

IMPACT OF FIREFIGHTING VEHICLE TECHNICAL PARAMETERS ON FIREFIGHTING EFFICIENCY

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Abstract. The efficiency of firefighting vehicles is crucial for effective fire suppression, firefighter safety, and the overall success of emergency response operations. This study investigates the impact of key technical parameters - such as water tank capacity, pump performance, fuel efficiency, and maneuverability - on operational effectiveness across diverse fire scenarios. A mixed-method approach was adopted, combining computational simulations, empirical performance assessments, and structured interviews with firefighting professionals from multiple regions. Findings underscore the need for region-specific vehicle configurations, as urban, rural, and forest environments each present unique operational challenges. The study further emphasizes the importance of data-driven engineering improvements and cross-border knowledge exchange to enhance vehicle performance, resource efficiency, and environmental sustainability. Key engineering recommendations include the implementation of hybrid-electric powertrains, modular water tank designs, and AI-enhanced navigation systems to improve firefighting vehicle adaptability and operational efficiency.

Keywords: firefighting vehicles, technical specifications, regional adaptation, operational efficiency, European firefighting strategies.

Introduction

In recent years, global climate change has significantly increased the frequency and intensity of wildfires, while rapid urbanization has created new challenges for fire departments operating in densely populated environments. These evolving risks have amplified the demand for advanced firefighting vehicles capable of operating efficiently under extreme conditions, ensuring timely and effective fire suppression.

To address these demands, smart firefighting technologies have emerged - including predictive analytics, real-time monitoring systems, and autonomous drone-assisted reconnaissance - each contributing to improved situational awareness and more coordinated response efforts [1]. AI-enhanced navigation systems further optimize route planning, decreasing average response times by up to 20% [2], while hybrid-electric drivetrains reduce fuel consumption, operational costs, and emissions, thereby supporting international sustainability goals [3].

Furthermore, innovations like modular water tank designs and advanced pump systems have improved firefighting efficiency by maintaining a stable water supply and enabling flexible resource allocation across different operational settings [4].

This study systematically assesses the influence of key vehicle parameters - water supply capacity, propulsion system efficiency, operational adaptability, and maintenance requirements - on overall firefighting effectiveness. The findings aim to support the development of more efficient, adaptable, and sustainable firefighting vehicle designs that meet the growing demands of modern fire suppression operations.

Previous studies have emphasized the importance of alternative powertrains and energy-efficient systems in emergency response vehicles [5], as well as the impact of vehicle stability on operational safety in complex terrains [6]. Additionally, failure rate analysis of firefighting fleets has highlighted the necessity of predictive maintenance strategies and AI-driven diagnostics to improve vehicle reliability and availability [7].

Materials and methods

This study employs a mixed-method approach, integrating computational simulations, empirical data collection, and expert interviews to comprehensively assess the efficiency of firefighting vehicles. Computational models simulate vehicle performance under different environmental conditions, evaluating key parameters such as suppression effectiveness, response time, and fuel efficiency.

Additionally, real-world data from fire departments – including maintenance records, fuel consumption reports, and operational logs – were analysed to identify performance trends and reliability

factors. Structured expert interviews with firefighters, fleet managers, and fire response coordinators provided qualitative insights into the strengths and limitations of current firefighting vehicle designs.

The study evaluates key performance indicators, including vehicle response time, suppression capacity, and adaptability in urban, rural, and forested environments. Data sources include an extensive literature review from indexed journals and field tests conducted in collaboration with fire safety organizations.

The methodology is structured as follows:

1. Computational Simulations – Vehicle dynamics and fire suppression capabilities are modeled under various environmental conditions [8].
2. Empirical Data Analysis – Maintenance logs, fuel consumption reports, and operational performance data from multiple firefighting departments are analysed [7].
3. Expert Interviews – Structured discussions with emergency response professionals provide qualitative insights into real-world firefighting vehicle challenges and technological gaps [6].
4. Comparative Case Studies – Real-world fire response scenarios are examined to evaluate different vehicle configurations and suppression strategies.

By integrating these methodologies, this study ensures a comprehensive evaluation of firefighting vehicle efficiency, highlighting the need for adaptive technologies and engineering improvements tailored to various operational environments.

Over the past decades, firefighting vehicles have undergone continuous advancements, driven by increasing operational demands, regulatory requirements, and the rapid development of vehicle engineering technologies. The need for enhanced efficiency, safety, and sustainability has led researchers to explore innovative solutions that optimize vehicle performance under diverse fire suppression scenarios. Previous studies have primarily focused on several key aspects: (1) improvements in water supply and pumping systems to ensure uninterrupted fire suppression capabilities [4], (2) alternative powertrains aimed at enhancing fuel efficiency and reducing environmental impact [5], (3) vehicle maneuverability and stability for improved navigation in urban and rural environments [6], and (4) advancements in fire suppression technologies, including AI-assisted systems and real-time monitoring solutions [1].

