

FIRE SAFETY IN PARKING GARAGES

*How modern vehicles challenge current
design assumptions and regulations*

WHITE PAPER ON RISKS, COMPLIANCE, AND MITIGATION STRATEGIES - 2026



EXECUTIVE SUMMARY

Core Message

- Fire safety design assumptions for parking garages are no longer valid.
- The dominant risk driver is not vehicle propulsion technology, but **increased vehicle fire loads**, altered **fire dynamics**, and **longer fire durations**—combined with regulatory frameworks that remain decoupled from energy release and societal consequence.

What Is New and Why It Matters

- **Modern vehicles**, regardless of propulsion type, introduce significantly **higher fire loads** and **fire spread potential** than assumed in existing design standards.
- **Electric vehicles (EVs)** introduce **additional challenges** related to fire duration, re-ignition, gas release, and interaction with confined spaces—with charging scenarios requiring particular attention.
- Existing **size-based regulatory thresholds** fail to reflect **real fire risk and consequence**.

What Current Practice Gets Wrong

- **Fire safety requirements** are still primarily area-based rather than **energy- or consequence-based**.
- **EV-related risks** are often discussed primarily in terms of ignition probability, while fire development and consequence receive less attention.
- Existing parking structures are treated as if they were designed for **modern vehicle fire characteristics**—which they were not.

Key Technical Findings

- **Fire loads** in modern vehicles exceed legacy design assumptions by a factor that challenges both **structural resistance** and **suppression effectiveness**.
- EV fires are **less frequent** but **significantly more complex** to manage, particularly in enclosed and underground garages.
- **Ventilation, spacing, and structural protection** play a decisive role in preventing cascading failures and societal disruption.

Differentiated Risk Perspective

- Not all parking garages require the same level of fire protection, the right approach should ensure that **fire safety measures are proportional** to the specific risks and consequences of each facility.
- **Life safety** is the primary concern in **residential, underground, and high-occupancy garages**
- **Asset protection** drives decisions in **commercial and insurance contexts**

- **Societal resilience** becomes critical for garages linked to essential infrastructure (e.g., hospitals or airports).

Priority Recommendations (Top-Level)

- Shift from area-based to **energy- and consequence-based** fire safety requirements, explicitly adopting a **probability × consequence** framework.
- Introduce **explicit EV- and charging-related design** and **operational provisions**, with particular emphasis on enclosed and underground garages.
- Apply **differentiated strategies** for new construction and existing facilities.
- Strengthen **early detection, containment,** and **structural resilience** in high-consequence garages including existing structures.
- Support **regulatory updates** with technical guidance grounded in real fire behaviour of modern vehicles.

"Success does not consist in never making mistakes but in never making the same one a second time."
 — George Bernard Shaw, *Mrs. Warren's Profession* (1893)

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1. MAIN ELEMENTS

This analysis reveals critical gaps in current fire safety practices for parking garages, while offering clear, actionable solutions to address both immediate and long-term risks.

Decision implications

- The main risk lies in continuing to apply outdated assumptions to modern parking garages.
- The largest near-term safety challenge is the existing building stock, not future new builds.
- Decision-makers should act now using available knowledge rather than waiting for complete scientific certainty.

1.1. Key Findings

1. Modern Vehicles Introduce Elevated Fire Risks (sections 3, 6)

- **Fire loads in modern vehicles**, both electric (EVs) and internal combustion (ICEVs), **have nearly doubled**, reaching 8 GJ per vehicle, primarily due to increased plastic content (up to 17.7% by weight).
- The **critical metric is risk × consequence**: **Lithium-ion batteries in EVs**, while statistically less likely to ignite than ICEVs, lithium-ion battery fires release energy faster and can reignite, escalating consequences in confined spaces like garages. **Thermal runaway (TRA)** can release up to 14 times the battery's stored electrical energy.
- **Charging infrastructure**, while not inherently high-risk, can introduce **additional electrical hazards** if improperly installed or maintained, requiring rigorous safety protocols.
- The debate needs to be reframed into a **probability × consequence measurement**: Not which vehicle burns more often, but where fires occur, how they escalate, and whether mitigation occurs early enough to make a difference.

2. Danish Building Regulations (BR18) Lag Behind International Standards (section 4)

BR18 fails to address modern fire risks adequately:

- **Sprinkler thresholds** in BR18 (1,000 m² for most garages, 2,000 m² in some cases) are **less stringent** than international recommendations, such as NFPA's 465 m² requirement.
- **BR18 lacks specific provisions for EV safety**, including requirements for charging stations, which is particularly concerning in **underground and residential-integrated garages**, where fire spread and evacuation challenges along fire consequences are amplified.
- The **regulatory gap** is further exposed in high-density parking configurations, where **rapid fire spread** and **structural failures** (e.g., unprotected steel reaching critical temperatures) create catastrophic conditions.

3. Recent High-Profile Fires Underscore Urgent Need for Updated Safety Measures (section 3)

Recent garage fires (e.g., Jacksonville 2025, Märsta 2021, Stavanger 2020) demonstrate how quickly fires can escalate in modern parking environments:

- **High-density parking and outdated structural designs**—such as unprotected steel components and limited vehicle spacing—**accelerate fire spread** and **overwhelm passive ventilation**, leading to rapid escalation and structural collapses under prolonged high temperatures.
- The combination of **increased plastic content**, **battery failures**, and **inadequate suppression systems** creates a "perfect storm" for catastrophic fires.

4. A Holistic and Up-to-date Approach to Fire Safety Is Required (sections 5, 6 and 7)

Mitigating these risks demands a **comprehensive, multi-faceted strategy**:

- Apply **tiered safety measures**—sprinklers/ventilation for 150–1,000 m² garages, mandatory sprinklers for >1,000 m²/underground/automated garages—and prioritize high-consequence sites (residential, hospitals, airports) for structural upgrades.
- **Restrict compartment sizes** using EI 60 fire-rated walls, and upgrade **load-bearing elements** to R120 fire resistance to prevent collapses during prolonged fires.
- Position **EV charging stations** near exits with 1m clearance to minimize fire spread. Use dry sprinklers or water mist systems in EV zones and ensure mechanical ventilation to clear smoke and toxic gases.
- Train firefighters in **TRA response** and require **pre-incident planning**. Maintain EV charger inspections and annual structural checks for spalling/corrosion.

A **holistic approach**—integrating **structural resilience, advanced detection, effective suppression, and emergency preparedness**—is the only viable path forward in addressing the complexities of modern vehicle fire risks. Stakeholders must act now to **close regulatory gaps, upgrade infrastructure, and implement the Decision Matrix** to ensure proportional and effective mitigation.

1.2. Recommendation Matrix

For At-a-Glance Decision-Making

Stakeholder	Priority Action	Key Focus Areas	Cost	Impact
Public Authorities	Revise BR18	Lower sprinkler thresholds	Medium	High
	Introduce energy-based thresholds (GJ)	Link requirements to fire load	Medium	High
Garage Owners	Assess facility vulnerabilities	Use DBI's Decision Matrix to assess risks and strategies and/or conduct a risk mapping	Low	Medium
	Upgrade infrastructure	Focus on underground garages, sprinklers and load-bearing elements	High	High
	Enhance EV charging safety (sprinklers, >1m clearance)	Reduce fire spread risks in charging areas	Medium	High
Firefighters	Train for EV-specific risks (TRA, toxic gas management)	Conduct quarterly TRA simulation drills	Medium	High
	Equip responders with specialized PPE	Protect against gas exposure and toxic residues	Medium	High
Insurers	Educate clients on modern risks	Encourage risk assessments and infrastructure upgrades	Low	Medium
	Update insurance policies	Incentivize documented risk assessments, sprinklers, ventilation, and EV safety	High	High
Car Park Designers	Use updated fire load assumptions in designs	Reflect risks posed by modern vehicles	Low	Medium
	Balance cost/safety in design decisions (e.g., 3m+ ceilings, R120 materials)	Conduct lifetime cost optimization (LCO) analysis	Medium	High
Researchers	Collaborate to update safety standards	Reflect latest scientific findings and real-world fire incident data	Low	Medium
	Conduct advanced studies on battery technologies	Focus on TRA prevention and suppression methods	Medium	Medium

Table 1: Recommendation Matrix

For detailed actions, see **Chapter 7 Recommendations**

1.3. Decision Matrix for Fire Safety in Parking Garages

To provide concrete support to **key stakeholders** (i.e., regulators, insurers, building owners, and fire brigades), DBI has designed a **Decision Matrix for Fire Safety in Parking Garages**. This consequence-based matrix stands to support stakeholders' assessment and prioritization of fire safety measures for parking garages **based on risk level**. It is grounded in fire load data, case studies, and regulatory comparisons from the white paper, ensuring a practical, evidence-based approach without introducing new numerical thresholds.

