion ratio exceeding 10, it effectively tackles fire types A and B, covering ordinary solid combustibles and flammable liquids. Notably, this solution offers advantages including minimal storage requirements, cost-effectiveness, extended shelf life, and efficient discharge via a high expansion generator. Moreover, the synthetic hydrocarbons utilized are biodegradable in soil and readily degrade in water with minimal bio accumulative potential. These key physical and chemical characteristics supported the selection of this foaming agent for the T-Fire system.

Preliminary tests showed the efficiency in using such an extinguishing foam, confirming an expansion factor x10, drainage time of 5 hours, and a maximum jet range of 9 m. The advantages related to the selected foaming solution include the easiness of implementation (plug and play) and parameters monitoring system, and a water-synthetic hydrocarbon mixture (CAF) composed by a 6% foam solution + water (6.7% volume/volume) suitable for extinguishing classes A and B (EN 2:1992), and free from environmental toxicity. The following paragraphs is dedicated to the description of the various steps designed to produce, assemble and store the T-Fire System.

4. Production of the T-Fire System

The need to design a semi-automatic plant for assembling, producing and storing the T-Fire System arises from a careful analysis conducted by the technical department of Item Oxygen Srl to ensure optimal production standards. The analysis has comprised minimization of production costs and processing cycle times, as well as reduction of physical strain for operators and harmful emissions for the environment. The new production plant enables the automatic manufacturing of some components related to the T-Fire System such as the tanks and the supporting structure. The production line comprises three main stations (or modules) (Figure 2).

The first module consists of: a structure for raw material storage (cylindrical tubes 6 [m] long), an automatic trolley necessary for advancing the cylindrical tube during the cutting process and an automatic station with an anthropomorphic robot equipped with a laser cutting gun. The anthropomorphic robot has been positioned in such a way that it can operate on three workbenches: cutting the cylindrical tube, making holes on the closing cups and cutting the metal sheet for the construction of the supporting structure. This solution has optimized the use of space in production area.

Continuing along the production line, the second module includes a second station where an anthropomorphic robot equipped with a laser welding gun can work in parallel on both sides (left and right) for the construction of the tanks and the supporting structure of the T-Fire System. The robot can weld the cylindrical tube-closing cups system at 360° on a horizontal rotary table, creating a uniform and high-quality weld bead. Meanwhile, the welding of the supporting structure is performed by spot welding (98 welding points have been planned), joining the cut parts of the sheet metal positioned within a specially designed structure.

The design of the customized support structure for the T-fire system, consisting of sheet metal parts made by laser cutting, seem to provide several advantages:

- Economic utility. Using the laser cutting station in the first phase avoided the implementation of further processes such as bending.
- Reduced timing in the assembly operation. The cut sheet metal elements are designed to be assembled according to an interlocking procedure which simplifies and accelerates the operations, reducing possible human errors. 98 laser welding spots can be realised in about half the time compared to previous manual procedures.
- Weight reduction. It has been estimated that the frame realised following this innovative methodology has reduced the weight of the system by 15% compared with the methodology where the frame has been realised manually by using welding tubulars.

In the last station of the line, the semi-finished products are sorted on workbenches *via* rollers for final assembly. A pneumatic manipulator and a tilting workbench are implemented to assist the technical operator in testing procedures (according to PED directive) and storage of the final T-Fire System device consisting of a toolbox and an innovative fire extinguishing module.

The overall system allows all the operations described to be performed by a single operator, thus reducing working time and enabling an ergonomic and safer work.

Figure 3 depicts the first two modules implemented in the production line of the Item Oxygen Srl. Figure 3 left shows the robot employed for plasma cutting, and the station where an aluminium sheet is positioned and plasma-cut to be subsequently welded in the station of the second module to form the supporting structure of the T-Fire system; within this structure, the extinguishing foam tanks will be positioned. Figure 3 right shows instead the station where the cylindrical part of the tanks and the closing cups and the supporting structure are welded.

To ensure that the production of the T-Fire System and the compatibility of the extinguishing foam employed is compliant with current regulations and directives, a key step necessary for an effective realization is to provide all the certifications required. Therefore, the next paragraph is devoted to describing the certification procedures undergone in relation to the T-Fire System.