Firefighting vehicles have undergone significant advancements over the past decades, driven by the need for enhanced efficiency and safety. Studies have highlighted the role of hybrid-electric propulsion systems in reducing fuel dependency and operational costs [2], while AI-driven predictive maintenance strategies have been shown to improve fleet reliability and reduce downtime [7]. Additionally, water mist and compressed air foam systems (CAFS) have emerged as highly effective fire suppression methods, reducing water consumption while increasing extinguishing efficiency [8].

Water Supply and Pumping Systems

The effectiveness of firefighting vehicles is highly dependent on their water supply capabilities and the efficiency of their pumping systems. A stable and high-pressure water flow is critical for ensuring successful fire suppression, particularly in environments where external water sources may be limited. Positive displacement pumps, as analysed by Han et al. [4], have demonstrated superior efficiency in pressure control and water flow stabilization. These pumps operate by displacing a fixed volume of fluid per cycle, ensuring consistent water delivery even under variable operational conditions.

In addition to pump efficiency, the capacity of onboard water tanks plays a crucial role in sustaining firefighting operations, especially in remote or rural areas where access to hydrants is restricted. Research has shown that vehicles equipped with high-capacity water tanks can extend their operational duration and enhance firefighting effectiveness in large-scale incidents [5]. Modular tank designs have also been proposed to improve adaptability and reduce vehicle weight, optimizing manoeuvrability and fuel efficiency [6].

Table 1 presents key technical parameters of firefighting vehicles, including water tank capacity, pump performance, and fuel consumption. These parameters directly influence vehicle endurance, suppression capability, and overall firefighting efficiency.

Table 1

Technical parameters of firefighting vehicles [4]

Parameter	Value
Water Tank Capacity, m ³	5
Foam Tank Capacity, m ³	0.5
Maximum Pump Power, m ³ ·s ⁻¹	0.0667
Maximum Traction Force, N	68646.55
Average Fuel Consumption, l·(100 km) ⁻¹	22.5

Alternative Powertrains and Fuel Efficiency

In recent years, alternative powertrains have gained increasing attention in the firefighting industry due to their potential to improve operational efficiency, reduce environmental impact, and lower fuel dependency. Traditional diesel engines, while offering robustness and high torque, remain the dominant power source for firefighting vehicles. However, they are associated with high fuel consumption and significant CO₂ emissions, prompting the search for more sustainable alternatives [2; 3].

Hybrid-electric propulsion systems provide a balanced approach, integrating an internal combustion engine with an electric motor to enhance energy efficiency, particularly in urban firefighting operations where frequent stops and low-speed maneuvers are required. Dweik et al. [3] demonstrated that hybrid drive systems improve vehicle maneuverability, reduce fuel dependency, and optimize energy use in densely populated environments. By utilizing regenerative braking and energy recuperation, hybrid vehicles can achieve up to 30% fuel savings compared to conventional diesel models. Additionally, hybrid systems allow for silent operation in sensitive environments, such as residential areas and enclosed spaces, where noise pollution is a concern [5; 6].

Fully electric firefighting vehicles are emerging as a promising solution for reducing emissions and operational costs. With zero direct CO₂ emissions, electric fire trucks align with global sustainability goals and help municipalities meet stringent environmental regulations [1; 4]. Several cities, including Berlin and Los Angeles, have piloted fully electric fire trucks with promising initial results, demonstrating their viability in urban fire response scenarios. However, electric powertrains present operational challenges, particularly related to battery capacity, charging infrastructure, and energy replenishment during extended emergency missions. The current generation of electric fire trucks typically has an operational range of 200-250 km per charge, which may be insufficient for large-scale rural or forest fire incidents [6; 7].

Despite these limitations, advancements in battery technology and fast-charging solutions are progressively enhancing the feasibility of electric fire trucks. New lithium-ion and solid-state battery designs are expected to improve energy density and charging times, addressing the primary concerns surrounding electric vehicle adoption in firefighting [7; 8]. Some manufacturers have introduced dual-power hybrid models, which combine electric propulsion with an auxiliary diesel generator to extend operational range when needed.

Table 2

Fuel efficiency of different drive types [2-5]

Drive Type	Fuel consumption, l·(100 km) ⁻¹	Max operating range, km	CO ₂ emissions, g·km ⁻¹
Diesel Engine	22.5	400	600
Hybrid Drive	15.8	600	350
Electric	0	250	0

Maneuverability and Stability in Different Terrains

The ability of firefighting vehicles to maneuver efficiently and maintain stability across different terrains is crucial for ensuring rapid response and operational safety. Firefighting operations often take place in urban, rural, and forest environments, each presenting distinct mobility challenges. In urban areas, narrow streets and dense traffic necessitate high maneuverability and compact vehicle designs. Rural and forested terrains, however, require enhanced suspension systems, traction control, and optimized center-of-mass distribution to prevent rollovers and maintain stability on uneven surfaces [4].