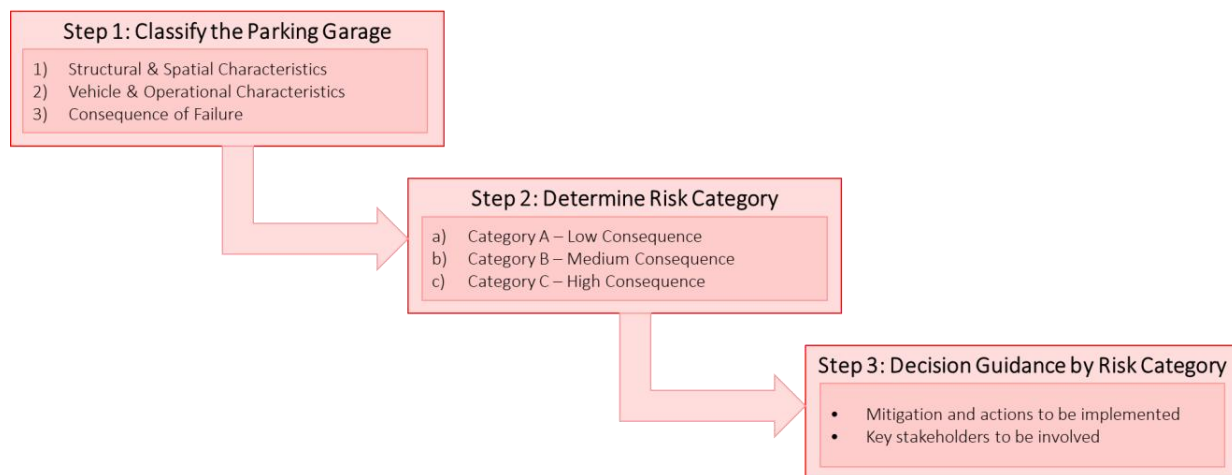


Figure 1: Structure of the Decision Matrix for Fire Safety in Parking Garages

Step 1: Classify the Garage - Evaluate the garage using the highest-risk characteristic across three dimensions:

- Structural & Spatial (i.e., garage type, ceiling height, compartmentation, etc.)
- Vehicle & Operational (i.e., vehicle density, EV charging, fire detection, etc.)
- Consequence of Failure (i.e., life safety, asset value, societal impact)

Step 2: Determine Risk Category

- Category A (Low Consequence): Open or well-ventilated garages with limited occupancy and low societal impact.
- Category B (Medium Consequence): Enclosed garages with moderate occupancy, assets, or business impact.
- Category C (High Consequence): Underground, integrated, or strategically located garages where failure has life-safety or societal consequences.

Step 3: Decision Guidance by Risk Category – Provide decision guidance for specific stakeholders.

For Stakeholders, this **Decision Matrix** provides immediate, actionable guidance for key groups:

- Regulators: Pinpoint gaps where current compliance falls short.
- Insurers: Tailor underwriting and risk mitigation by garage risk category.
- Building owners: Prioritize upgrades across portfolios based on consequence.
- Fire brigades: Focus pre-incident planning on high-consequence garages.

For detailed guidance, see **Annex 1: Decision Matrix for Fire Safety in Parking Garages**.

2. STRUCTURE OF THE WHITE PAPER

This white paper examines the **evolving fire risks in parking garages**, driven by changes in vehicle design, materials and technologies.

Decision implications

- Fire safety challenges in parking garages are driven by changes in vehicle fire behaviour, not by non-compliance with existing rules.
- Compliance with current regulations does not necessarily imply adequate safety for modern vehicles.
- Decision-makers should reassess accepted risk levels for parking garages designed under legacy assumptions.

2.1. Purpose and Scope

This white paper examines the critical intersection of **fire safety and modern parking garage design**, with a particular focus on the unique challenges posed by **modern vehicles** (incl. EVs and ICEVs), lithium-ion batteries (LIBs), charging infrastructures, and high-density parking configurations. The analysis centers on three core areas: Danish regulatory compliance—specifically the Building Regulations 2018 (BR18)—international best practices from NFPA and ISO standards, and the risks associated with EV adoption and automated parking systems. By evaluating **current safety measures against real-world fire incidents**, this paper identifies **gaps in existing protocols** and proposes **actionable strategies** for garage owners, facility managers, insurance companies and fire safety professionals. The goal is to bridge the divide between **regulatory requirements** and the **evolving fire risks introduced by modern vehicle technologies**, ensuring that safety standards keep pace with industrial and technological advancements.

The scope of this analysis extends beyond theoretical compliance to practical implementation, addressing immediate risks such as **thermal runaway** (TRA) in LIBs, and the **structural vulnerabilities** of garage infrastructures. It also explores long-term considerations, including the **integration of automated fire detection systems**, advancements in **suppression technologies**, and the **adaptation of building codes** to accommodate future vehicle innovations. By synthesizing data from case studies, regulatory frameworks, and technological developments, this paper provides a **holistic view of parking garage fire safety**, offering **evidence-based recommendations** for stakeholders across the industry.

2.2. Target Audience

This white paper is written for a diverse audience of professionals who play pivotal roles in shaping, implementing, and enforcing fire safety standards within parking infrastructures.

- **Parking garage owners and operators**, whether managing commercial, residential, or municipal facilities—will find actionable insights on upgrading fire protection systems, optimizing garage layouts, and navigating regulatory compliance. The recommendations are particularly relevant for those overseeing **unprotected structures** or high-risk environments such as **underground garages** and **automated parking systems**, where fire risks are amplified by design limitations and outdated safety measures.
- **Facility managers** responsible for safety compliance will benefit from the detailed breakdown of current regulatory requirements under **BR18**, as well as the comparative analysis of **international standards** like

NFPA 88A and ISO 21542. The paper highlights critical gaps in Danish regulations, such as the **lack of EV-specific provisions** and the **inadequate thresholds for sprinkler systems**, providing a roadmap for aligning local practices with global best practices.

- Additionally, **fire safety professionals**—including consultants, inspectors, and emergency responders—will gain valuable perspectives on the unique challenges of EV fires, such as **TRA** along with strategies for mitigating these risks through advanced detection and suppression techniques.
- **Policymakers and regulatory authorities** will find the comparative assessment of BR18 against international standards highly relevant to their work. The analysis highlights the need to **reassess existing thresholds**—such as the **1,000 m² sprinkler requirement** and related exceptions —and to **develop targeted regulations** for EV-specific risks, given the rapid growth of electric vehicles in Denmark. By **examining real-world incidents** (e.g., Stavanger, Liverpool, etc.), the paper supports **informed decision-making to modernize fire safety codes**, ensuring they keep pace with technological advancements and risks in parking infrastructure.

2.3. Context: Danish Market and Regulatory Landscape

Denmark's rapid adoption of EVs has transformed the fire safety landscape for parking garages, introducing new risks that existing regulations are only partially addressing. In 2024, Denmark's electric vehicle market experienced a pivotal shift, with **EVs alone accounting for 51.5%** of all new passenger car registrations for the entire year a dramatic increase from just 4.2% in 2019 (*European Alternative Fuels Observatory, 2025; Danish Ministry of Climate, Energy and Utilities, 2022*). This surge in EV popularity has outpaced regulatory adaptations, leaving garage owners and facility managers to navigate a **complex interplay of aging infrastructure, evolving vehicle technologies, and inadequate safety standards**. The current regulatory framework, BR18, was designed for traditional vehicles and does not account for the **fire load carried by modern vehicles**.

Under BR18, garages exceeding 1,000 m², or even 2,000 m², are required to install sprinklers or ventilation systems, while underground or residential-integrated garages face stricter rules due to their higher evacuation risks (*BR18, 2018*). However, these thresholds—established before the EV boom—are **increasingly inadequate for modern fire loads**, which have **risen by 40% to 100% due to the greater** plastic content in new vehicles (*NFPA, 2020*). The regulatory gaps are most pronounced in garages with unprotected structures, which operate under outdated 600 m² sprinkler exemptions, and automated parking systems, which lack any specific fire protection mandates under BR18 (*Danish Emergency Management Agency, 2021*). These shortcomings create a dangerous **disconnect between regulatory compliance and real-world fire risks**, exposing garages to catastrophic events like those seen in Stavanger (2020) and Alcorcón (2025), where rapid fire spread and structural failures led to widespread destruction.

The Danish market's transition toward electrification and high-density urban parking further exacerbates these challenges. As EV adoption continues to rise, the **absence of EV-specific regulations**—dedicated charging zone protections—leaves garages vulnerable to uncontrolled fires (*RISE, 2023*). Meanwhile, the growing prevalence of **automated parking systems**, which limit firefighter access, introduces additional risks that BR18 does not address (*BRE, 2019*). Without urgent updates to building codes and safety protocols, Denmark's parking infrastructures will struggle to keep pace with the evolving demands of modern vehicle technologies, **placing lives and property at unnecessary risk**.