Figure 2. Production steps of the T-Fire System

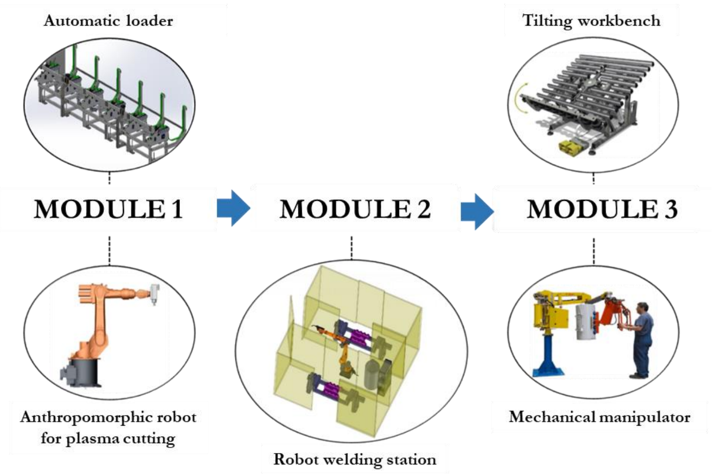
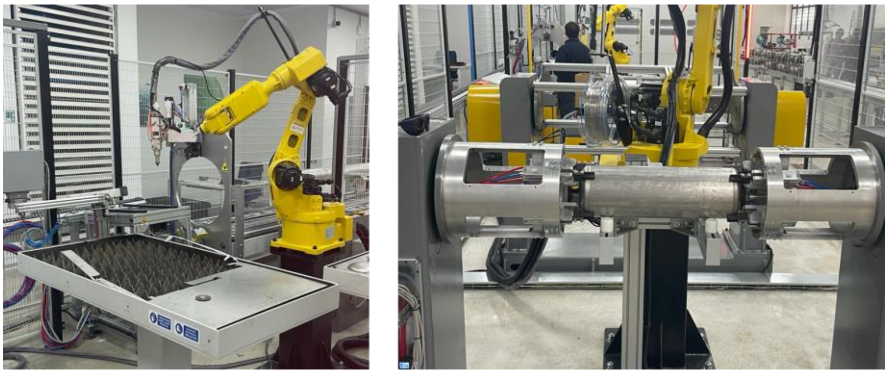


Figure 3. Details of robots employed for module 1 (left) and module 2 (right)



5. Certification Procedure of the T-Fire System

The Item Oxygen Srl company has developed the T-Fire System, an innovative fire prevention and extinguishing system designed for installation on heavy vehicles. Table 3 shows all the regulations and standards employed for the T-Fire System certification procedure. The device has been designed and implemented in compliance with the strict European regulations governed by the ADR Agreement (Accord Dangereuses Route), latest version of 2023 (ADR, 2023).

The T-Fire System is placed inside a toolbox to be installed on board of heavy vehicles, certified as a side protection device in accordance with regulation No. 73 of the United Nations Economic Commission for Europe (UN/ECE) (UN/ECE n. 73, 2012). According to this regulation, the toolboxes must provide effective protection for road users and be able to withstand a horizontal static force of 1 kN without deforming.

Internally, the T-Fire System is equipped with a fire extinguishing agent collection tank at a pressure of 10 bar, manufactured according to harmonized standards EN 13445 and certified according to the Pressure Equipment Directive (PED) which regulates the design, production, installation, and use of pressurized equipment (DIRECTIVE 2014/68/UE, 2014). Additionally, the foam liquid provided in the tank complies with the EN 1568-4 (2018) standard, as it is free from fluorinated organic compounds.

Furthermore, the T-Fire System contains a nitrogen cylinder internally for pressurizing the foam liquid in the tank. This cylinder is designed to withstand pressures up to 350 bar and is certified according to Directive 2010/35/EU, also known as the Transportable Pressure Equipment Directive (T-PED), which governs the design, manufacture, and conformity assessment of transportable pressure equipment to improve their safety and ensure their free circulation in the European market (DIRECTIVE 2010/35/UE, 2010).

The welding process during the assembly stages of the T-Fire System is carried out in accordance with EN ISO 15614-1 standard (EN ISO 15614-1, 2017) to guarantee a controlled production process at the Item Oxygen Srl company, to ensure the defined parameters and variables, and to reduce the possibility of structural defects in tanks and hydraulic fittings.

6. Discussion

As described in the introduction of the article, the significant safety and economic implications associated with heavy vehicle fires are well established, as also confirmed by diverse American and Italian statistical analyses underscoring the importance to adopt precise prevention and suppression measures. The design of an integrated monitoring and firefighting system for heavy vehicles aimed at minimizing harm and economic losses has also been detailed, with particular focus on the T-Fire System, including its features, specifications, and the use

of Compressed Air Foam (CAF) as an environmentally sustainable extinguishing agent.
The T-Fire System is designed for easy integration into heavy vehicles, requiring minimal structural alterations. It incorporates a diagnostic process for ignition fire detection and utilizes a monitoring system comprising detection and monitoring blocks. The detection block includes TPMS wireless sensors and temperature sensors, while the monitoring block consists of a central operating system that collects and analyses data in real-time.