A study by Almazov et al. [6] utilized LS-Dyna simulations to investigate center-of-mass fluctuations in fire tankers, emphasizing the risk of rollovers on sloped and unstable terrains. The findings indicated that vehicles with a high-mounted water tank experience significant instability during sharp turns and emergency braking, particularly when operating on loose gravel or wet surfaces. To mitigate these risks, the study highlighted the necessity of adaptive suspension systems and electronically controlled stability programs (ESP) that can dynamically adjust the vehicle's weight distribution based on real-time terrain conditions [7].

Furthermore, research has shown that tire selection, chassis design, and vehicle weight distribution significantly impact maneuverability. Firefighting vehicles equipped with low-pressure off-road tires exhibit superior traction in muddy or sandy conditions, while rigid axle configurations contribute to better load distribution but may reduce turning agility [5]. Active suspension technologies, which automatically adjust damping levels based on terrain roughness, have demonstrated up to a 25% reduction in rollover risk compared to traditional fixed-suspension setups [1].

The application of all-wheel-drive (AWD) systems in firefighting vehicles has also proven beneficial, particularly in areas prone to floods, snow, or steep inclines, where increased traction is essential [3]. Additionally, modern vehicles are increasingly incorporating torque vectoring technology, which enables precise control over individual wheel torque, further enhancing maneuverability in confined spaces and adverse conditions [2].

Innovations in Fire Suppression Technology

The continuous evolution of fire suppression technologies has led to significant improvements in firefighting efficiency, allowing for faster fire containment, reduced water consumption, and enhanced firefighter safety. Among the most promising advancements are compressed air foam systems (CAFS) and water mist technology, which provide superior fire suppression capabilities compared to conventional water-based methods [4].

Wang et al. [8] demonstrated that third-generation fire trucks equipped with CAFS exhibit superior penetration and cooling effects, particularly in structural fires and industrial fire incidents. CAFS technology utilizes compressed air to generate a highly stable foam mixture, which adheres to surfaces and forms an insulating barrier, preventing re-ignition and minimizing water runoff. This method has been shown to reduce water usage by up to 50% while increasing suppression efficiency by 30% compared to traditional water jets [5].

Similarly, water mist technology has gained recognition for its ability to extinguish fires while minimizing collateral damage. By dispersing ultra-fine water droplets, water mist systems enhance heat absorption and oxygen displacement, making them particularly effective in enclosed spaces such as tunnels, aircraft hangars, and high-rise buildings [1]. Studies indicate that water mist suppression reduces overall water consumption by up to 65%, while also improving firefighter visibility due to reduced smoke production [2].

The integration of AI-driven suppression control systems has further optimized the deployment of CAFS and water mist technologies, enabling automated detection, real-time fire intensity analysis, and adaptive suppression strategies based on fire behavior patterns [7]. Additionally, hybrid systems combining water mist and CAFS have been developed for specialized applications, such as forest fire management and hazardous material fires, where rapid suppression and minimal environmental impact are critical [3].

These innovations highlight the shift toward more sustainable and resource-efficient firefighting solutions, paving the way for future advancements in autonomous firefighting drones, robotic suppression units, and intelligent fire prediction systems [6].

Table 3

Impact of advanced fire suppression technologies [3; 8]

Technology	Efficiency increase, %	Water consumption reduction, %
AI Navigation	20	0
Compressed Air Foam System	30	50
Water Mist Technology	25	65
Automatic Control Systems	18	0

Key Technical Parameters Influencing Firefighting Efficiency

Water Tank Capacity and Pump Performance

Efficient water usage is fundamental in fire suppression, as it directly affects the operational capacity of firefighting vehicles and their ability to sustain fire attack strategies. The ability to maintain a stable and high-pressure water flow is critical, particularly in large-scale fires or remote locations where external water sources are scarce.

Research by Han et al. [4] indicates that the integration of positive displacement pumps improves pressure control, ensuring a more stable water flow regardless of fluctuating demand. These pumps operate by delivering a constant volume of water per cycle, making them highly reliable for continuous suppression efforts. Their efficiency is particularly advantageous in high-rise buildings and industrial fires, where maintaining consistent water pressure over long hose lengths is a challenge.

Additionally, high-capacity water tanks play a crucial role in prolonging firefighting operations, especially in rural and forested areas where access to hydrants is limited [6]. Vehicles equipped with modular tank systems allow for rapid water replenishment and adaptive capacity adjustments, enabling firefighters to maximize operational autonomy. The use of lightweight composite materials in modern water tanks has further enhanced vehicle weight distribution and fuel efficiency, reducing overall energy consumption during emergency responses [5].