The following sections analyze these challenges, establishing the context for regulatory and safety assessments.

3. FIRE RISKS IN PARKING GARAGES

Parking garages face **increased fire loads and ignition risks** due to advancements in vehicle materials and technology. Most existing structures were designed for outdated fire loads and are ill-equipped to handle today’s hazards—leading to catastrophic fires, structural collapses, and life-threatening situations.

Decision implications

- Modern vehicle fire loads exceed legacy design assumptions → area-based thresholds alone are unreliable as safety indicators.
- Fire duration and re-ignition risk are decisive for damage and response → suppression systems should be evaluated for containment, not extinguishment.
- Confined and underground garages amplify consequences → higher levels of protection are required than in open or detached structures.

3.1. Fire Load and Ignition Sources

The fire load of modern vehicles has increased dramatically compared to older models, primarily due to the **expanded use of plastic materials** in their construction.

- Modern vehicles—including EVs and ICEVs—incorporate **at least 2–4 times more plastic than older models**, increasing the average fire load per vehicle (*NFPA, 2020*). However, recent data suggests these estimates may be understated, as new vehicle designs now include **~17.7% plastic by weight** (*JRC, 2023*), significantly exceeding prior assumptions (i.e., <10% of plastic by weight). This material shift directly impacts fire dynamics, as plastics is the primary source of heat release in EV fire, it substantially **elevates heat release rates (HRR), intensifying fire severity and complicating suppression efforts** (*Dehghani et al., 2025*).
- While EVs and ICEVs differ in their energy storage mechanisms, their **overall fire risks are more comparable than often assumed**. EV batteries, for example, have a lower energy density (2–4 MJ/kg) compared to gasoline (42–43 MJ/kg), but the total energy release in a fire is similar due to the greater weight of lithium-ion battery (LIB) packs (*RISE, 2017*). Conversely, ICEVs tend to exhibit a higher initial HRR from fuel tank combustion, but EVs sustain heat for longer durations, creating prolonged exposure risks for structures and responders.

Key lessons from comparative fire tests reveal distinct differences in how EVs and ICEVs behave during fires have been highlighted in the following table:

	EVs			ICEVs		
	<i>Tesla Model 3</i>	<i>Chevrolet Bolt</i>	<i>SUV (2020; 80 kWh)</i>	<i>SUV (2020)</i>	<i>Car mini (1990s)</i>	<i>Car light (1990s)</i>
Peak heat release rates (HRR)	~ 6MW	~ 12MW	~ 8MW	~ 5MW	~ 3.5MW	~ 4.5MW
Total energy release (fire load)	~ 8GJ	~ 8GJ	~ 4GJ	~ 4GJ	~ 3GJ	~ 4.5GJ
Specificities	Thermal runaway (TRA), battery jetting			N/A*		

	and higher reignition risk	
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Table 2: Results from comparative fire tests between EV and ICEV – source Peter Sturm et al., 2022 & Dehghani et al., 2025 & Mohd Tohir, et al., 2013

*: One of the observations from the Liverpool fire (2017) was that burning liquid fuel, from plastic fuel tank, significantly contributed to the rapid spread of the fire.

The table highlights that while EVs and ICEVs release similar total energy (6.4 GJ vs. 5.0–5.3 GJ), EVs sustain lower but prolonged heat release (6 to 12 MW) and reignition risks due to thermal runaway (TRA), whereas ICEVs peak at 10–12 MW with shorter burn times. These values appear in their respective publications and point in several directions.

- Lithium-ion batteries** introduce unique fire risks that distinguish EVs from traditional vehicles. TRA—a self-sustaining exothermic reaction—can be triggered by overheating (>85°C), mechanical damage (e.g., crashes or punctures), or internal short circuits, though the latter remains rare but catastrophic when it occurs (RISE, 2017). The consequences of TRA are severe: **heat release can reach up to 14 times the battery’s electrical energy**, (Larsson et al., 2017). These chemical hazards pose significant risks to first responders, who may inhale toxic fumes or suffer chemical burns without proper **personal protective equipment** (PPE).
- Charging infrastructure** adds another layer of risk, as electrical faults in poorly installed chargers or damaged cables can ignite fires. A Finnish case study (2015–2019) revealed that **3 of 11 EV fire incidents occurred during charging**, a finding that underscores charging as a high-risk scenario due to thermal stress on batteries and potential electrical faults (Linja-aho, 2020). This emphasizes the **need for rigorous installation standards** and **regular inspections** to mitigate such risks. Unlike traditional fuel-related fires, charging-related fires often involve electrical arcs or overheated components, which can smolder undetected before erupting into flames. This delayed ignition **complicates early detection**, making **automatic monitoring systems**—such as thermal imaging and detectors—**essential for preventing catastrophic events**.

When it comes to toxicity, **gas emissions from LIB TRA events pose significant toxicity and flammability risks**; however, further research is needed to provide a comprehensive assessment, guidance on mitigation, and the establishment of safety standards (Bugryniec, 2024). Concurrently, **ICEVs also emits harmful pollutants** like particulate matter (PM10, PM2.5), sulfur dioxide (SO₂), nitrogen oxides (NO_x), and volatile organic compounds (VOCs), which are linked to severe environmental and health impacts (Maria Quant, 2023)

A statistical analysis of fire risks reveals notable differences between EVs and ICEVs, but probability alone is misleading. The **critical metric is probability × consequence**: While EVs have a lower ignition probability, their fires release energy faster and can reignite—escalating consequences in confined spaces like garages. This reframes the debate: Not which vehicle burns more often, but where fires occur, how they escalate, and whether mitigation happens early enough to matter. However, the purpose of this section is to present the available data rather than to make direct comparisons, which would require careful consideration of factors such as fleet age, usage patterns, and exposure.

- Fire probability data from Norway (2024)** shows that ICEVs are almost four times more likely of catching fire than EVs.

	ICEVs	EVs	Hybrid	Other
Total car registered	2,995,311	837,251	372,325	4,685
% of total cars registered	87%	7%	4%	2%

Fire incidents	1,173	89	49	30
% of total fire incidents	71%	20%	9%	0%
Fire incidents per registered car	0.0392%	0.0106%	0.0132%	0.6403%

Table 3: Comparison of Fire Incident Rates by Vehicle Type in Norway - 2024

Source: Brannstatistikk.no & SSB.no

- In Denmark (2022-2023), the fire incidence rate for EVs increased modestly from 1.1 to 1.7 per 10,000 vehicles between 2022 and 2023, even as the fleet grew from 220,000 to 330,000 vehicles—far below the ICEV fire incidence rate of 3.6 per 10,000 vehicles reported in 2023.

	2022	2023
Total EV fleet registered	~220,000	~330,000
Number of EV fire incident	20	46
Fire incidence rate per 10,000 vehicles	1.1	1.7

Table 4: EV Fire Incidence Rates in Denmark (2022–2023) and Fleet Growth Context

Source: Beredskabsstyrelsen, 2024

The **severity of EV fires** presents unique challenges that distinguish them from traditional vehicle fires. EVs typically exhibit a **longer fire duration due to sustained battery combustion**, which can reignite hours or days after extinguishing—a phenomenon rarely seen in ICEVs (*RISE, 2017*). The **composition of released gases** during a fire varies depending on the materials in the vehicles, the type of lithium-ion battery, and oxygen availability, among other factors. Extinguishing difficulties further complicate EV fire response, as battery encapsulation often limits access for firefighters, and **reignition risks** may require submersion in water for 2+ weeks to fully stabilize the battery. In contrast, **ICEVs—while more likely to ignite**—tend to burn out faster, with **lower reignition risks** and **a different emission profile**, making them easier to suppress with conventional methods.

The comparison of EV and ICEV fire risks ultimately highlights the **need for tailored safety strategies**.

- ICEVs present higher ignition probabilities but risks are relatively mastered
- EVs introduce more complex suppression challenges, including prolonged cooling requirements, toxic gas management, and reignition risks.

These distinctions underscore the importance of **updated regulations, specialized firefighting training, and advanced detection systems** to address the evolving landscape of vehicle fire safety. **Without such adaptations, parking garages will remain vulnerable to devastating fires that outpace traditional suppression capabilities.**

3.2. Case Studies of Parking Garage Fires

Real-world parking garage fires offer critical insights into the behavior of modern vehicle fires and the effectiveness of current safety measures. The table below presents a non-exhaustive list of major fires in parking garage facilities since 2015, highlighting key incidents.

