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Classification of Modern Vehicle Hazards in Parking Structures & Systems – Ph II

Final Report by:

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Foreword

The evolution of modern vehicle design and manufacturing methods, including changes in production techniques, material types, and material usage in construction, has brought new challenges to the fire protection community. The introduction of alternative fuel technologies, such as battery electric vehicles, hydrogen fuel cells, and hybrid vehicles, presents new vehicle configurations and burn characteristics that differ significantly from traditional internal combustion engine vehicles. These technological advancements, particularly the use of large lithium-ion batteries and hydrogen fuel cells, have introduced new types of fire hazards, prompting changes in fire protection and firefighting techniques within parking structures.

In 2020, the Fire Protection Research Foundation (FPRF) published a comprehensive report addressing the fire hazards associated with modern vehicles in parking garages. The report highlighted the persistent risk of vehicle fires in these structures, with a particular concern about the potential for fire spread from one vehicle to multiple neighboring vehicles, potentially leading to large-scale conflagrations. This finding underscored the need for updated and expanded fire safety analyses, given the ongoing changes in vehicle material composition and parking garage design standards.

This Phase II effort aimed to update the 2020 report's analysis and identify fire safety knowledge gaps. The expanded analysis covered various aspects, including parking structure characteristics, parking garage fire statistics, vehicle composition data, applicable codes and standards, and representative fire incidents. Additionally, it reviewed published data on full-scale fire tests with modern vehicles, compiling this information into a database for further analysis.
Three primary knowledge gaps emerged from this analysis:

- NFPA 13 Hazard Classification for Modern Vehicles: The current NFPA 13 hazard classification for modern vehicles in parking garages lacks testing data to support its accuracy. Despite evolving codes and standards requiring sprinklers in new parking garages and increasing the necessary sprinkler water density, the technical justification for these water density selections remains unclear.
- Worst-Case Scenario Conditions: The specific conditions leading to the worst-case scenario for vehicle fires in parking garages are not well understood. Variables such as vehicle size and type, fire ignition location, sprinkler placement, window positions, and other configuration-specific details can significantly affect fire development and spread.
- Fire Safety in Vertical Vehicle Stackers and Automated Parking Structures: There is a notable deficiency in experimental data regarding fire safety in modern vehicles parked in vertical stackers and automated parking structures. Existing data and guidance on proper fire safety measures in these types of parking facilities are extremely limited.

To address these knowledge gaps, a testing plan was developed, outlining a test matrix, necessary data, and evaluation criteria. The proposed testing initiatives aim to enhance our understanding of fire hazards in parking structures and improve fire protection strategies, ultimately ensuring safer environments as vehicle technologies and parking facility designs continue to evolve.

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Keywords: modern vehicles, internal combustion engine vehicles, ICE, electric vehicles, EV, parking garages, parking systems, sprinkler systems, sprinkler density.

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Executive Summary

The impact on fire hazards from changes in road vehicle design and changes in production techniques, material types and material usage in construction has recently become more of an issue in the fire protection community. The adoption of different motor technologies and the use of alternative fuels such as battery electric vehicles, hydrogen fuel cells (which also include batteries), and hybrid battery electric/internal combustion engine vehicles present different vehicle configurations and burn characteristics as compared to traditional vehicles powered solely by internal combustion engines. Large lithium-ion batteries and hydrogen fuel cells in vehicles represent a change in the type of hazard and has altered the fire protection and firefighting techniques utilized in parking structures. These developments have had significant implications touching on many different areas, such as design of parking garages and vehicle carriers, suppression systems, as well as firefighter tactics.

In 2020, the Fire Protection Research Foundation (FPRF) published a report detailing the landscape of the fire hazards related to modern vehicles in parking garages. One of the more consequential findings of that report was that while vehicle fires in parking garages can and do occur, and will continue to occur, the biggest concern with these fires is vehicle-to-vehicle fire spread whereby a fire in a single vehicle spreads to many neighboring vehicles, potentially leading to a large conflagration. Since that report, changes have been made to codes and standards related to parking garages, and the material composition of vehicles has continued to evolve. Therefore, a further study was warranted to both update the analysis in the 2020 report, as well as to expand that analysis in order to identify fire safety knowledge gaps and to propose a full-scale testing plan to address those issues. The updated and expanded analysis examined parking structure characteristics, statistics on parking garage fires, statistics on vehicle composition, applicable codes and standards, and representative fire incidents in parking garages. Additionally, the published data on full-scale fire tests with modern vehicles was examined and ultimately compiled in a database for further analysis.

Based upon the analysis, three primary knowledge gaps were identified. First, the proper NFPA 13 hazard classification for modern vehicles in a parking garage is unclear and unsupported by testing data. While codes and standards have evolved to require sprinklers in new parking garages and have also increased the necessary sprinkler water density, the technical justification for selection of the water density is lacking. Second, the conditions that would lead to the reasonably foreseeable worst-case scenario for a vehicle fire in a parking garage are also unknown. The specific size and type of vehicle, ignition location of the fire, location of the sprinklers (if present), position of the windows (fully open, closed, etc.), and other configuration-specific details all can affect the development of a fire in a modern vehicle and, hence, can influence the ability of a fire to spread from the origin vehicle to neighboring vehicles. Finally, there is a lack of experimental data regarding the fire safety of modern vehicles in parking facilities which utilize vertical vehicle stackers and in automated parking structures. The available data and guidance regarding proper fire safety measures in these types of parking structures is extremely limited.

A testing plan was formulated to address these knowledge gaps. An outline of the test matrix, necessary data, and evaluation criteria necessary to meet the objective of filling some or all of the identified knowledge gaps is presented. The testing could be implemented with a limited number of full-scale vehicle tests or with the creation of a standardized mock-up fire source. A combination approach, where some vehicles are used for creation of the standardized mock-up fire source and others are used as validation tests is also outlined. The standardized mock-up fire source approach may allow for more tests to be performed without the need for expensive

test resources such as a vehicle for each test, and may provide flexibility to test more variables and to continue to test as vehicles, parking structures, and fire protection in parking structures continue to evolve. A small number of vertical stacker tests is also proposed. All of these proposed testing approaches would be focused on evaluating and preventing vehicle-to-vehicle fire spread in parking structures.

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Introduction

The impact on fire hazards from changes in vehicle design and changes in production techniques, material types and material usage in vehicle construction has recently become more of an issue in the fire protection community. The adoption of different motor technologies and the use of alternative fuels such as battery electric vehicles, hydrogen fuel cells (which also include batteries), and hybrid battery electric/internal combustion engine vehicles present different vehicle configurations and burn characteristics as compared to traditional vehicles powered solely by internal combustion engines. Large lithium-ion batteries and hydrogen fuel cells in vehicles represent a change in the type of hazard and has altered the fire protection and firefighting techniques utilized in parking structures. These developments have had significant implications touching on many different areas, such as design of parking garages and vehicle carriers, suppression systems, as well as firefighter tactics.

Recently, the Fire Protection Research Foundation sponsored a project to assess the fire hazards posed by modern vehicles in parking structures and vehicles carriers [1]. This study highlighted the changes in vehicle composition (i.e., the adoption of more plastics in the vehicle construction) as well as the increasing size and weight of the average vehicle as important factors in understanding the fire hazards posed by vehicles in parking structures. Though this study did not find any marked changes in overall heat release rate for modern vehicles compared to those from the previous decade, it did note that the replacement of metal components with plastic components could significantly impact fire spread rates.

In the time since the release of the initial report [1], a number of significant experimental studies have been performed to look at the differences between vehicles with internal combustion engines (ICE) and battery-powered vehicles (EV). Furthermore, changes have been adopted by the Technical Committees that generate the building and fire protection codes and standards that govern parking structures. With this additional information on hand, the objective of this project is to assist in defining the landscape of modern parking structures, in terms of helping to understand how parking structures are currently designed, what parking systems are in place, and how these designs and systems may change in the near and intermediate term. With this understanding in place, the fire hazards posed to these structures and systems can be assessed and gaps in knowledge identified for future analysis.

To accomplish the overall objective of the project, a review of the trends in parking structures, parking systems and vehicle composition has been conducted. Additionally, a detailed review and analysis of several representative vehicle fire events in parking structures was made, with specific emphasis on fires in garages with and without sprinklers. Furthermore, a comprehensive database of vehicle fire testing, emphasizing studies of vehicles built within the past decade, has been compiled.