Advancements in automated water distribution systems have also contributed to improving firefighting efficiency. Smart control units can now adjust water flow rates in real time, optimizing suppression efforts based on fire intensity, wind conditions, and nozzle configurations [1]. These adaptive systems minimize water wastage and improve firefighting effectiveness, particularly in urban high-risk zones where water conservation is a priority [7].

In summary, the combination of high-capacity, modular water tanks and advanced pumping systems has significantly enhanced the operational efficiency of firefighting vehicles. Future research should focus on integrating predictive analytics and real-time monitoring to further optimize water usage and improve overall suppression performance [3; 8].

Fuel Efficiency and Alternative Powertrains

Traditional diesel engines in firefighting vehicles have been the industry standard for decades due to their high torque, durability, and reliability in extreme conditions. However, their high fuel consumption and significant CO₂ emissions present operational challenges, particularly in urban areas with strict emission regulations and rising fuel costs. Additionally, diesel-powered vehicles require frequent maintenance, leading to increased lifecycle costs for fire departments [4; 5].

Recent advancements in hybrid-electric powertrains have demonstrated significant advantages in reducing fuel dependency and operational costs, particularly in stop-and-go urban firefighting scenarios. Dweik et al. [3] showed that hybrid-electric systems can reduce fuel consumption by up to 30% while allowing for zero-emission electric propulsion at low speeds. This not only enhances maneuverability in dense urban environments but also reduces noise pollution, which is beneficial during nighttime operations and in sensitive areas such as hospitals and residential zones [2]; [7].

Fully electric fire trucks represent the next step in sustainable emergency response solutions. These vehicles produce zero direct CO₂ emissions, making them an attractive alternative for cities aiming to meet climate targets. Early implementations in Berlin, Amsterdam, and Los Angeles have demonstrated lower operating costs and improved energy efficiency, particularly for short-response urban firefighting missions [1; 8]. However, battery limitations and the lack of a robust charging infrastructure remain critical challenges. Most electric fire trucks currently have a range of 200-300 km per charge, which may be insufficient for extended emergency operations [3; 6]. The deployment of fast-charging stations and battery-swapping solutions is still in its early stages, requiring further investments and urban planning integration [7].

Hydrogen Fuel Cell Hybrid Systems

An alternative solution to battery-powered electric fire trucks is the integration of hydrogen fuel cell hybrid vehicles (FCHV). Luciani & Tonoli [2] conducted a study evaluating proton exchange membrane (PEM) fuel cell efficiency in hybrid vehicles. Their findings suggest that with an optimized

control strategy, fuel cell system efficiency can reach 33%, and hydrogen consumption can be reduced by 30%.

Hydrogen-powered fire trucks offer a longer operational range compared to battery-electric vehicles while maintaining zero-emission performance. Additionally, hydrogen refuelling is significantly faster than electric charging, reducing downtime between emergency calls.

However, one of the primary challenges in integrating hydrogen fuel cell technology is its complex storage requirements, as hydrogen must be kept at extremely high pressures (350-700 bar) or cryogenic temperatures (-253°C). Furthermore, the lack of a widespread hydrogen refuelling infrastructure remains a significant barrier to large-scale adoption. To better illustrate the differences in fuel efficiency and operational range, Figure 1 provides a comparative overview of fuel consumption for different drive types, while Figure 2 visualizes the CO₂ emissions associated with each technology [3; 4; 8].

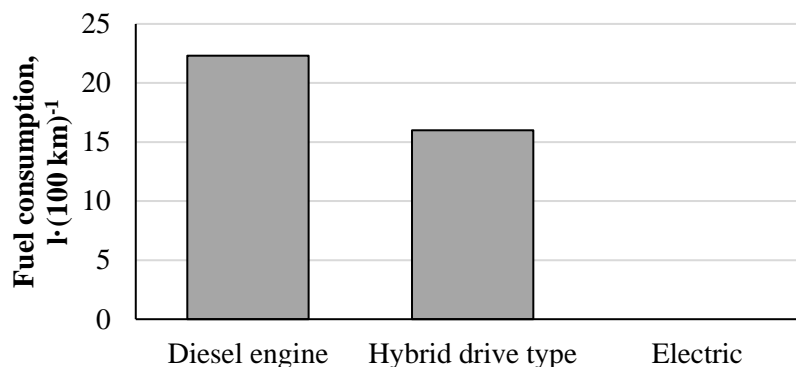


Fig. 1. Fuel consumption for different drive types [3; 4]

Firefighting vehicles rely on a combination of fuel efficiency and operational range to ensure sustained fire suppression efforts. Diesel engines provide higher torque and longer operational range, but their emissions and fuel consumption are significantly higher than alternative powertrains. Hybrid vehicles reduce fuel dependency by incorporating regenerative braking and energy-efficient electric motors, while fully electric fire trucks eliminate direct emissions but require extensive charging infrastructure.