Location	Year	Garage Type	Consequences	Source
Alcorcón, Madrid, Spain	2025	Underground, residential	10+ cars destroyed; 2 death, 15 injured	El País (2025) ; SUR (2025)
Jacksonville International Airport, USA	2025	Multi-story, open-air	50+ cars destroyed; airport/business disruptions	Jacksonville.com (May 2025) ; News4JAX (May 2025)
Incheon, South Korea	2024	Underground, residential	140+ cars destroyed; 700+ residents evacuated; 23 hospitalized for smoke inhalation; water/power outages.	The Korea Times, 2024 ; Fortune, 2024
Luton airport, UK	2023	Multi-story, open-air	1,300+ cars damaged; airport/business disruptions	Bedfordshire Fire & Rescue Service (2023) ; BBC (2024)
Warsaw, Poland	2021	Underground, building complex	<50 vehicles destroyed, 150 persons evacuated	European Fire Sprinkler Network (2020)
Märsta, Sweden	2021	Multi-story, closed	200+ vehicles destroyed	SVT (2021) ;
Stavanger airport, Norway	2020	Multi-story, open-air	300+ cars; airport/business disruptions	Storesund et al., 2020 ; RISE (2020)
Cork, Ireland	2019	Multi-story, open-air	60 vehicles destroyed; business disruption	The Irish Times (2019)
Münster/Osnabrück Airport	2019	Multi-story, open-air	65 vehicles destroyed	Rheinische Post (2019)
King Plaza, New-York, USA	2018	Multi-story, open-air	120+ vehicles destroyed, 21 persons injured	CBS News (2018) ; CTIF (2018)
King Dock, Liverpool, UK	2017	Multi-story, closed	1,100+ vehicles damaged and 4,000+ persons evacuated; business disruption	Merseyside Fire & Rescue Service (2018) ; BBC (2018)

Table 5: Non-exhaustive list of parking garage fires

- The **Jacksonville International Airport parking garage fire (May 2025)** demonstrates the rapid escalation risks associated with modern vehicle fires in multi-story, open-air facilities. The fire originated in a single vehicle that had been parked for approximately four hours before smoke and flames were detected. Security footage showed the vehicle fully engulfed within minutes, with rapid fire spread to adjacent cars. The lack of automatic sprinklers—likely due to local building code exemptions—contributed to the uncontrolled growth of the fire. Structural damage, including a partial collapse of the second and third floors, rendered the garage unsafe for use, disrupting airport operations. The delayed suppression response, exacerbated by heavy smoke, highlighted the critical need for early detection systems and active fire protection in high-traffic parking facilities.

- The **Stavanger Airport fire (2020)** stands as one of the most devastating recent examples, where 400 cars were consumed in just 8 minutes. The rapid spread was driven by strong winds and the high fire load of modern vehicles, which contain significantly more combustible materials (e.g., plastics) than older models. The absence of automatic sprinklers and insufficient structural fire resistance led to the collapse of unprotected steel beams as temperatures exceeded 900°C. While the exact parking gap distances were not officially documented, the dense vehicle arrangement facilitated flame propagation between cars. The fire's intensity overwhelmed the garage's smoke ventilation system, filling the space with thick smoke and toxic gases, which delayed firefighter access and led to the collapse of the building structure.

Based on current knowledge, the primary challenge for parking garage fire safety in the coming decades lies not in new construction (i.e., assuming performance-based design uses updated data) but in the large stock of **existing garages designed for outdated vehicle fire characteristics**. The lessons from these cases— highlights the necessity for multi-layered fire protection systems that account for vehicle fire loads, structural resilience, and emergency response efficiency in modern parking facilities.

4. REGULATORY COMPLIANCE VS. FIRE SAFETY

This section compares **Danish building regulations** with **international fire safety standards** to identify compliance gaps.

Decision implications

- Area-based regulatory thresholds do not reflect real fire risk from modern vehicles.
- Energy release and consequence are more robust decision parameters than floor area alone.
- Authorities should supplement prescriptive rules with risk- and performance-based assessments.

4.1. Danish Building Codes

The evolution of Danish building regulations reflects a **gradual recognition of fire risks in parking garages**, though current standards remain less stringent than many international benchmarks.

- **Prior to 1972**, Denmark **had no detailed fire safety regulations for garages**, leaving fire protection measures largely at the discretion of local authorities and building owners. This lack of standardization contributed to **inconsistent safety levels**, with many older structures lacking even basic suppression systems.
- **Between 1972 and 2004**, regulations improved significantly, mandating sprinklers or ventilation for garages exceeding 600 m²—a threshold that, while progressive for its time, has since been **outpaced by modern fire risks**.
- The **post-2004 shift to function-based rules under BR18** further raised sprinkler thresholds to 1,000 m² (or 2,000 m² for single-story garages), a decision that **prioritized cost savings over adapting to increased fire loads from modern vehicles**.

However, these **size-based thresholds fail to account for modern hazards**, such as increased plastic content in vehicles and LIB fires, which can overwhelm systems designed for older fire loads. **Critical gaps** in BR18 compliance further compromise fire safety and can be identified as the following:

- **Older garages (pre-2004)**—many still in use—operate under outdated 600 m² thresholds, which are insufficient for contemporary fire risks, particularly given the 40% to 100% increase in fire loads in modern vehicles.
- **Newer garages (built after 2004)** have even **higher sprinkler thresholds**—up to 1,000 m² or 2,000 m², depending on the building’s use. This exposes facilities to **greater fire risks**, as larger areas can go without sprinklers or proper fire protection.
- **There is no gradual or tiered system** for fire safety requirements, which contradicts recommendations from the **Danish Institute of Fire and Security Technology (DBI)** for more flexible, risk-based standards.
- **Automated garages**, which rely on robotic parking systems, lack specific BR18 regulations, leaving fire protection measures to voluntary standards rather than mandatory codes.
- Perhaps most concerning is the **absence of EV-specific rules**, as BR18 does not set requirements for charging stations (e.g., location, emergency access, etc.) — a glaring oversight given the unique hazards of LIB fires and TRA.

These regulatory shortcomings highlight the **urgent need for BR18 updates** to align with **modern fire risks** and **international best practices**.

4.2. International Best Practices

The following table compares well-known **international fire safety standards** with Danish regulations (BR18), highlighting key differences in sprinkler thresholds, ventilation, EV-specific rules, and structural requirements—and revealing critical gaps in current Danish practices:

Standard	Sprinkler Threshold	Ventilation Requirements	EV-Specific Provisions	Structural Requirements
NFPA 88A (U.S.)	465 m ² (strict enforcement)	Mechanical systems required (active smoke control)	Dedicated EV parking areas with extra clearance.	Performance-based (varies by risk)
ISO 21542 (International)	Performance-based (varies by country)	Mechanical systems preferred (reliable smoke control)	Indirectly covered via structural/accessibility rules.	R120 fire resistance for load-bearing elements. Wider aisles (2.4 m min) for firefighter access.
BR18 (Denmark)	1,000 m ² (exemptions allowed – 2,000 m ² for single story)	Flexible (either automatic fire ventilation or automatic sprinkler systems required)	None	Performance-based (varies by risk, described in the guidance)

Table 6: Comparison of Parking Garage Fire Safety Standards: BR18 (Denmark) vs. International Best Practices (NFPA 88A & ISO 21542)

- **NFPA 88A** adopts a stricter approach than BR18, requiring **sprinklers for garages over 465 m²** and **mechanical ventilation** to control smoke and toxic gases—critical for modern vehicle fires. It also **addresses**

EV risks with HF gas detectors and dedicated charging zones, gaps entirely absent in BR18.

- **ISO 21542** strengthens structural and operational safety by **mandating R120 fire resistance for load-bearing elements** and **2.4 m aisles for firefighter access**—requirements BR18 lacks. Its **performance-based approach replaces BR18’s size-based thresholds**, enabling tailored solutions for high-risk garages (*ISO 21542, 2023*).

A direct comparison of BR18 with NFPA 88A and ISO 21542 reveals critical disparities in fire safety rigor:

- **Sprinkler thresholds:** BR18 allows exemptions up to 1,000 m², while NFPA 88A (465 m²) and ISO 21542 (performance-based) adopt stricter limits, reflecting a more conservative response to modern fire risks.
- **Ventilation:** BR18 states that either automatic fire ventilation or automatic sprinkler systems should be installed, whereas NFPA 88A/ISO 21542 mandate mechanical systems for effective smoke control.
- **EV-specific risks:** BR18 lacks provisions for EV fires, unlike NFPA 88A’s HF detection and ISO 21542’s structural protections, leaving Danish garages vulnerable to hazards.

These gaps underscore the urgency of **reforming the Danish Building Regulation to align with the current level of risks and international best practices**—a necessity for mitigating modern fire risks. To address **these regulatory and operational challenges, practical solutions must be explored**, including sharing knowledge, providing training to relevant stakeholders, updated safety protocols and mitigation strategies, testing advanced suppression technologies, and structural improvements tailored to the evolving demands of parking garage fire protection. The findings highlight deficiencies in current practices, necessitating improved safety strategies.