Parking Structure Design Guidelines

Dimensions of parking spaces (non-accessible spaces) have been generally determined based on guidelines presented in various handbooks, such as the Transportation and Traffic Engineering Handbook [2] or similar guides [3] [4]. Figure 1 shows several schemes for designing parking spaces in the United States.

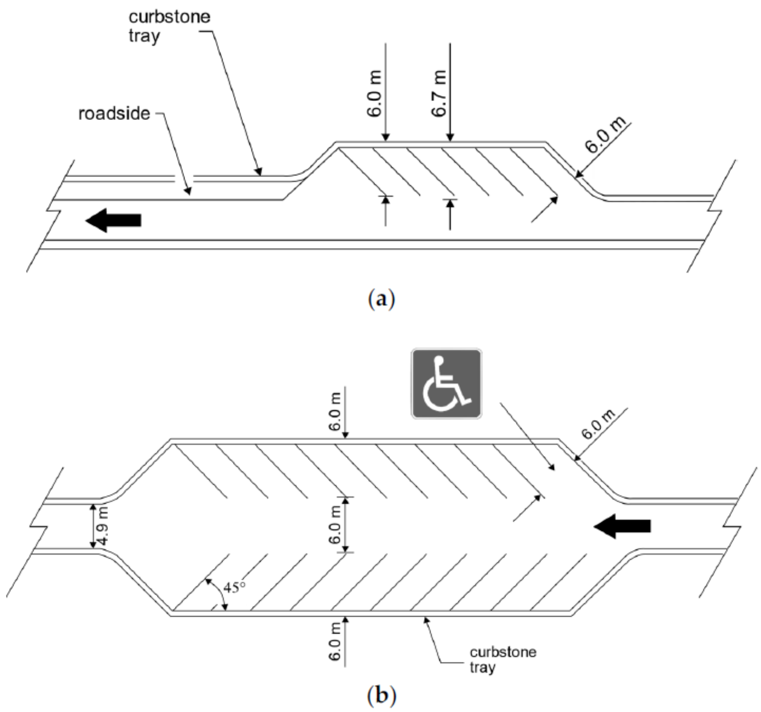

Figure 1. Schemes of planning of parking spaces for passenger cars with one-sided (**a**) and two-sided (**b**) placement in the USA.

Figure 1. Schemes of planning of parking spaces for passenger cars with one-sided (a) and two-sided (b) placement in the USA [3].

Design guides for parking structures and parking space sizes typically utilize a 'design' vehicle to determine proper dimensions that will accommodate the majority of vehicles. Design vehicles are prescribed by organizations such AASHTO (American Association of State Highway and Transportation Officials) and are used for a variety of design functions involving vehicle transportation operations, including roads, highways, and parking facilities. AASHTO publishes a guide titled "A Policy on Geometric Design of Highways and Streets," commonly known as the Green Book, which presents design vehicles that generally have larger physical dimensions than most vehicles in their class [5]. Figure 2 shows the dimensions (in feet) of the passenger car established as the design vehicle by AASHTO which can then be used for sizing parking spaces and designing parking structures. Per The Traffic Engineering Handbook [6], the size of the design vehicle was unchanged from 1998 to the printing of that guide (2016), since there were only small changes (1 or 2 inches in any dimension) in the size of the 85th percentile vehicle which the model used for determining the design vehicle. It should be noted that in the 2020 FPRF report [1], it was found that some vehicles had width increases of 3-8 inches, though this was from a wider timeframe (1970s to 2018).

Table 1. Current design vehicle dimensions.

Design vehicle type	Symbol	Dimensions (ft) Overall Height	Overall Width	Overall Length	Overhang Front	Overhang Rear	WB_1	WB_2	S	T	WB_3	WB_4	Typical kingpin-to-center-of-rear tandem axle
Passenger car	P	4.3	7.0	19.0	3.0	5.0	11.0	—	—	—	—	—	—
Single-unit truck	SU-30	11.0–13.5	8.0	30.0	4.0	6.0	20.0	—	—	—	—	—	—
Single-unit truck (three-axle)	SU-40	11.0–13.5	8.0	39.5	4.0	10.5	25.0	—	—	—	—	—	—
Buses													
Intercity bus (motor coaches)	BUS-40	12.0	8.5	40.5	6.3	9.0[a]	25.3	—	—	—	—	—	—
	BUS-45	12.0	8.5	45.5	6.2	9.0[a]	28.5	—	—	—	—	—	—
City transit bus	CITY-BUS	10.5	8.5	40.0	7.0	8.0	25.0	—	—	—	—	—	—
Conventional school bus (65 passengers)	S-BUS-36	10.5	8.0	35.8	2.5	12.0	21.3	—	—	—	—	—	—
Large school bus (84 passengers)	S-BUS-40	10.5	8.0	40.0	7.0	13.0	20.0	—	—	—	—	—	—
Articulated bus	A-BUS	11.0	8.5	60.0	8.6	10.0	22.0	19.4	6.2[b]	13.2[b]	—	—	—
Combination trucks													
Intermediate semitrailer	WB-40	13.5	8.0	45.5	3.0	4.5[a]	12.5	25.5	—	—	—	—	25.5
Interstate semitrailer	WB-62*	13.5	8.5	69.0	4.0	4.5[a]	19.5	41.0	—	—	—	—	41.0
Interstate semitrailer	WB-67**	13.5	8.5	73.5	4.0	4.5[a]	19.5	45.5	—	—	—	—	45.5
Double bottom semitrailer/trailer	WB-67D	13.5	8.5	72.3	2.3	3.0	11.0	23.0	3.0[c]	7.0[c]	22.5	—	23.0
Rocky Mountain double semitrailer/trailer	WB-92D	13.5	8.5	97.3	2.3	3.0	17.5	40.0	4.5	7.0	22.5	—	40.5
Triple semitrailer/trailers	WB-100T	13.5	8.5	104.8	2.3	3.0	11.0	22.5	3.0[d]	7.0[d]	22.5	22.5	23.0
Turnpike double semitrailer/trailer	WB-109D*	13.5	8.5	114.0	2.3	4.5[a]	12.2	40.0	4.5[e]	10.0[e]	40.0	—	40.5
Recreational vehicles													
Motor home	MH	12.0	8.0	30.0	4.0	6.0	20.0	—	—	—	—	—	—
Car and camper trailer	P/T	10.0	8.0	48.7	3.0	12.0	11.0	—	5.0	17.7	—	—	—
Car and boat trailer	P/B	—	8.0	42.0	3.0	8.0	11.0	—	5.0	15.0	—	—	—
Motor home and boat trailer	MH/B	12.0	8.0	53.0	4.0	8.0	20.0	—	6.0	15.0	—	—	—

Source: AASHTO 2018.

* Design vehicle with 48.0-ft trailer as adopted in the 1982 Surface Transportation Assistance Act (STAA).
** Design vehicle with 53.0-ft trailer as grandfathered in with the 1982 Surface Transportation Assistance Act (STAA).
[a] This is the length of the overhang from the back axle of the tandem axle assembly.
[b] Combined dimension is 19.4 ft and articulating section is 4.0 ft wide.
[c] Combined dimension is typically 10.0 ft.
[d] Combined dimension is typically 10.0 ft.
[e] Combined dimension is typically 12.5 ft.
WB_1, WB_2, WB_3, and WB_4 are the effective vehicle wheelbases, or distances between axle groups, starting at the front and working toward the back of each unit.
S is the distance from the rear effective axle to the hitch point or point of articulation.
T is the distance from the hitch point or point of articulation measured back to the center of the next axle or the center of the tandem axle assembly.

Figure 2. Current design vehicle dimensions [5].

Various handbooks, such as the Transportation and Traffic Engineering Handbook [2] and the Traffic Engineering Handbook [6] provide guidance to designers on the size requirements for parking spaces. Figure 3 shows the dimensions for parking spaces based on the design vehicle criteria such as shown in Figure 2. In the U.S, there does not seem to be any national guidance or criteria for parking space size. However, many municipalities do enforce their own requirements for parking space size.

Similarly, the spacing between floors, which will determine the overhead clearance in the garage, is a consideration for parking garage designers, with minimum values set to avoid vehicle impact with structural elements. Chrest et al. (2012) [4], mentions a minimum of 7 ft (2.13 m) overhead clearance in post-tensioned parking facilities as a guideline.