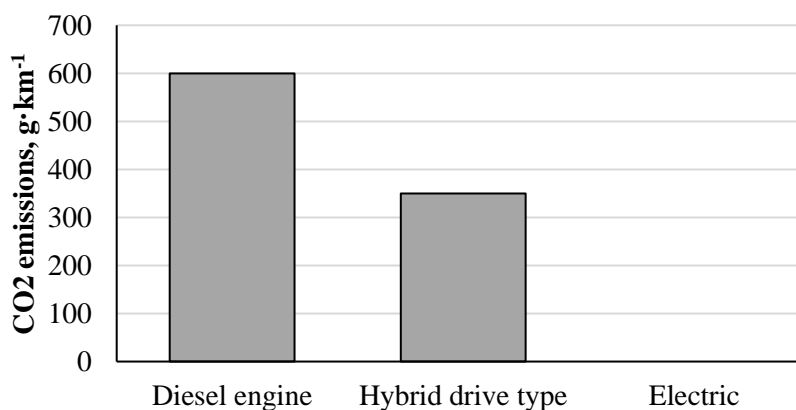


Fig. 2. CO₂ emissions for different drive types [3; 8]

CO₂ emissions are a significant concern in firefighting operations, especially in densely populated urban areas where air quality regulations are stringent. Hybrid-electric and fully electric fire trucks offer substantial reductions in greenhouse gas emissions, aligning with global sustainability goals. However, electric fire trucks require further advancements in battery technology and infrastructure development to match the reliability of conventional firefighting fleets [5; 6].

Maneuverability and Stability

Firefighting vehicles must navigate diverse and often challenging terrains, making maneuverability and stability crucial for effective emergency response. Urban areas demand highly agile vehicles capable

of navigating narrow streets and heavy traffic, while rural and forested regions require robust suspension systems and all-terrain capabilities to traverse uneven landscapes. In industrial zones, where fire hazards may involve hazardous materials or complex infrastructure layouts, enhanced traction and stability control are essential for ensuring firefighter safety [5].

As shown in Figure 3, response time varies significantly across different environments. Urban areas typically exhibit shorter response times due to well-developed road infrastructure and close proximity to fire stations. Conversely, rural and forested environments experience longer response times, as firefighters must navigate uneven terrain and limited road access, often requiring specialized vehicles with enhanced suspension and off-road capabilities [6; 7; 9].

Multiagent Systems for Maneuverability Optimization

Recent advancements in multiagent fuzzy transportation systems (FTS) have introduced new ways to improve firefighting vehicle maneuverability. Akopov et al. [10] developed a parallel biobjective real-coded genetic algorithm that optimizes vehicle interactions and lane changes under dynamic traffic conditions. This system, which integrates real-time routing and predictive modeling, has the potential to reduce congestion delays and enhance emergency vehicle response times.

The implementation of FTS-based maneuvering algorithms in urban and rural emergency response planning could significantly improve vehicle handling, minimize congestion-related delays, and enhance firefighter safety. By dynamically adapting to road conditions and traffic density, such systems offer a data-driven approach to optimizing emergency response operations.

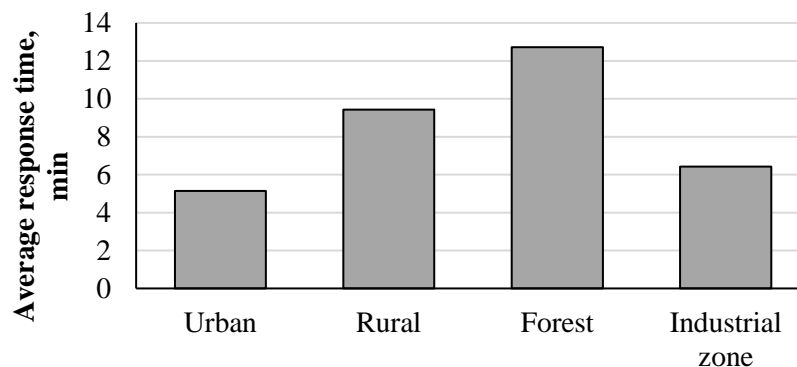


Fig. 3. Response time in different environments [6; 7; 9]

Water consumption during firefighting operations also differs based on the operational environment. Figure 4 illustrates that urban firefighting typically requires lower water usage per call, as fire hydrants and municipal water supplies are readily available. In contrast, forest and rural fires necessitate larger water reserves, given the absence of nearby hydrants and the increased area affected by fire spread [6; 7; 9].