5. FIRE SAFETY STRATEGIES FOR PARKING GARAGES

Modern parking garages require a multi-layered approach to fire safety, integrating architectural design, passive protection, active suppression systems, and emergency response planning. Fire safety in parking garages requires balancing three competing objectives—life safety, asset protection, and societal resilience—each with different risk tolerances, stakeholders, and regulatory requirements:

- **Life safety** focuses on evacuation and survival, governed by authority-driven minimum requirements (e.g., building codes like BR18).
- **Asset protection** targets property and business continuity, shaped by insurance standards and owner risk appetite.
- **Societal resilience** addresses broader consequences, such as disruptions to critical infrastructure (e.g., garages near airports or hospitals), requiring case-specific, consequence-driven assessments.

These objectives often conflict: what suffices for life safety may fall short for asset protection or societal resilience. **Not all garages demand the same level of protection**—risk acceptability hinges on the potential consequences of failure. For example, a standalone garage in a low-density area may prioritize life safety, while an underground facility beneath a residential complex demands enhanced structural and suppression measures to mitigate cascading societal impacts. Explicitly distinguishing these objectives clarifies priorities for stakeholders and ensures proportional, context-aware mitigation strategies.

Decision implications

- A uniform fire safety solution for all parking garages is neither technically justified nor economically efficient.
- Structural protection, ventilation, and detection must be selected based on consequence, not minimum compliance.
- In high-consequence garages, structural robustness may govern safety more than active suppression alone.

5.1. Architectural and Organizational Measures

The design and organizational layout of parking garages play a critical role in mitigating fire risks, particularly as modern vehicles introduce new hazards that traditional structures were not built to handle.

- **Fire compartmentalization** is one of the most effective strategies for limiting fire spread, and current best practices recommend, without sprinklers, **restricting compartment sizes to <1,000 m², or even lower in high-risk areas** such as underground garages or facilities with dense vehicle parking (*NFPA 88A, 2023*). These compartments should be separated by **fire-rated walls** (EI 60), which provide a minimum of 60 minutes of fire resistance, preventing flames and smoke from rapidly engulfing larger areas. Without such division, a single vehicle fire can escalate uncontrollably, as seen in incidents like the Stavanger garage fire, where poor compartmentalization contributed to the destruction of hundreds of vehicles (*DBI & TI, 2022*).
- **Ventilation systems** are another key architectural consideration, as they directly impact fire behavior and evacuation safety. **Mechanical ventilation with impulse fans should be standard in modern garages**, as these systems can actively direct smoke away from evacuation routes, improving visibility and reducing toxic gas exposure during a fire (*SINTEF, 2023*). For **ventilation**, openings totaling at least 5% of the floor area must be incorporated to allow heat and smoke to escape naturally, delaying the buildup of dangerous conditions (*ISO 21542, 2023*). In garages where passive ventilation is insufficient, **mechanical systems** become even more critical, particularly in enclosed or underground facilities where smoke accumulation can hinder evacuation and firefighting efforts.
- **Evacuation routes** must be carefully designed to ensure rapid and safe progress in the event of a fire. Garages exceeding 600 m² should be equipped with **at least two independent exits**, positioned at opposite ends of the facility to prevent bottlenecks and ensure redundancy if one route is blocked (*BR18, 2018*). Additionally, the maximum travel distance to an exit should not exceed 30 meters, a requirement that aligns with BR18 standards and supports timely evacuation (*Danish Building Regulations, 2018*). In multi-level garages, escape stairs must be clearly marked, well-lit, and free of obstructions, with emergency lighting to guide occupants even in low-visibility conditions. These design considerations are not optional but essential for life safety, as poor evacuation planning has been a contributing factor in multiple garage fire fatalities.
- The **positioning of EV infrastructure** within parking garages requires special attention due to the unique risks associated with LIBs. EV charging stations (EVCS) should be strategically located near exits or open areas—and preferably on ground or upper levels rather than underground—to facilitate quick access for both users and emergency responders. While challenging for most parking facilities, keeping **at least 1**

meter of clearance between charging EVs and other vehicles could significantly reduce fire spread risk—supported by research showing that closer spacing speeds up flame propagation. By segregating EVs and optimizing their placement, garage operators can minimize the potential for cascading fires while enhancing emergency response effectiveness.

5.2. Passive Fire Protection

Passive fire protection forms the foundation of garage fire safety, providing structural resilience and compartmentation that active systems alone cannot achieve. **Fire-resistant materials** are critical in delaying fire spread and preventing structural collapse, particularly in high-temperature events involving modern vehicles.

- **Structural steel**, for instance, must be protected with intumescent coatings to achieve an R120 fire resistance rating, ensuring it can withstand temperatures exceeding 1,000°C without losing load-bearing capacity (*ISO 21542, 2023*). **Unprotected steel**, especially in low-ceiling garages, has been shown to fail rapidly in fires, contributing to catastrophic collapses such as those observed in the Liverpool garage fire (*FM Global, 2023*). Similarly, **concrete structures** must utilize spalling-resistant mixes to prevent delamination, a phenomenon where high heat causes surface layers to break away, compromising structural integrity and accelerating fire spread (*BRE, 2019*).
- **Cladding materials** used in walls and ceilings must also meet **non-combustibility standards**, with mineral wool or equivalent fire-rated panels recommended to prevent flame propagation across surfaces (*NFPA 285, 2022*). The use of **combustible cladding** has been linked to rapid fire growth in multiple garage incidents, underscoring the need for stringent material selection.

Compartmentalization is a critical aspect of fire safety, extending beyond fire doors to include walls and decks, which must also meet the EI 60 / A2-s1,d0 standard. This means that walls and decks must be constructed from non-combustible materials to ensure they resist fire for at least 60 minutes. By integrating these **passive measures**, garage designs can significantly enhance fire resistance and buy critical time for evacuation and suppression efforts.

5.3. Active Fire Protection Systems

While passive protection provides the first line of defense, **active fire protection systems are equally vital** in detecting fires early and suppressing them before they escalate – or at least preventing the fire from spreading to other vehicles.

- **Automatic fire detection** is a cornerstone of modern garage safety, with different detector types suited to specific applications. **Smoke detectors** are highly effective in general garage areas, providing early warning of fires before they grow uncontrollable (*NFPA 72, 2022*). In EV charging zones, however, **multi-criteria detectors**—which combine smoke, heat, and gas sensing—are preferred, as they reduce false alarm (*RISE, 2023*). **Heat detectors**, though slower to respond, remain valuable near charging stations, where ambient conditions (e.g., engine heat, exhaust fumes) might trigger false alarms in smoke-based systems.
- **Suppression systems** must be tailored to the specific risks posed by modern vehicles, particularly EVs. **Sprinkler systems** remain the most reliable for general fire control, with a minimum flow rate of 10 mm/min recommended for EV fires to ensure adequate cooling of battery cells (*RISE, 2020*). In garages, **dry sprinkler systems** are needed to prevent freezing in cold climates, while **water mist systems** offer an alternative for

cooling batteries without the conductivity risks of direct water application (*Ghiji et al., 2023*). For **high-risk areas**—such as automated garages where human intervention is limited—**deluge systems** provide rapid, large-scale suppression, flooding the area to prevent fire spread before emergency responders arrive. Sprinklers might not be able to extinguish a fire located in the battery case of the vehicle, however it will prevent it from spreading to other vehicles.

- **Smoke extraction** is another critical active measure, with mechanical ventilation systems—particularly those using impulse fans—proven to create smoke-free zones that facilitate evacuation (*SINTEF, 2023*). **Computational fluid dynamics (CFD) modeling** should be employed to optimize airflow, ensuring that smoke is directed away from exits and toward extraction points. Even in passive ventilated garages, openings totaling 5% of the floor area must be maintained to allow **passive smoke clearance**, delaying the onset of untenable conditions (*ISO 21542, 2023*). Without effective smoke management, visibility can drop to near-zero within minutes, trapping occupants and hindering firefighting operations.

5.4. Emergency Response Planning

A **comprehensive emergency response plan** is essential for minimizing casualties and property damage in garage fires, particularly as EVs introduced new hazards that traditional protocols may not address.