Utilizing the guidance provided in Figure 3 for the size of the design vehicle and parking space width, typical distances between parked cars will be on the order of 1.5 ft to 2.4 ft (0.46 m to 0.73 m), but could be closer depending on how well centered the vehicles are within the parking space. Maximum distances between two design vehicles (parked in a non-angled space) will be approximately 3.3 ft to 4.8 ft (1 m to 1.5 m). These distances should be considered when determining spacing between vehicles for potential future fire testing and/or analyses.

Table 13-3. Stall and Module Dimensions

			All Levels of Service				
			Angle	Veh. Proj. (VP)	Wall Offset (WO)	Overhang (O)	Stripe Offset (SO)
			45	17′–5″	10′–8″	1′–9″	16′–6″
			50	18′–0″	9′–5″	1′–11″	13′–10″
	Width	Length	55	18′–5″	8′–3″	2′–1″	11′–7″
Design Vehicle	6′–7″	17′–1″	60	18′–9″	7′–2″	2′–2″	9′–6″
Stripe Projection (SP)		16′–6″	65	18′–11″	6′–1″	2′–3″	7′–8″
			70	19′–0″	5′–0″	2′–4″	6′–0″
Parallel Stall Length		23′–0″	75	18′–10″	3′–10″	2′–5″	4′–5″
			90	17′–9″	1′–0″	2′–6″	0′–0″

Minimum Level of Comfort						Generous Level of Comfort					
Angle	Width Proj. (WP)	Module (M)	Aisle (A)		Interlock (I)	Angle	Width Proj. (WP)	Module (M)	Aisle (A)		Interlock (I)
0	8′–3″	28′–6″	12′–0″	1	0′–0″	0	9′–0″	33′–0″	15′–0″	1	0′–0″
0	8′–3″	38′–10″	22′–4″	2	0′–0″	0	9′–0″	43′–4″	25′–4″	2	0′–0″
45	11′–8″	46′–10″	12′–0″	1	2′–11″	45	12′ 9″	49′–10″	15′–0″		3′–2″
50	10′–9″	48′–3″	12′–3″	3	2′–8″	50	11′–9″	51′–3″	15′–3″		2′–11″
55	10′–1″	49′–6″	12′–8″		2′–4″	55	11′–0″	52′–6″	15′–8″		2′–7″
60	9′–6″	51′–0″	13′–6″		2′–1″	60	10′–5″	54′–0″	16′–6″		2′–3″
65	9′–1″	52′–3″	14′–5″		1′–9″	65	9′–11″	55′–3″	17′–5″		1′–11″
70	8′–9″	53′–6″	15′–6″		1′–5″	70	9′–7″	56′–6″	18′–6″		1′–6″
75	8′–6″	54′–6″	16′–10″		1′–1″	75	9′–4″	57′–6″	19′–10″	1	1′–2″
90	8′–3″	58′–6″	23′–0″	4	0′–0″	90	9′–0″	61′–6″	26′–0″	4	0′–0″

All dimensions rounded to nearest inch.

1. Minimum aisle width for one-way traffic controls module; no further reduction in aisle may be taken with wider stall.
2. Minimum aisle width for two-way traffic controls module; no further reduction in aisle may be taken with wider stall.
3. Aisle is close to minimum (see 1 and 2), restricting adjustment for wider stall.
4. Module for one-way traffic flow same as two-way; controlled by turn into stalls.

Figure 3. Parking Space and Module Dimensions [6].

Trends in Parking

Mixed-Use Buildings With Parking Structures

An emerging trend in the design and utilization of parking garages is the design of mixed-use separated buildings, also known as pedestal or podium construction. In these designs, one floor (typically the ground floor) is used for purposes other than parking, such as retail and recreation, with the parking areas on the upper floors. Conversely, other purposes could be storage or housing, which would be located on the top floors [7], with the parking areas on the ground floor or underground. In both cases, the different uses in the same physical structure are separated by a fire-resistance rated horizontal assembly, essentially separating the building into two separate entities from a code-perspective. Mixed-use structures will require some additional considerations from a fire protection standpoint, as the fire load and ignition sources will vary from a typical parking garage. Life-safety concerns, which are typically minimized in stand-alone parking structures, will become much more pronounced in mixed-use spaces.

Automated Parking

Automation of parking has been seen as an emerging trend for a number of years. A mechanical parking facility utilizes devices to store and retrieve vehicles as opposed to having the vehicle parked by patrons or attendants. Wolshan & Pande [6] discuss automated mechanical parking facilities (AMPFs) and car stackers, though these types of facilities are differentiated. Car stackers are a more condensed version of a mechanical parking device, where the vehicles are moved vertically via a lift to allow several vehicles to occupy one parking location. Figure 4 shows an example of a two-tier car stacker within a garage space. AMPFs use a loading compartment to transport a car to individual storage slot. Figure 5 shows a conceptual automated parking system which uses a lift system to move vehicles from the ground level to a higher tier [8]. On the higher tier, the vehicle is placed onto a rotating table for storage on the outer ring.

The operational benefits of AMPFs include the ability to reduce vehicle emissions (from ICE engines) as the engine is not operating which minimizes the need for lighting and ventilation for the facility since humans are not present in or around the vehicles. Also, parking density can be increased since the vehicle does not have to consider the opening of doors for the driver and/or passengers to exit and enter the vehicle. Hence, fire protection codes and practices must account for the increased density of vehicles, with the possibility of more rapid flame spread from vehicle to vehicle.