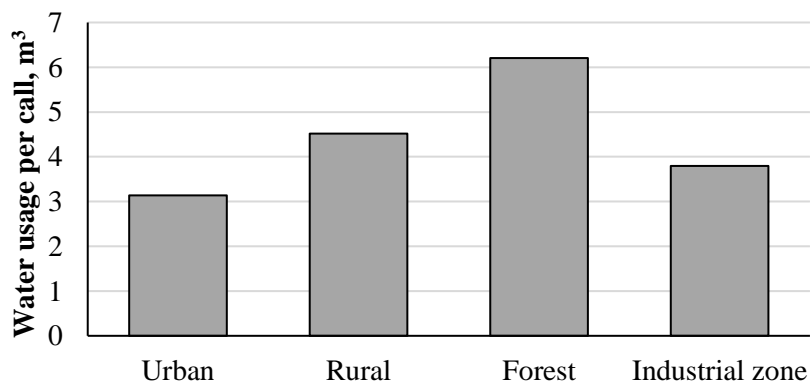


Fig. 4. Water usage per call in different environments [6;7; 9]

Firefighting vehicles often navigate challenging terrains, particularly in rural and forested areas. To further assess operational efficiency, Table 4 presents a comparative analysis of response time, water

consumption, and maneuverability limitations across different terrains. The table highlights how terrain conditions directly impact vehicle maneuverability, emphasizing the need for adaptive suspension systems, optimized weight distribution, and electronic traction control to improve performance in demanding environments.

Table 4

Operational efficiency in different environments [6; 7; 9]

Environment	Average Response Time (min)	Water Usage per Call (m ³)	Maneuverability Limitations (1-10)
Urban	5.2	3.1	3
Rural	9.5	4.5	5
Forest	12.8	6.2	7
Industrial Zone	6.4	3.8	4

These findings emphasize the necessity of terrain-specific vehicle designs that balance maneuverability, water supply capacity, and stability. Further integration of real-time navigation systems and AI-assisted route planning could mitigate terrain-based limitations, improving firefighting response efficiency in complex operational environments [1; 2].

Failure Rates and Maintenance Considerations

The reliability of firefighting vehicles is a critical factor in ensuring uninterrupted emergency response capabilities. Frequent mechanical and electrical failures can lead to prolonged downtime, increasing the risk of operational delays and higher maintenance costs. Effective preventive maintenance strategies and technological advancements in diagnostics and predictive maintenance are essential for minimizing breakdown rates and extending the service life of firefighting fleets.

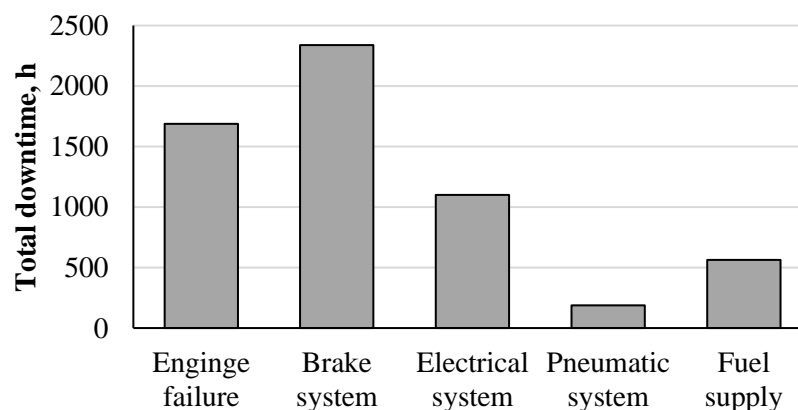
AI-Powered Predictive Maintenance

Jiang et al. [1] demonstrated how AI-driven predictive maintenance systems can monitor vehicle battery health, energy consumption, and mechanical stress factors in real-time. These AI models allow for proactive maintenance scheduling, reducing failure risks and optimizing fleet reliability.

By integrating real-time AI diagnostics into fire truck maintenance programs, cities can extend vehicle lifespan, reduce unplanned downtime, and optimize resource allocation for maintenance crews.

A reliability analysis of heavy firefighting vehicles, conducted by Selech et al. [7], revealed distinct failure patterns between chassis components (engine, brakes, fuel supply) and firefighting superstructures (pumps, hydraulic systems, and electrical components). The study highlights that engine and brake system failures account for the highest total downtime, significantly affecting vehicle availability and response efficiency [6].

Figure 5 illustrates the total downtime for different failure types, emphasizing the most time-consuming repair categories, while Figure 6 provides insights into the average downtime per individual failure, highlighting components that require frequent servicing.

**Fig. 5. Total downtime for different failure types [7]**

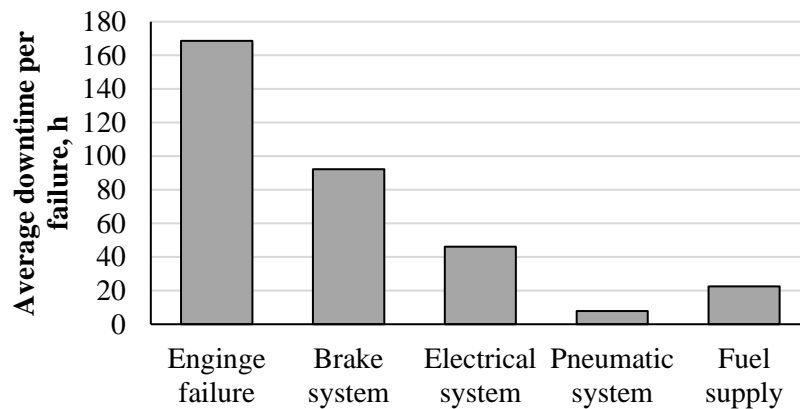


Fig. 6. Average downtime per failure type [7]

Reliability analysis of heavy firefighting vehicles reveals distinct failure patterns between chassis components and firefighting superstructures. To further assess the impact of mechanical failures on operational readiness, Table 5 presents a comparative analysis of failure rates and maintenance downtime for key vehicle subsystems.