- **Pre-incident planning** in collaboration with local fire brigades is a critical first step, ensuring that building layouts, and high-risk areas are fully disclosed before an emergency occurs (*NFPA 1620, 2022*).
 - a) **From building-owner's perspective:** It can be done as a standalone folder or even just a card available at the garage for the firefighters. This **proactive sharing of information** allows firefighters to develop tailored strategies, such as optimal entry points, ventilation control tactics, and suppression priorities, which can save critical minutes during a response.
- **From firefighters' perspective:** **TRA-specific response protocols** must be integrated into these plans, including prolonged cooling procedures, as standard firefighting approaches may be ineffective or dangerous when applied to LIB fires.
- **Training and maintenance** are equally vital components of emergency preparedness.
 - a) Building owners would benefit from receiving **training** in understanding and identifying modern fire risks and mitigation strategies (inc. fire load, EV shutdown procedures, etc.).
- Firefighters, meanwhile, require **specialized drills** every six months to practice TRA scenarios, gas exposure protocols, and evacuation tactics in low-visibility conditions as well as **proper equipment**.
 - a) **System maintenance** cannot be overlooked, with weekly test/inspections still being required and accelerator test being a quarterly under BR18 guideline. **Annual structural inspections** (focusing on spalling, corrosion, and load-bearing integrity) could ensure all safety measures remain operational on the longer run.
- **Post-incident planning**, after a fire, building owners should have a plan to minimize disruptions. This includes pre-planning how to safely remove burning vehicles, addressing the issue of contaminated water which will most likely contain Per- and polyfluoroalkyl substances (PFAS), maintaining a strong business continuity plan, and knowing how to restore operations as quickly as possible to reduce downtime.

By combining pre-incident planning, training, and maintenance, parking **garages can develop a robust 360-degrees emergency response framework** that adapts to the evolving risks of modern vehicle fires. By addressing these elements holistically, facility operators can mitigate risks—especially those introduced by electric vehicles—going beyond the minimal requirements to ensure fire safety for today’s vehicles, while ensuring compliance with evolving safety standards.

6. MITIGATION OF EV-SPECIFIC RISKS

EVs pose distinct fire risks, ranging from thermal runaway to toxic gas emissions which require different mitigation strategies than those for ICEVs. Given the evolving nature of research in this field, detailed discussion on gas toxicity falls outside the scope of this white paper.

Decision implications

- The primary EV-related challenge in parking garages is prolonged fire behaviour in confined spaces, not ignition likelihood.
- Gas release and interaction with ventilation systems require explicit consideration in enclosed and underground garages.
- Charging installations introduce additional operational risks that must be managed through location, detection, and access.

6.1. Fire Risks during EV Charging

The electrification of transportation introduces unique **fire risks during EV charging**, primarily stemming from **electrical system failures** and **thermal management challenges**. Preliminary data indicates that around 15% of EV fires occur while charging (EV Fire Safe, 2024). To mitigate these hazards several actions can be taken when it comes to **EV charging stations (EVCS)**:

- **Charger installation** must adhere to strict safety protocols, beginning with the requirement that all installations be performed by **certified electricians** who are trained in EV-specific electrical standards (*IEC 61851, 2022*). This ensures compliance with wiring regulations and load capacity requirements, which are critical for preventing overheating and short circuits. Additionally, **thermal imaging inspections** should be conducted post-installation and periodically thereafter to detect hotspots—early indicators of potential electrical faults—before they escalate into fires (*NFPA 70, 2023*). These proactive measures are essential, as faulty installations have been identified as a leading cause of EV charging-related fires in multiple incident reports.
- **Cable management** represents another critical safety consideration in EV charging infrastructure. The practice of daisy-chaining extension cords—a common but highly dangerous workaround—must be strictly prohibited, as it increases resistance, generates excessive heat, and elevates fire risk (*UL 2021*). Instead, **permanent, dedicated wiring** should be used, with cable trays employed to organize and protect charging cables while preventing trip hazards and mechanical damage. Poor cable management not only creates physical safety risks but also exposes wires to environmental stressors, such as moisture and abrasion, which can compromise insulation and trigger electrical fires. By enforcing these cable management

standards, facility operators can reduce both fire and operational hazards associated with EV charging.

- The **electrical infrastructure supporting EVCS** must be designed to handle continuous **high-power demands without overloading circuits**. Dedicated circuits should be mandatory for each charger, as shared outlets create a risk of overcurrent, which can lead to cable overheating and fire ignition (*IEC 60364, 2022*). Overcurrent protection is equally vital, with circuit breakers rated for continuous loads—rather than standard intermittent use—required to prevent thermal overload. Many EV charging fires have been traced back to inadequate circuit protection, where breakers failed to trip under sustained high-power conditions.

Implementing these **electrical safety measures**, alongside a **proper installation-maintenance plan**, ensures that **EVCS operate within safe parameters**, minimizing the risk of fire during charging operations.

6.2. Lithium-Ion Battery Safety

Lithium-ion batteries (LIBs) present distinct fire risks due to their chemical instability under thermal or mechanical stress, making **thermal runaway (TRA) prevention** a top priority for EV safety. Inside the vehicle, **Battery Management Systems (BMS)** play a central role in mitigating these risks by continuously monitoring critical parameters such as temperature, voltage, and state of charge (SoC) (*IEC 62619, 2022*). A well-designed BMS can detect early warning signs of thermal instability—such as unusual voltage fluctuations or rapid temperature increases—and initiate automatic shutdowns before conditions escalate to TRA. The threshold for shutdown should be set at $>60^{\circ}\text{C}$, as this temperature range often precedes exothermic reactions that can trigger uncontrollable battery fires (*RISE, 2023*). Without real-time monitoring, LIBs remain vulnerable to internal short circuits and thermal decomposition, both of which can lead to catastrophic failures.

When a **LIB fire does occur**, **cooling and containment become paramount** to prevent fire spread, reignition and limiting toxic gas release.

- **Active cooling systems**, such as water mist, are highly effective in lowering battery temperatures and suppressing flames without the conductivity risks associated with direct water application (*Ghiji et al., 2023*). Controlling an EV fire typically requires **10,000 to 30,000 litres of water**, though some incidents may demand **up to 90,000 litres within less than an hour** (*IAFC, 2021 and CTIF, 2022*).
- For **post-fire cooling**, **submersion tanks/container** provide a controlled environment to fully extinguish smoldering battery cells, which can reignite hours, days or even weeks after initial suppression.

Without proper cooling protocols, the risk of secondary fires and toxic exposure remains unacceptably high. Parking facilities must be designed to handle large volumes of water quickly and safely, including planning for the proper disposal of contaminated runoff, as it will contain harmful PFAS.

7. RECOMMENDATIONS

Addressing the **increased fire risks** introduced by modern vehicles in parking garages requires **collaboration among stakeholders**: garage owners, insurers, public authorities, firefighters and researchers. Each group must take action to **close regulatory gaps, upgrade infrastructure, and ensure preparedness** for the evolving challenges of EV and ICEV fires.

Decision implications

- New parking structures should be designed using performance-based approaches reflecting modern vehicle fire behaviour.
- Existing parking garages require risk screening and proportional mitigation rather than uniform retrofitting.
- Fire safety investments should be prioritised where life safety or societal consequence is high.

To guide implementation, the recommendations below are organized by stakeholder and ranked by cost, impact, and urgency. The following definitions apply to the rankings:

Scale	Cost	Impact
Low	Minimal financial and time investment (e.g., training, education, risk assessments, policy updates) – implementation <6 months.	Improves awareness and/or compliance but has limited direct effect on fire safety outcomes.
Medium	Moderate investment (e.g., infrastructure upgrades, PPE, maintenance plans, R&D partnerships) – implementation <1 year.	Significantly enhances safety (e.g., risk assessments, EV charging safety, training).
High	Major investment (e.g., structural retrofitting, advanced suppression systems, full-scale testing) – implementation >1 year.	Critical for reducing fire spread, structural collapse, or life-safety risks.

Table 7: Recommendations' ranking definitions

Cross-Cutting Recommendation: Whenever possible, shift from area-based to **energy- and consequence-based fire safety requirements**, explicitly adopting a **probability × consequence framework**. This approach ensures that low-probability, high-consequence risks—such as EV fires in underground garages—receive proportionate mitigation, while avoiding unnecessary over-engineering for low-consequence scenarios. Cost: **Low** / Impact: **High**

7.1. For Public Authorities

- **Review BR18 regulations** to adapt them to current fire risks, with an emphasis on personal safety, but also taking into account the **safety of property and valuables**. Fire safety measures should be **tiered by garage size and energy release potential**, not just area:
 - a) **smaller facilities** (<150 m²) should face no sprinkler mandates—provided their fire load remains below 100 GJ.
 - b) **larger structures** (150–600 m²) should incorporate fire ventilation if sprinklers are absent.