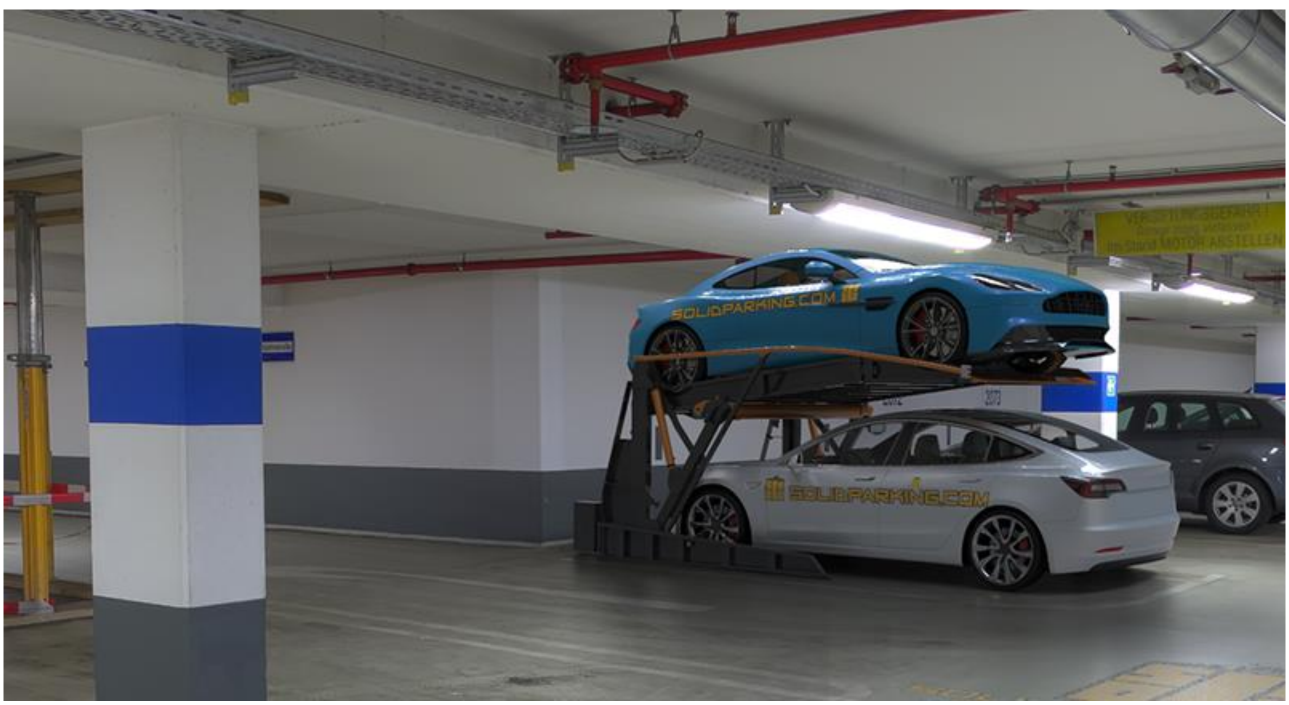

Figure 4. Example of a two-tier car stacker. Source: solidparking.com

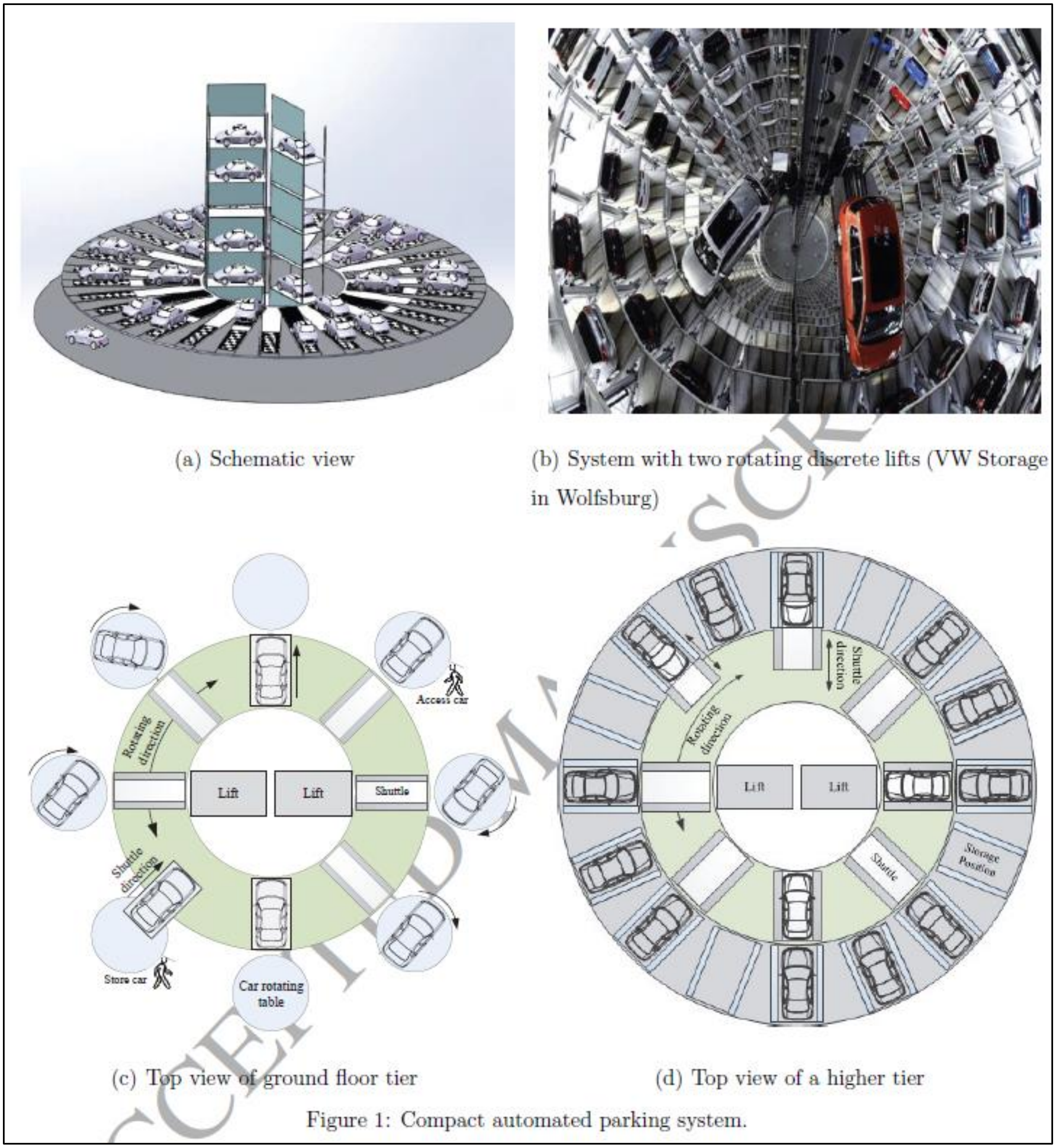

Figure 5. Schematic of a conceptual automated parking system. Reproduced from [8].

Autonomous Vehicle Parking Garages

Another area of gathering interest is the development of autonomous vehicles (e.g., self-driving cars) which are seen as a method for reducing vehicle density in cities as the passengers could be dropped off at a location and then park itself at a remote location [9] [10]. This would reduce the need to have parking facilities in high-usage areas. Furthermore, parking structures designed for autonomous vehicles would have similar operational benefits. However, the fire protection concerns as discussed for AMPFs would apply to these parking garages. The benefits include reduced costs for facility construction, including the reduction of lane width and the elimination of elevators and staircases. The facility operation costs would also be reduced, as well as the ability to increase the parking density, as space needed for opening doors can be eliminated. Figure 6 shows the significant difference in potential parking density between conventional parking facilities and one designed for autonomous vehicles. Consideration must be made for the fire protection requirements of a facility with such high vehicle density, which leads to small spacing between vehicles and greater potential for vehicle-to-vehicle fire spread.

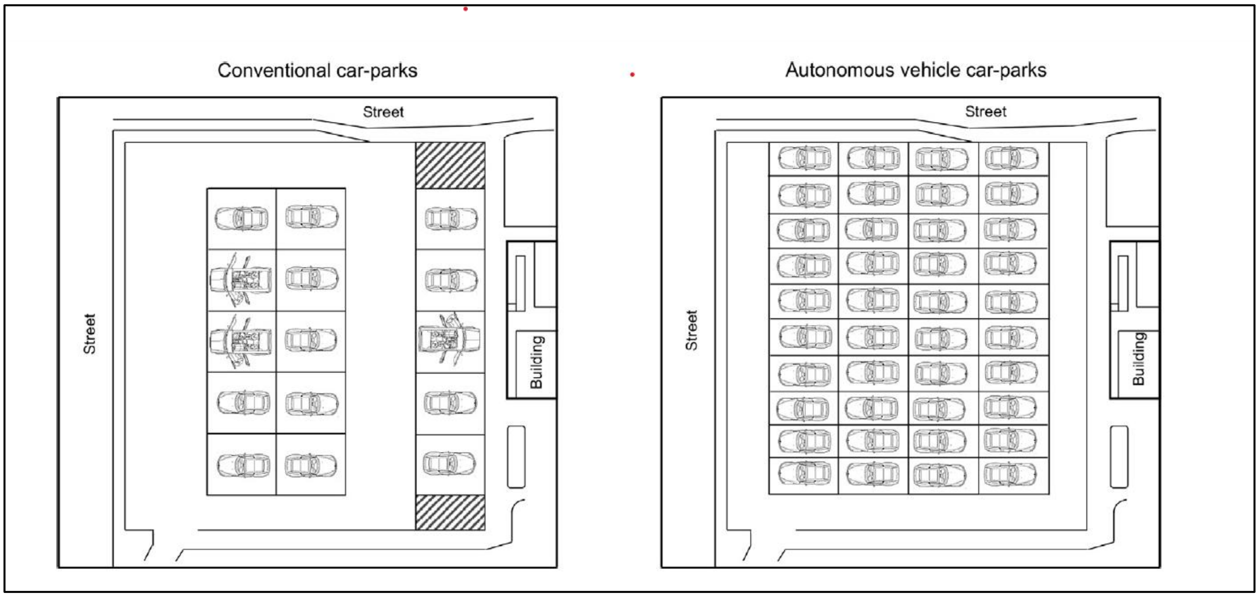

Figure 6. Potential differences between conventional parking garages (car-parks) and autonomous vehicle parking garages (car-parks) (reproduced from [9]).

Vehicle Composition

The material composition of a vehicle has a direct impact on the fire hazard of a vehicle. As was identified in the 2020 FPRF report [1], the increasing use of plastics and combustible materials in vehicles since the 1970s, while having a relatively insignificant effect on the heat release rate, was identified as a significant contributing factor in the ability of a fire to spread from vehicle to vehicle in a parking garage setting. The references used in the 2020 report included data through 2018. The use of plastics in vehicles was re-examined to see if the trends have continued or changed over the past few years. Additionally, as EVs have begun to proliferate the market, an additional consideration is the presence of a relatively large battery in some vehicles. Therefore, the literature was also examined to determine trends in battery capacities in EVs as the number of these vehicles on the road continues to increase.