Table 5

Failure rates and maintenance downtime [7]

Failure Type	Total downtime, h	Avg downtime per failure, h
Engine Failure	1685.8	168.6
Brake System Failure	2330.7	93.2
Electrical System Failure	1085.4	45.2
Pneumatic System Failure	176.3	7.7
Fuel Supply System Failure	548.7	22.9

Technological Solutions to Reduce Failure Rates

To mitigate the impact of mechanical failures and enhance vehicle reliability, modern firefighting fleets are integrating advanced diagnostic and predictive maintenance systems, including the following.

- **AI-Based Predictive Maintenance** - Uses real-time sensor data to detect potential failures before they occur, reducing unplanned downtime.
- **Automated Engine Monitoring Systems** - Continuously track fuel efficiency, temperature variations, and component wear, preventing critical failures [2].
- **Brake Wear Sensors and Automated Alerts** - Improve brake system reliability, reducing the risk of sudden brake failures during emergency operations.
- **Smart Battery Management for Electrical Systems** - Enhances battery longevity and reliability, minimizing electrical failures.
- **Cloud-Based Fleet Management Software** - Allows remote monitoring of vehicle health, optimizing maintenance schedules and reducing repair costs.
- **Hybrid Power Backup Systems** - Ensure continuous operation of key vehicle components in case of electrical failures, reducing downtime [11].

The adoption of these technologies has been shown to decrease maintenance costs by up to 25% and reduce average repair time by 40%, ensuring that firefighting vehicles remain in peak operational condition.

Intelligent Driving and Safety Systems: Curve Speed Warning Systems (CSWS) for Fire Trucks

Excessive speed in curves is a major contributor to fire truck rollovers and fatal accidents [12]. Fire trucks, due to their high center of gravity and heavy loads, are particularly vulnerable to instability when navigating sharp turns, especially at high speeds during emergency responses.

To mitigate these risks, a Curve Speed Warning System (CSWS) was developed and tested. Simulator-based trials demonstrated that CSWS significantly improves driver reaction times, enabling

firefighters to adjust their speed pre-emptively and reduce the likelihood of rollovers while maintaining response efficiency [12].

Integrating CSWS technology into modern fire truck fleets could enhance driver safety, particularly in urban environments with tight corners and in high-speed rural response scenarios. Future research should explore the integration of CSWS with AI-driven vehicle stabilization systems, allowing real-time adjustments based on road conditions, weather factors, and vehicle load distribution to further improve fire truck safety.

Emergency Vehicle Scheduling and Resource Allocation: AI-Optimized Firefighting Resource Deployment

Recent advancements in AI-based resource allocation models have significantly improved emergency response efficiency by optimizing vehicle dispatch and resource management. Wu et al. [13] developed an AI-powered scheduling system that dynamically reallocates firefighting vehicles based on fire severity and real-time incident reports, ensuring optimal response times and minimizing operational delays. In addition, Tian et al. [14] proposed a hybrid optimization algorithm, incorporating a gravitational search approach to enhance scheduling efficiency for large-scale forest fire incidents. This algorithm effectively balances limited firefighting resources with emergency priorities, allowing more strategic deployment in multi-fire scenarios.

Potential Benefits for Fire Departments

The implementation of AI-driven scheduling algorithms offers the following advantages:

- Reduced response times through real-time vehicle reallocation.
- Optimized resource distribution, minimizing fuel consumption and operational costs.
- Enhanced coordination in simultaneous fire incidents, allowing dynamic prioritization based on fire intensity and location.

Discussion

The findings of this study highlight the critical role of vehicle technical parameters in determining firefighting efficiency. By examining water supply capacity, propulsion systems, maneuverability, and maintenance reliability, this research provides a comprehensive assessment of the operational effectiveness of firefighting vehicles. The results underscore several key challenges and opportunities for future improvements in emergency response capabilities.