- c) For garages between 600–1,000 m², either sprinklers or ventilation should be requested, though residential-integrated facilities face stricter rules due to higher evacuation risks.
 - d) Garages exceeding 1,000 m²—as well as all underground structures and automated garages—should be required to have mandatory sprinklers. *Cost: Medium / Impact: High*
- Introduce energy-based thresholds in regulations or guidance, linking fire safety requirements to the maximum potential energy release (GJ) based on vehicle density and type. *Cost: Medium / Impact: High*
 - Introduce specific provisions for EVs and charging stations (e.g., including automatic fire detection, sprinklers, centralized power disconnection, first-responder access, removal, etc.). Tailor requirements based on voltage thresholds, with lower-voltage charging stations facing fewer requirements than higher-voltage stations, reflecting the increased ignition risk at higher voltages. *Cost: Medium / Impact: Medium*
 - Establish a public-private consortium for targeted R&D funding (e.g., SPARKLE project). Partners to co-fund full-scale fire testing and numerical simulations for modern vehicles in parking structures, focusing on cost-effective, scalable to address budget constraints while accelerating innovation. *Cost: Medium / Impact: Medium*

7.2. For Parking Facility Owners

- Assess your facility’s vulnerabilities by leveraging DBI’s decision matrix and conducting a risk mapping to identify hazards introduced by newer vehicles and undergo specific training on parking garage fire safety. Use a structured inspection checklist-style assessment to evaluate structural integrity, pinpoint gaps, and identify cost-effective mitigation strategies tailored to your facility. *Cost: Low / Impact: High*
- Upgrade your infrastructure based on the recommended garage size and energy release thresholds by installing dry sprinkler systems, especially in underground garages, to ensure rapid activation even in freezing conditions. If sprinklers are not installed, strengthen load-bearing elements—such as steel and concrete—to achieve R120 fire resistance, preventing structural failure during high-temperature fires. *Cost: High / Impact: High*
- Enhance EV charging safety by designating dedicated charging zones equipped with automatic fire detection and maintaining a 1-meter clearance between charging EVs and other vehicles to reduce fire spread risks. Ensure emergency access for firefighters to quickly deploy cooling or suppression measures. *Cost: High / Impact: High*
- Establish a strict maintenance plan to keep fire systems operational. Regularly inspect sprinklers, ventilation, and structural integrity, and check EV charging stations monthly for faults. This prevents system failures, reduces fire risks, and ensures long-term safety in your facility. *Cost: Medium / Impact: Medium*
- Collaborate with fire safety authorities to conduct detailed risk assessments, focusing on TRA risks, toxic gas hazards, and evacuation challenges. Proactively share building plans and layouts with local fire brigades to enable tailored emergency response strategies and improve overall preparedness. *Cost: Low / Impact: Medium*

7.3. For Firefighters

- Train regularly on EV-specific fire risks, focusing on lithium-ion battery fires, which require prolonged cooling and hazardous gas management. Conduct TRA simulation drills to gain experience in managing

battery fires. *Cost: Medium / Impact: High*

- **Equip responders with specialized PPE** to protect against gas exposure, which can cause severe respiratory and skin injuries. Train on decontamination procedures to handle toxic residues safely. *Cost: Medium / Impact: High*
- **Ensure firefighters have sufficient resources and training** to respond effectively to modern vehicle fires, including EV-specific gear and ongoing education on risks and suppression techniques. *Cost: High / Impact: High*

7.4. For Insurers

- **Educate clients on modern vehicle fire risks** and the importance of upgrading fire safety measures in parking garages. Encourage **risk assessments** and **infrastructure upgrades** to mitigate potential losses. *Cost: Low / Impact: Medium*
- **Develop insurance policies** acknowledging the risks associated with modern vehicles, incentivizing **fire safety improvements**, such as installing sprinklers, ventilation systems, and EV-specific requirements. Offer **premium discounts** for facilities willing to provide sound fire risk analysis. *Cost: High / Impact: High*
- **Collaborate with fire safety authorities** to **update guidelines** and **training programs**, ensuring clients are prepared for the evolving risks of EV and ICEV fires. This partnership can enhance overall fire safety and reduce claim costs. *Cost: Low / Impact: Low*

7.5. For car park designers

- **Use updated fire load assumptions** in the designs to reflect the risks posed by modern vehicles. This ensures that performance-based designs accurately address real-world fire hazards and help prevent potential disasters. *Cost: Low / Impact: Medium*
- **Prioritize safety in design decisions and openly discuss the economic trade-offs**. While solutions like higher ceilings (e.g., above 3 meters), sprinkler systems, and proper vehicle spacing increase upfront costs, a lifetime cost optimization (LCO) analysis can help balance these expenses against long-term safety benefits. *Cost: Medium / Impact: High*

7.6. Researchers

- **Collaborate with industry and regulators** to **update safety standards** and **guidelines**, ensuring they reflect the latest scientific findings and real-world fire incident data. *Cost: Low / Impact: Medium*
- **Educate, train and provide resources** to fire safety engineers, firefighters, facility managers and insurers on EV-specific risks, suppression methods and mitigation strategies, bridging the gap between research and practical application. *Cost: Medium / Impact: Medium*
- **Conduct advanced studies** on battery technologies and their fire behavior, focusing on thermal runaway prevention, toxic gas emissions, fire load, water contamination and effective suppression methods. Develop **new technologies** for early detection and cooling of battery fires. *Cost: High / Impact: Medium*

By implementing these recommendations, we can **better understand fire risks** and **enhance emergency preparedness** in an era of evolving vehicle technologies. This will **minimize the consequences of fires inside parking garages** and **future-proof facilities** against challenges in vehicle technology and materials.

8. OPENING

8.1. Call to Action

The findings in this report call for urgent action from everyone involved in fire safety. For parking garages, the core issue is **risk acceptance**: the old assumptions about fire loads no longer apply to modern vehicles, and we still lack a new standard. Once we understand the risks, we must assess their potential impact. A structural collapse in a remote, standalone garage will cause far less economic and societal damage than one near an airport or beneath a residential building—and most garages are located in high-density areas. The stakes are high, and the time to act is now.

- **Garage owners and operators** must take the lead in upgrading their facilities. They should start by installing modern fire suppression systems in all garages larger than 150 m². They should also implement specialized safety measures for EV charging areas, such as dedicated parking layouts with enough space between vehicles and proper ventilation and access. Structural improvements should focus on using fire-resistant materials, especially for load-bearing components, to ensure they hold up during long, high-temperature fires.
- **Regulatory bodies** must update building codes to address current fire risks. The Danish BR18 regulations need urgent changes to match international standards, including lowering sprinkler thresholds and adding EV-specific safety rules. Requiring fire detection systems in all garages, no matter their size, would help detect fires earlier. Policymakers should also set clear guidelines for structural fire resistance, considering the higher energy release from modern vehicle fires. Working with international standards organizations will help ensure these updates follow global best practices.
- **Automakers and battery manufacturers** are responsible for developing safer energy storage technologies. They must speed up research on batteries that resist thermal runaway, while recognizing that new designs, like solid-state batteries, may bring different risks. Standardizing safety protocols for EV charging—such as requiring certified installations and thermal monitoring—would help reduce electrical fire risks. Manufacturers should also share detailed safety data with emergency responders to improve fire response strategies.
- **Fire safety researchers and technology developers** play a key role in improving suppression technologies. While water-based systems work, they may not be the best solution for all lithium-ion battery fires. Developing alternative suppression methods that cool fires effectively and reduce toxic gas is a critical area of research. Exploring AI for early fire detection and prediction could offer new solutions. As vehicle technology advances, ongoing research is necessary to identify and address new fire risks before they cause real-world incidents.
-

8.2. Future Outlook

The **future of fire safety in parking facilities** will be shaped by technological advancements, practical adaptations, and sustainable innovation as vehicle designs and infrastructure evolve. While **solid-state batteries** may reduce some fire risks compared to traditional lithium-ion batteries, they would also introduce **new failure modes** that require thorough research and **low-tech safeguards**, such as **improved thermal insulation and manual inspection protocols**.

Automated parking systems present unique challenges, as their robotic operations can restrict **firefighter access** and traditional suppression methods. Solutions may include modular firebreaks, manual override systems, and clearly marked emergency access points to ensure that **human intervention remains possible** even in highly automated environments.

Technologies like **AI and machine learning** hold promise for **early fire detection and predictive analytics**, particularly in identifying thermal runaway risks before they escalate. However, low-cost alternatives—such as enhanced thermal sensors, regular maintenance checks, and training—can provide immediate, scalable improvements while high-tech solutions mature.

Innovation in **suppression agents** is another critical area. While water remains the primary extinguishing medium, its limitations in lithium-ion battery fires are well-documented. **Gel-based coolants, eco-friendly foams, and even sand or dry powder** (for containment in low-resource settings) may offer effective alternatives, but their environmental impact must be carefully assessed. **Circular economy principles**—such as recyclable suppression materials and closed-loop water systems—could help align fire safety with **sustainability goals**, ensuring that **solutions do not create new ecological burdens**.

Looking ahead, the future of fire safety in parking facilities must balance **effectiveness, accessibility, and environmental responsibility** to address evolving risks while minimizing ecological impact. This requires integrating sustainable material innovations—such as fire-resistant, recycled, or bio-based building components—alongside community-driven safety initiatives, including localized firefighter training and shared emergency resources. Policy support for low-impact suppression technologies will further ensure that advancements in fire safety align with broader sustainability goals. As vehicle technologies advance, a **holistic approach**—combining **cutting-edge solutions with practical, scalable measures**—will be essential to safeguard lives, infrastructure, and the environment for the long term.