Plastics Use in Vehicles

In the Phase I report [1], the total weight of vehicles was examined, as well as the weight of plastics present in the average vehicle. This led to two important graphs in the 2020 report, which are included here as Figure 7 and Figure 8. Most of these statistics came from an American

Chemistry Council (2019) report and are based on vehicle curb weight, which is the weight of the vehicle with standard equipment and the necessary fluids (and sometimes fuel), but no cargo or passengers. As can be seen in these figures, vehicle weight is trending up. And despite heavier vehicles potentially implying denser materials, the opposite is true, with more plastics being used in vehicles.

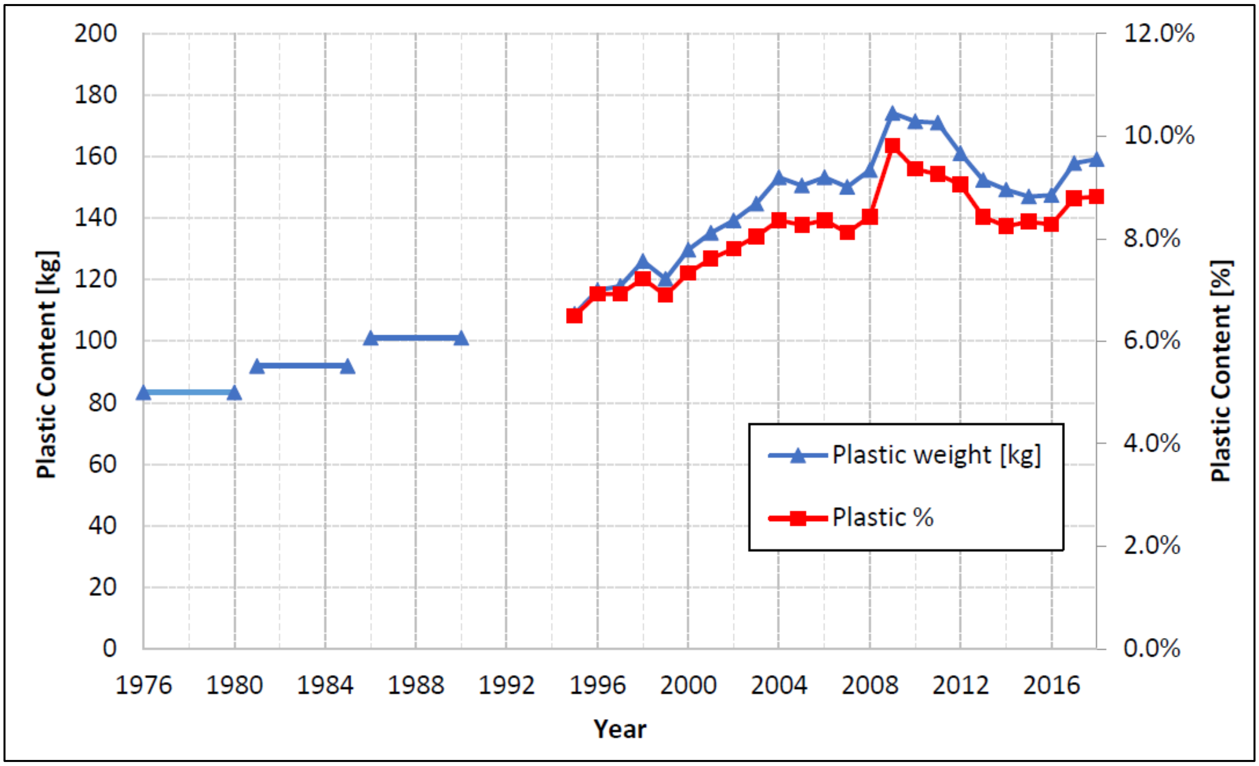

Figure 7. Plastic weight and plastic percentage of vehicle curb weight as a function of time (Figure 2 from [1]).

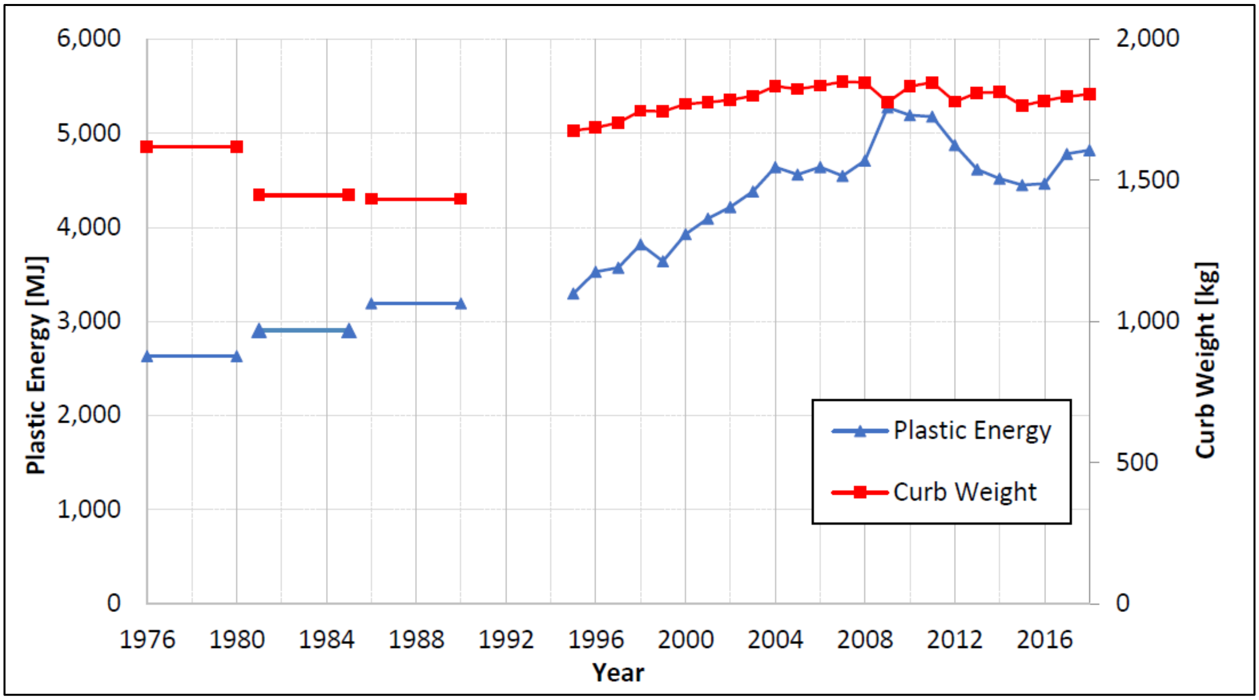

Figure 8. Calculated plastic energy and vehicle curb weight as a function of time (Figure 6 from [1]).

The American Chemistry Council has since released another report regarding the polymer industry's role in the automobile market. In 2023, they released a report entitled "Chemistry and Automobiles: Lighting the Way to the Future of Motor Vehicles" [11]. This report included further data regarding automobiles and the plastic material contribution to these vehicles. This report had slightly different data than that included in the 2019 American Chemistry Council report, even for years included in both reports. It is unknown what contributed to the differing values. The 2023 report includes data through 2021. The average vehicle weight is shown as Figure 9. The plastics weight and percentage of total curb weight with the updated data is included as Figure 10.