One of the most significant insights is the importance of water supply and pump efficiency in sustaining firefighting operations. High-capacity water tanks and advanced positive displacement pumps improve operational endurance, particularly in rural and forested environments where hydrant access is limited. The introduction of modular water suppression systems, such as compressed air foam systems (CAFS) and water mist technology, has demonstrated the potential to enhance fire suppression effectiveness while reducing overall water consumption. Regarding fuel efficiency and powertrains, hybrid-electric propulsion has proven beneficial in reducing fuel dependency and operational costs. Hybrid vehicles offer increased maneuverability in urban environments, while fully electric fire trucks present an alternative solution for sustainability-focused municipalities. However, battery limitations and charging infrastructure remain obstacles to widespread electric vehicle adoption in firefighting applications. Future research should explore alternative fuels such as hydrogen fuel cells and synthetic fuels to further enhance zero-emission firefighting vehicle capabilities.

Maneuverability and stability are also crucial factors influencing response time and safety in different operational terrains. Firefighting vehicles require advanced suspension and traction control systems to navigate challenging environments such as forests, rural areas, and industrial sites. The adoption of electronic stability control (ESC), torque vectoring, and adaptive suspension has significantly reduced rollover risks and improved vehicle handling.

Failure rates and maintenance reliability directly impact the availability of firefighting fleets. The analysis of maintenance trends reveals that engine and brake system failures account for the highest downtime, leading to costly repairs and operational disruptions. Predictive maintenance solutions, powered by AI-driven diagnostics and real-time monitoring, offer a promising approach to reducing unplanned failures and improving fleet readiness.

Furthermore, although the empirical foundation of this study is based primarily on European data, its recommendations are adaptable to a wider range of operational contexts. In developing regions with limited firefighting infrastructure, scalable innovations such as modular water systems, hybrid propulsion units, and AI-assisted diagnostics can offer accessible and impactful improvements. These technologies enable progressive integration into constrained settings, enhancing emergency response capacity without the need for fully modernized fleets.

Overall, this study emphasizes the necessity of data-driven vehicle optimization, real-time monitoring, and innovative suppression technologies to enhance firefighting efficiency.

Conclusions

The findings of this study indicate that firefighting vehicle efficiency can be significantly enhanced through the integration of modern technologies, improved design methodologies, and adaptive engineering solutions. Addressing key operational limitations, such as fuel consumption, vehicle stability, and suppression system performance, is critical to optimizing firefighting response capabilities.

This research highlights that hybrid-electric propulsion, AI-driven navigation, advanced fire suppression technologies, and predictive maintenance strategies are essential for increasing operational efficiency and sustainability. For example, hybrid-electric systems have demonstrated up to 30% fuel savings, AI-assisted navigation can reduce response times by approximately 20%, and modern CAFS and water mist technologies decrease water usage by 50-65% while improving suppression efficiency by up to 30%. Moreover, improvements in lightweight materials and modular vehicle designs contribute to greater adaptability and reduced fuel dependency.

Based on these findings, the following recommendations are proposed to enhance firefighting vehicle performance and reliability:

1. Adopt hybrid-electric propulsion systems
 - This will reduce fuel consumption and enhance vehicle maneuverability, particularly in stop-and-go urban environments where frequent acceleration and deceleration are required.
2. Implement AI-driven predictive maintenance systems
 - AI-powered diagnostics will increase fleet reliability and reduce maintenance downtime by detecting potential failures in advance, minimizing unexpected breakdowns. Studies have shown that such systems can reduce unplanned maintenance costs by up to 25% and shorten average repair time by approximately 40%.
3. Develop modular fire suppression systems
 - Integrating Compressed Air Foam Systems (CAFS) and water mist technologies will optimize water use, allowing for more efficient and targeted suppression while reducing overall resource consumption.
4. Enhance vehicle stability and traction control
 - Features such as active suspension, electronic stability control (ESC), and torque vectoring will minimize rollover risks, particularly in off-road and extreme terrain conditions, which, according to recent simulations, reduce rollover risk by up to 25% compared to traditional fixed-suspension systems.
5. Integrate lightweight composite materials
 - The use of high-strength, lightweight composites will reduce overall vehicle weight, leading to lower fuel consumption while maintaining durability and structural integrity.

As technology advances, future research should focus on integrating real-time data analytics into firefighting vehicle operations, allowing for data-driven decision making and dynamic resource allocation. Additionally, the feasibility of alternative fuels, such as hydrogen fuel cells and synthetic e-fuels, should be assessed to achieve zero-emission firefighting fleets.

Finally, the development of autonomous or semi-autonomous firefighting support systems, including AI-assisted suppression robots and drone-based reconnaissance, should be explored to further enhance firefighter safety and response efficiency.

Author contributions

Conceptualization, V.P.; methodology, V.P. and J.P.; validation, M.J. and V.J.; formal analysis, V.P. and M.J.; investigation, V.P., J.P., V.J. and M.J. data curation, V.P., V.J. and M.J.; writing - original draft preparation, V.P.; writing - review and editing, V.P. and J.P.; project administration, J.P.; funding acquisition, V.J. All authors have read and agreed to the published version of the manuscript.

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