Table 3. T-Fire System certification procedure

Name	Year	Description
Regulation ADR	2023	ADR sets out the rules and regulations for the safe transport of dangerous goods by road. It provides specific information on the classification of dangerous goods and the requirements for the identification of goods, labelling, packaging and transport.
Regulation UN/ECE n°73	2012	United Nations Economic Commission for Europe (UN/ECE) - Uniform provisions concerns the approval of commercial vehicles, trailers and semi-trailers with regard to their lateral protection.
EN 13445	2021	The det of standards specify requirements for the construction of unfired pressure vessels and their parts, made of steel, including fittings with non-pressure parts. It specifies requirements for material traceability, manufacturing tolerances, requirements for welding and permanent joints other than welding, testing during production, forming, heat treatment, repairs and finishing operations.
Directive PED 2014/68/UE	2014	Product Directive is issued by the European Union, governing the design, manufacture and conformity assessment of pressure equipment and assemblies subjected to a maximum allowable pressure greater than 0.5 bar.
EN 1568-4	2018	The standard defines requirements for chemical and physical properties, and minimum performance requirements for low-expansion foams suitable for surface application to water miscible liquids. The standard also provides requirements for marking.
Directive TPED 2010/35/UE	2010	The directive lays down detailed rules concerning transportable pressure equipment sets out the rules and procedures to be followed for the certification of transportable pressure equipment. Such equipment must bear a special marking, indicated by the symbol π, which is mandatory for commissioning and marketing within the European Union.
EN ISO 15614-1	2017	This European Standard defines the conditions for performing welding procedure qualification tests and the limits of validity of a qualified welding procedure.

The system employs intelligent algorithms and a cloud-based platform to optimize tyre utilization and enhance safety. Regarding the fire extinguishing foam, the article discusses its types, application techniques, and legislation requirements. It highlights the selection of a foam concentrate containing synthetic hydrocarbon foaming agents and stabilizers for the T-Fire System, emphasizing its compliance with relevant European and national standards and regulations. The foam of the T-Fire system is environmentally friendly, has high expansion capacity and efficient fire control capabilities. The realization of the T-Fire System involves the design of a semi-automatic production plant to ensure optimal production standards and minimize environmental impact. The production line comprises three main stations, each equipped with robotic systems for component manufacturing and assembly. The certification procedure for the T-Fire System has covered the compliance of the T-Fire system with European regulations and standards governing pressurized equipment, welding processes, and foam liquid composition.

7. Conclusion ad further research

The T-Fire System introduces a significant advancement in addressing heavy vehicle fire safety concerns. Its design, featuring plug-and-play installation and diagnostic fire detection, coupled with the use of environmentally sustainable Compressed Air Foam (CAF), appears to be highly promising to successfully mitigate fire incidents. This system's practicality is underscored by its minimal structural alterations and adaptability to existing heavy vehicle configurations. Moreover, the establishment of a semi-automatic production plant ensures efficient manufacturing while adhering to regulatory standards.
Environmental sustainability is a key element in the development of the T-Fire System, as regards the choice of CAF extinguishing agent. Its non-fluorinated composition and biodegradability align with environmental management goals. Looking ahead, there is potential for further research to enhance the system's environmental performance, possibly through optimizing foam composition or incorporating recycled materials in the production processes.
To introduce the T-Fire System on the market and to obtain the CE marking, the Item Oxygen Srl is currently undertaking the submission of the T-Fire System to the conformity assessment procedures according to modules B and C2 provided by the PED standard (DIRECTIVE 2014/68/UE, 2016), despite the system belong to a lower risk category (A). This constant commitment to compliance with the latest regulations represents a guarantee of greater safety and environmental compatibility of the T-Fire System, as a cutting-edge

technological innovation in the field of fire safety on heavy-duty vehicles.

Future advancements may involve integrating advanced sensors, predictive analytics, or autonomous capabilities to enhance system effectiveness and responsiveness.

In summary, the T-Fire System represents a significant step forward in both heavy vehicle fire prevention and drive safety. While its efficacy, practicality, and environmental sustainability are evident, ongoing research and collaboration will be critical in order to optimize the system performances and address evolving needs of drive safety in the automotive sector.

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