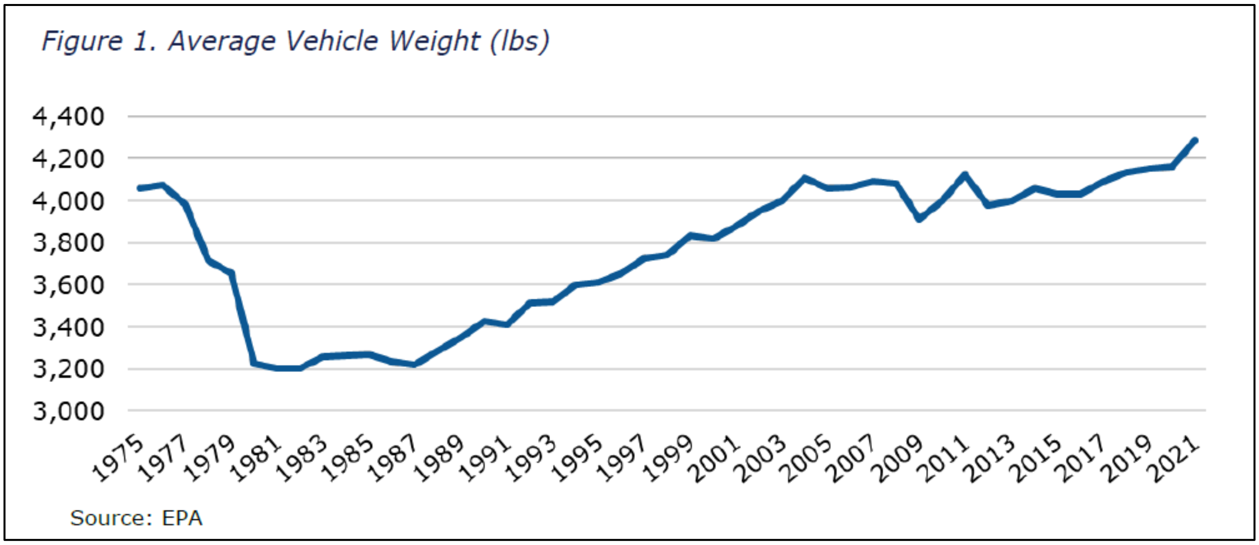

Figure 9. Vehicle curb weight as a function of time (American Chemistry Council, 2023).

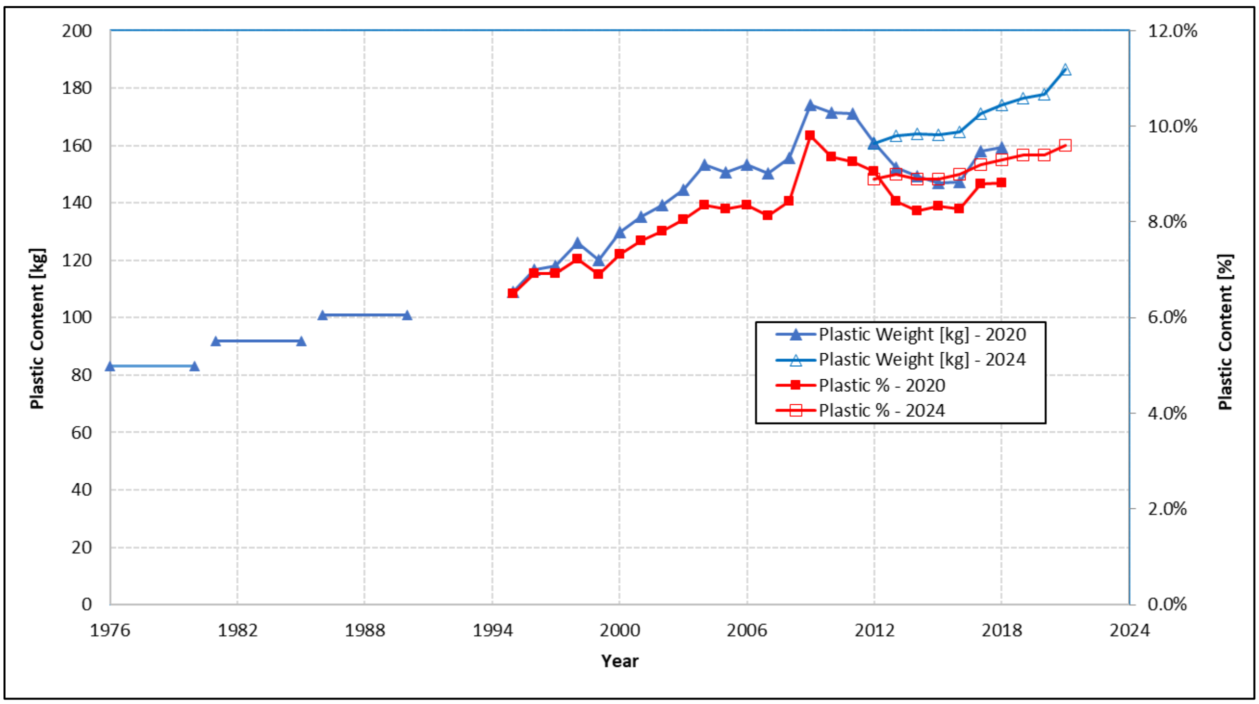

Figure 10. Vehicle plastic weight and weight percentage as a function of time (data source: American Chemistry Council, 2023)

As can be seen Figure 9, since 2018, the average vehicle weight continues to increase. There even appears to be a steeper increase in 2021. The American Chemistry Council report (2023) [11] postulates that some of the increase in the average weight in any given year is related to larger vehicles (i.e., trucks, SUVs, etc.) being purchased when gas prices are lower. The year 2021, though, was not one such year with lower gas prices, and there was actually a slight decrease in the production of trucks during the year. We therefore hypothesize that one such reason for the even steeper increase in 2021 is the purchase of more electric vehicles, with their heavier battery weights. It will be interesting to see how the vehicle weight and composition data evolves in the coming few years as EVs continue to increase in market share.

The new data in Figure 10 indicates a slightly higher mass of plastics in automobiles, as well as slightly higher percentage of plastic usage than was reported in the 2019 report (even for the same year). Again, the reasons for these differences are unknown. The most important findings are that the mass of plastic used in automobiles is continuing to increase and while the curb weight of vehicles is also increasing, the use of plastics is outpacing the increase in vehicle weight, resulting in an increasing percentage of the weight being plastics. Per the American Chemistry Council [11], in 2021 the average weight of a vehicle was 4,287 lbs (1944 kg). Additionally, plastics and polymer composites constitute 9.6% of the total weight of the vehicle as of 2021. This is 411 pounds (186 kg) of plastics on average per automobile. The additional mass of plastic in the average vehicle will certainly increase the overall available combustible energy available should a fire occur in a vehicle. Depending on the ignition scenario, this may cause a vehicle to have a higher heat release rate (though this is not seen in testing as discussed in [1]), have a longer duration of burning, or both. This is related not only to the additional available combustible energy from the plastic, but also the use of additional plastic, glass, and aluminum on the body panels of the automobile which, unlike steel, will fail during a fire, potentially causing a fire that otherwise would be contained and ultimately become ventilation-limited to be able to become only fuel-limited. As a result of all of this, this additional combustible plastic may increase the ability of a vehicle fire in a parking garage to spread to multiple vehicles, and may do further damage to the parking garage structure than older, legacy automobiles. In particular, the potential usage of more plastic materials on the exterior of a vehicle may have a significant effect on the ability and rate of a fire to spread from the vehicle of fire origin to nearby neighboring vehicles.

EV Batteries

The proliferation of EV vehicles on the road is an ongoing phenomenon. As was detailed in the initial report [1], some initial testing with EVs demonstrated that they burn similarly to ICEs from a heat release rate perspective. Nevertheless, EVs do have some differing fire safety considerations from ICEs. Specifically, the presence of a relatively large battery provides a potentially differing ignition scenario from an ICE if the battery reaches thermal runaway. The initial fire therefore could be a sideways jet flame that could ignite neighboring vehicles by direct flame impingement before much of the originating vehicle (the EV) has burned. Additionally, due to the need for significant water impingement to cool the battery, suppression of EV fires can be more difficult than ICEs for Fire Departments. Therefore, there is an interest in determining the characteristics, specifically the size, of batteries currently used in EVs.

Bloomberg has determined that the average lithium-ion battery pack size in an EV increased approximately 10% annually between 2018 and 2022, growing from approximately 40 kWh to approximately 60 kWh [12]. In total, this is a 50% increase in just a few years. This can be seen in Figure 11. The increase in battery size may be somewhat related to the increasing weight of the vehicles which therefore require more available energy, but as described in [12], is related mostly to consumer interest in increases in EV driving ranges on a single charge. McKerracher [12] explains that in some electric pickup trucks, battery sizes of 100 kWh and above are already commonplace and that this increase is likely to continue in the near term since consumers desire more range. However, at some point, this increase in size may put an unattainable demand on the battery supply chain. Nevertheless, a current database of available and upcoming electric vehicles indicates that the battery capacity of several EVs exceeds 100 kWh for SUVs and even exceeds 90 kWh for several smaller vehicles. A few of the higher vehicle capacities for different sizes of vehicles are shown in Table 1 (created from data in [13]) along with similar sized luxury vehicles which generally have even higher battery capacities. This data indicates that the conclusions of the Bloomberg work are generally correct with some battery capacities far in excess of those of the average vehicle in the class, and with many well over 100 kWh. Even some sedans are beginning to push close to 100 kWh for new model year vehicles (2024). If the gap analysis on vehicle fires in parking garages ultimately leads to full-scale testing of EVs, this increase in battery size will likely have to be considered to ensure any tests that include EVs have lasting relevance for some reasonable timeframe.