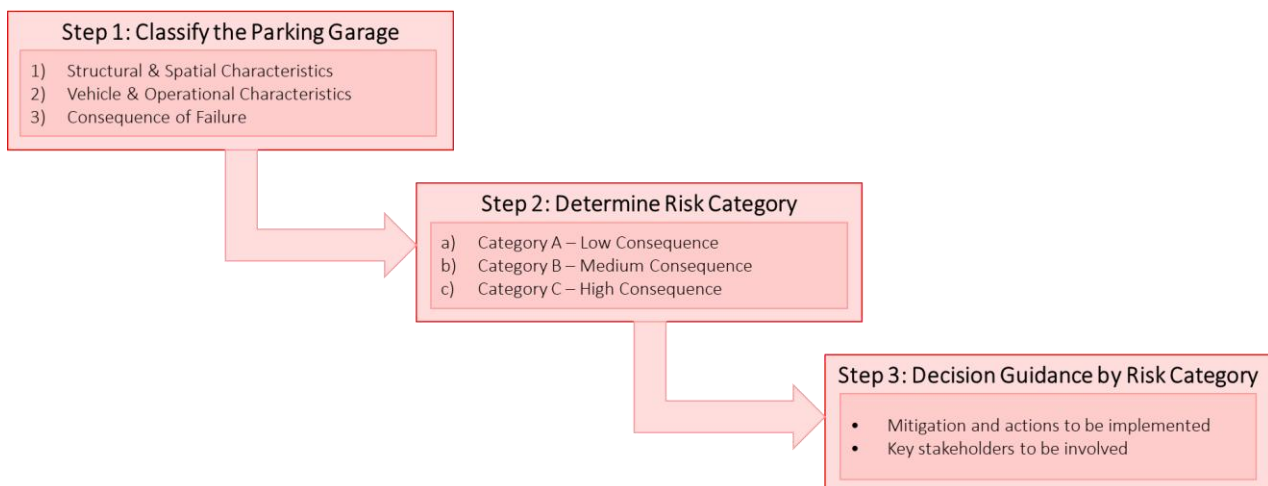
9. ANNEX 1: DECISION MATRIX FOR FIRE SAFETY IN PARKING GARAGES

Purpose:

This consequence-based decision matrix is designed for regulators, insurers, building owners, and fire brigades to assess and prioritize fire safety measures in parking garages. It is grounded in fire load data, case studies, and regulatory comparisons from the white paper and uses consequence-based escalation without introducing new numerical thresholds or models.

Approach:

- **Evidence-based:** Grounded in fire load data, case studies (e.g., Stavanger 2020), and regulatory comparisons.
- **Actionable:** Provides clear triggers for **regulators, insurers, building owners, and fire brigades.**
- **Flexible:** Uses **consequence-based escalation** to handle uncertainty without new models or thresholds.



Step 1: Classify the Parking Garage

- Assess the parking structure using the **highest-risk characteristic** across the following parameters:

Structural & Spatial Characteristics	Low	Medium	High
Garage type	Open-air, detached	Enclosed	Underground / integrated
Ceiling height	> 3.0 m	2.4–3.0 m	< 2.4 m
Compartmentation	Effective	Limited	None
Structural fire resistance	Protected	Partially protected	Unprotected

Vehicle & Operational Characteristics	Low	Medium	High
Vehicle density	Low spacing	Standard spacing	High-density parking
Modern vehicle share	Low	Moderate	High
EV charging	None	Limited	Extensive / clustered
Fire detection	Early / multi-criteria	Standard	Delayed / none
Fire suppression	Fully sprinkled	Localized sprinklers	None
Smoke exhaust ventilation	Mechanical	Natural	None
Maintenance and control	Extensive – beyond compliance	Standard – compliant	Poor – not compliant

Consequence of Failure	Low	Medium	High
Life safety	No occupancy / short stay	Regular users	Residential / vulnerable users
Asset value	Limited	Moderate	High / cascading loss
Societal impact	Local	Business disruption	Critical infrastructure impact

Step 2: Determine Risk Category

Risk Category	Description	Primary Stakeholders
Category A – Low Consequence	Open or well-ventilated garages with limited occupancy and low societal impact.	Building owners, Local authorities
Category B – Medium Consequence	Enclosed garages with moderate occupancy, assets, or business impact.	Building owners, Insurers, Fire brigades
Category C – High Consequence	Underground, integrated, or strategically located garages where failure threatens life safety or societal functions.	Regulators, Insurers, Fire brigades, Infrastructure owners

Step 3: Decision Guidance by Risk Category

- **Category A – Low Consequence Garages**
 - Action:
 - Compliance with existing regulations may be sufficient.
 - Focus on detection, basic containment, and operational preparedness.
 - Stakeholders: Building owners, local authorities.
- **Category B – Medium Consequence Garages**
 - Action:
 - Implement targeted mitigation: enhanced detection, improved ventilation, and limited

compartmentation.

- Fire safety systems should be evaluated for containment, not just extinguishment.
- Insurers may require documented fire risk assessments.
- Stakeholders: Building owners, insurers, fire brigades.

- **Category C – High Consequence Garages**

- Action:
 - Full fire risk assessment required, even if formally compliant.
 - Prioritize structural robustness, smoke/gas management, and firefighter access.
 - EV charging layout and confinement must be explicitly assessed.
 - Mandatory emergency response planning and information sharing with fire brigades.
- Stakeholders: Regulators, insurers, fire brigades, infrastructure owners.

Cross-Cutting Principles

- Fire duration, energy release, and consequence—not just ignition probability—drive decisions.
- Suppression systems must prevent fire spread, not only extinguish flames.
- Existing garages (pre-2004) are the primary near-term risk, as they were designed for outdated fire loads.
- EV risks are most critical in enclosed, underground, and charging-intensive environments.

How to Use This Matrix Immediately

- Regulators: Identify where prescriptive compliance is insufficient.
- Insurers: Differentiate underwriting and mitigation requirements.
- Building Owners: Prioritize investments across portfolios.
- Fire Brigades: Focus pre-incident planning on high-consequence sites.

This matrix is designed to be **practical, evidence-based, and immediately actionable** for all stakeholders involved in parking garage fire safety. For further details, refer to the main report.

10. APPENDIX A: GLOSSARY OF TERMS

Abbreviation	Explanation
AI	Artificial Intelligence
BA	Building Authority (Danish: <i>Bygningsautoritet</i>)
BESS	Battery Energy Storage System
BMS	Battery Management System
BR18	Danish Building Regulations 2018 (<i>Bygningsreglement 2018</i>)
BR	Building Regulations (<i>Bygningsreglement</i>)
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
DBI	Danish Institute of Fire and Security Technology (<i>Dansk Brand- og Sikringsteknisk Institut</i>)
DC	Direct Current
EI	Integrity and Insulation (fire resistance classification, e.g., EI 60)
EC	European Commission
EES	Electric Energy Storage
EI	European Standard (e.g., EN 13501 for fire classification)
EV	Electric Vehicle
EVCS	Electric Vehicle Charging Station
FED	Fractional Effective Dose (toxic gas exposure metric)
FM	Factory Mutual (FM Global, insurance/standards organization)
GJ	Gigajoule (unit of energy)
HF	Hydrogen Fluoride (toxic gas released in LIB fires)
HRR	Heat Release Rate
HCl	Hydrogen Chloride
HVAC	Heating, Ventilation, and Air Conditioning
ICEV	Internal Combustion Engine Vehicle
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
L-AUS	Low-Voltage Work Under Voltage ()
LIB	Lithium-Ion Battery

LFP	Lithium Iron Phosphate (a type of LIB)
LMO	Lithium Manganese Oxide (a type of LIB)
LTO	Lithium Titanium Oxide (a type of LIB)
MJ	Megajoule (unit of energy)
MW	Megawatt (unit of power)
NFPA	National Fire Protection Association (U.S.)
Ni	Nickel (toxic metal released in LIB fires)
PFAS	Per- og PolyFluorAlkyl-stoffer
PHEV	Plug-in Hybrid Electric Vehicle
PPE	Personal Protective Equipment
R	Fire Resistance (e.g., R60 = 60 minutes of fire resistance)
RISE	Research Institutes of Sweden
SoC	State of Charge (battery)
SO ₂	Sulfur Dioxide (toxic gas)
TI	Technological Institute (Danish: <i>Teknologisk Institut</i>)
TRA	Thermal Runaway (uncontrolled LIB fire)
UL	Underwriters Laboratories (safety certification organization)
UPS	Uninterruptible Power Supply
V	Volt (unit of electrical potential)
Wh	Watt-hour (unit of electrical energy)

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