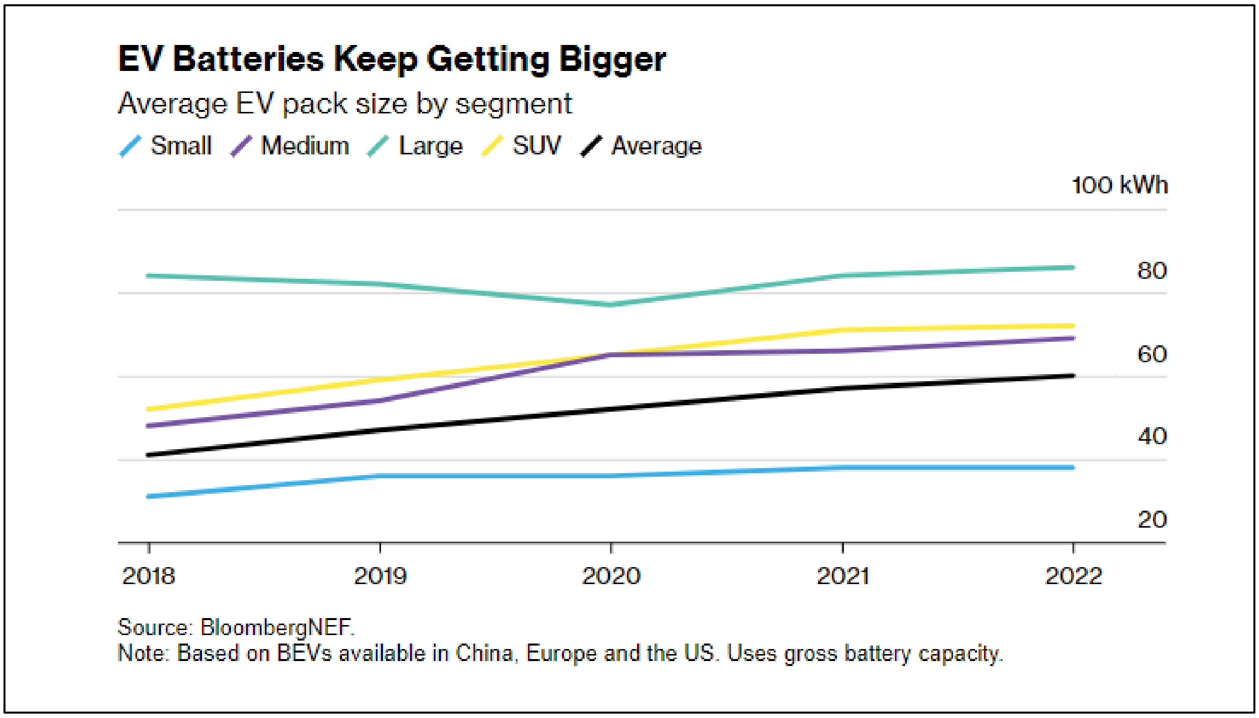

Figure 11. EV battery capacities as a function of time (source: Bloomberg).

Segment	Make	Model	Year Available	Useable Battery Capacity (kWh)
Small	Renault	Zoe ZE50 R135	2020	52
Luxury	Porsche	Taycan 4S Plus	2024	97
Medium	Peugeot	e-3008	2024	98
Luxury	Tesla	Model S Plaid	2024	95
Large	Fisker	Ocean Extreme	2023	106.5
Luxury	Kia	EV9	2023	96

Table 1. Several maximum electric vehicle battery capacities as of 2024 [13].

In sum, with three more years of data (2019-2021), the trends regarding vehicle composition have continued as described in the initial report [1]. The curb weight of the average vehicle is continuing to increase. Additionally, the weight and even the percentage of plastics being used in the average vehicle are also increasing. This may have implications towards the fire hazard of vehicles currently and moving forward. Additionally, the battery capacities in EVs are also generally increasing. These trends should all be considered in any full-scale testing and/or analyses of the vehicle fire hazard in parking garages moving forward.

Review of Fire Incidents

Before an assessment can be made regarding how to appropriately mitigate the risk associated with vehicle fires in parking garages, one must understand the magnitude and characteristics of the problem. To accomplish this, general statistical data on vehicle fires in parking garages was considered. Additionally, case studies of actual real fires in the field were reviewed. The general statistical data and its implications are described below, followed by the findings from the review of several relevant incidents.

General Statistical Data

In the 2020 FPRF report [1], overall statistics of fires in commercial parking garages from the U.S. were discussed. The statistics came from the National Fire Incident Reporting System (NFIRS) and were tabulated by the NFPA. The statistics used in the initial report [1] are included below as Figure 12 and indicate the landscape of parking garage fires in the United States between 2014 and 2018 [14]. NFPA has provided updated statistics related to the prevalence and magnitude of parking garage fires for the years 2017 to 2021 [15]. These are included as Figure 13.

Fires in commercial parking garages, by incident type
2014-2018 Annual averages

Incident type	Fires		Civilian Injuries		Direct Property Damage (in Millions)	
Structure fire	644	(35%)	8	(39%)	$15.6	(68%)
Non-confined	476	(26%)	8	(39%)	$15.6	(68%)
Confined	168	(9%)	0	(0%)	$0.0	(0%)
Vehicle fire	766	(41%)	10	(51%)	$6.1	(27%)
Outside or unclassified fires	447	(27%)	2	(9%)	$1.1	(5%)
Total	1,858	(100%)	20	100%)	$22.8	(100%)

Note: Sums may not equal totals due to rounding errors. Confined structure fires are identified by NFIRS incident types 113-118.

Source: NFIRS and NFPA fire department experience survey.

Figure 12. Parking garage fire statistics in the United States from 2014-2018 (Ahrens, 2020).

Fires in or at Commercial, General Vehicle or Fleet Parking Garages
2017–2021 Estimated Annual Averages

Incident Type	Fires		Civilian Deaths		Civilian Injuries		Direct Property Damage (in Millions)	
Structure Fire	620	(33%)	0	(0%)	9	(45%)	$15.8	(62%)
Vehicle Fire	730	(39%)	0	(0%)	10	(46%)	$8.9	(35%)
Outside or Unclassified Fire	530	(28%)	0	(100%)	2	(9%)	$0.9	(4%)
Total	1,880	(100%)	0	(100%)	21	(100%)	$25.6	(100%)

These are national estimates of fires reported to US municipal fire departments and so exclude fires reported only to Federal or state agencies or industrial fire brigades. Fires are rounded to nearest ten. Civilian deaths and injuries are estimated to the nearest one and direct property damage has been estimated to the nearest million dollars. Totals may not equal sums due to rounding errors.

Source: NFIRS 5.0 and NFPA fire experience survey.

Figure 13. Parking garage fire statistics in the United States from 2017-2021 (NFPA Research, 2023).

As can be seen in the statistics, the number of fires in parking garages, deaths, and injuries has remained consistent between the two time periods. The total direct property damage has risen slightly (~13%), though that may simply be a result of the time value of money (i.e., inflation). The total direct property damage initially seemed low, but $25.6 million dollars over 1,880 fires is an average of approximately $13,600 dollars per loss. This seems reasonable considering that it is likely that many of these losses are damage to a single vehicle, often perhaps just a small portion of the vehicle, with no corresponding damage to the parking structure itself. Conversely, some of these fires surely damaged more than one vehicle and caused some damage to the parking structure. Nevertheless, while the overall damage value initially seemed low, the number is reasonable given that, unlike some other international incidents, no major fires in parking structures have occurred in the United States during the time-period of evaluation.

The consistency in the statistics, particularly the property damage valuation and number of fires, is not surprising. As is described in other sections of this report, by 2021, new code provisions were just being released, implemented, and enforced. Therefore, it would not be expected that a significant portion of parking garages in the United States would be designed with sprinkler systems when they had not been 3 to 4 years previously. As an additional consideration, the statistics on parking garage fires, particularly the direct property damage, are likely driven by outliers in the data. In other words, fires in parking garages are often extinguished by Fire Departments with the fire confined to a single vehicle or perhaps only minimally spreading to other vehicles. There are known incidents in other countries, though, where the fire grew out of control into a conflagration, such as at the Stavanger airport, Liverpool parking garage, and Luton airport fires, where hundreds to thousands of automobiles were damaged or destroyed, and the parking garage itself either collapsed or was rendered unusable. In these cases, the parking garage was reportedly densely packed with vehicles, which likely contributed to vehicle-to-vehicle spread.

If one assumes 1000 cars are no longer salvageable and that the parking structure is no longer useable, it is obvious that the property damage is significant. In other words, the overall statistics have not changed much since 2018, but this is likely because the United States still has not had a catastrophic event as has occurred in some other countries. If one did occur in the United States, the monetary property damage statistic would likely rise considerably. One notable incident that has occurred in the United States is the Kings Plaza fire in Brooklyn, New York [16]. This fire ultimately damaged over 100 vehicles and resulted in 25 injuries, most of them Fire Department personnel. The parking garage was un-sprinklered. While this fire had a significant number of injuries and considerable property damage, since it occurred in 2018, it is captured in both ranges of data above. Additionally, this fire was initially an incendiary fire, reportedly ignited in the passenger compartment. Apparently only one vehicle was initially ignited, and rest were the result of vehicle-to-vehicle fire spread. The incendiary nature of the initial vehicle fire, though, may have played some role in the fire spreading to other vehicles quickly before the Fire Department could control and ultimately extinguish the fire.

Specific Incident Review

As indicated above, the general statistical data on vehicle fires in parking garages is indicating no change in the prevalence and magnitude of parking garage fires in the United States. Nevertheless, the statistics from the NFIRS data are very general and some of the more salient details on the drivers of modern vehicle fires in parking garages are not immediately apparent. Therefore, several specific case studies were more closely considered. The specific considered case studies were selected by attempting to gather a grouping of fires that occurred in both sprinklered and unsprinklered garages, as well as at least one more major fire that has occurred since the Phase I report. It should be noted that an effort was undertaken to identify an automated garage/stacker system fire incident for analysis, given that these systems appear to be increasing in use and may present differing hazards and concerns than standard parking garages. No such fire incident was found, which is in agreement with a similar search by RISE which did not identify public information on such an incident either in Norway or internationally [17].

Incident 1: Merriweather District, Columbia, Maryland, United States

In the early evening of June 23, 2022, a fire occurred in a parking garage in Columbia, Maryland on Symphony Woods Road. The parking garage serves a concert venue, Merriweather Post Pavilion, and nearby restaurants and apartments. This particular incident was selected for examination due to the close proximity to CSE's headquarters, thereby allowing a visit to the fire scene. CSE staff had no role in any events related to this fire, nor its suppression or subsequent investigation. Response to the fire was undertaken by the Howard County Fire and Rescue Services (HCDFRS) and the investigation was undertaken by the Office of the Fire Marshal, Fire Investigation Division, a department of HCDFRS. The fire investigation report was obtained as an electronic PDF file, which included small color photographs of the scene (i.e., not native photograph file formats). Most details discussed herein are from said fire investigation report. Additionally, photographs were taken during two post-fire visits by CSE staff to the parking garage after remediation and clean up from the fire.

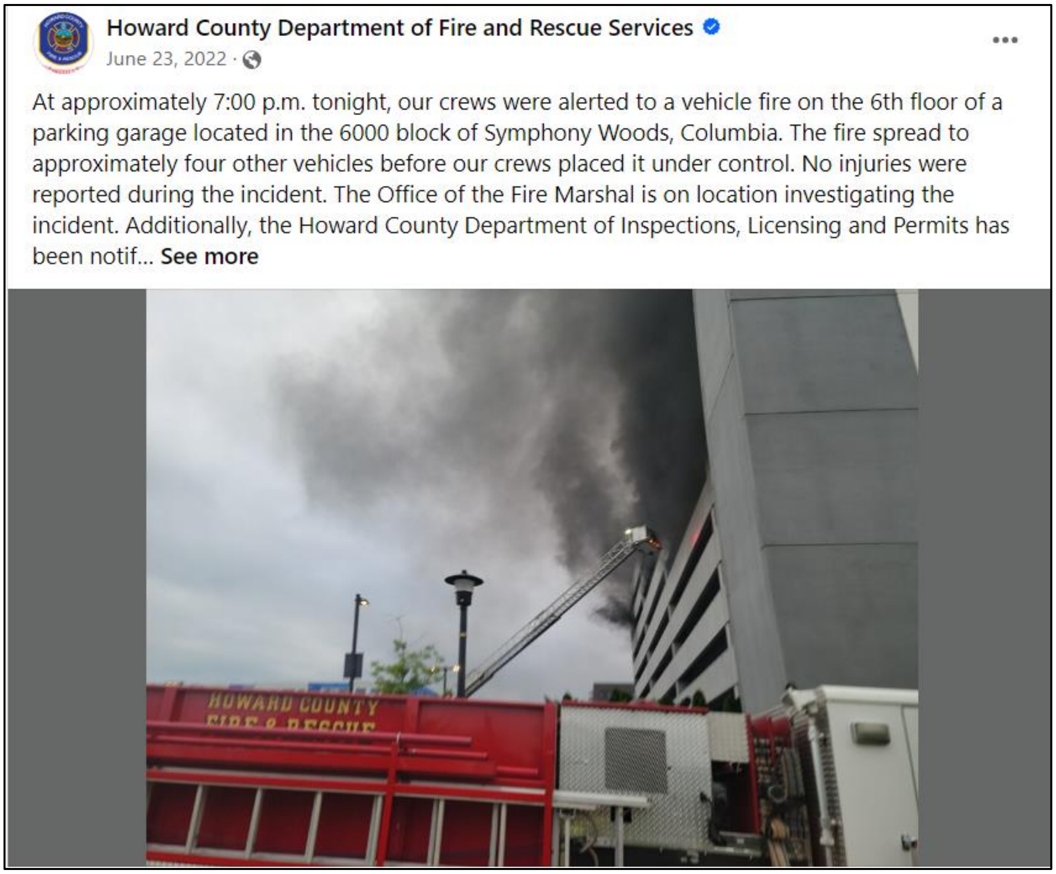

Figure 14. Facebook post from Howard County Fire and Rescue Services showing the fire at the parking garage near Merriweather Post Pavilion.

The fire took place on the sixth floor of the parking structure. The parking structure was unsprinklered, but did have standpipes. Upon arrival to the fire, HCDFRS found multiple vehicles involved in the fire and extinguished it with “a handline and additional crews” “without incident.” It was discovered that eight (8) vehicles sustained fire-related damage during the incident, with two vehicles showing the most significant damage that was attributed to one or the other of the vehicles being the area of origin. The vehicles were both GMC Yukons, with vehicle #1 being a green 2003 version and vehicle #2 being a black 2015 XL version. Both Yukons were ICE vehicles, as were the other vehicles involved based on the lack of mention of any of the vehicles being alternative-fuel or electric vehicles. The other six (6) fire-damaged vehicles along with the two (2) vehicles in the area of origin are listed in Table 2. Additionally, the approximate locations of the vehicles are shown as Figure 15. For consideration of the vehicle spacing and fuel available, five (5) of the vehicles, including the possible origin vehicles, were SUVs, while two of the vehicles were smaller sedans, with one vehicle likely larger than a sedan but smaller than an SUV (vehicle #8).

There were no deaths or injuries resulting from this fire, and the fire report estimated vehicle damage at $70,000 and the structural damage to the parking facility at $100,000. Among the materials provided to CSE was a short video of the fire which was made by one of the owners of one of the vehicles (vehicle #4). The video shows a fire in the front of vehicle #1/rear of vehicle #2, which had not yet spread to vehicle #4.

Vehicle #	Make	Model	Year
1	GMC	Yukon	2003
2	GMC	Yukon XL	2015
3	Nissan	Pathfinder	2008
4	Nissan	Pathfinder	2015
5	Chrysler	Aspen	2007
6	Toyota	Camry	2018
7	Nissan	Maxima	2012
8	Honda	Crosstour	2013

Table 2. Vehicles involved in the parking garage fire near Merriweather Post Pavilion, Columbia, MD USA.

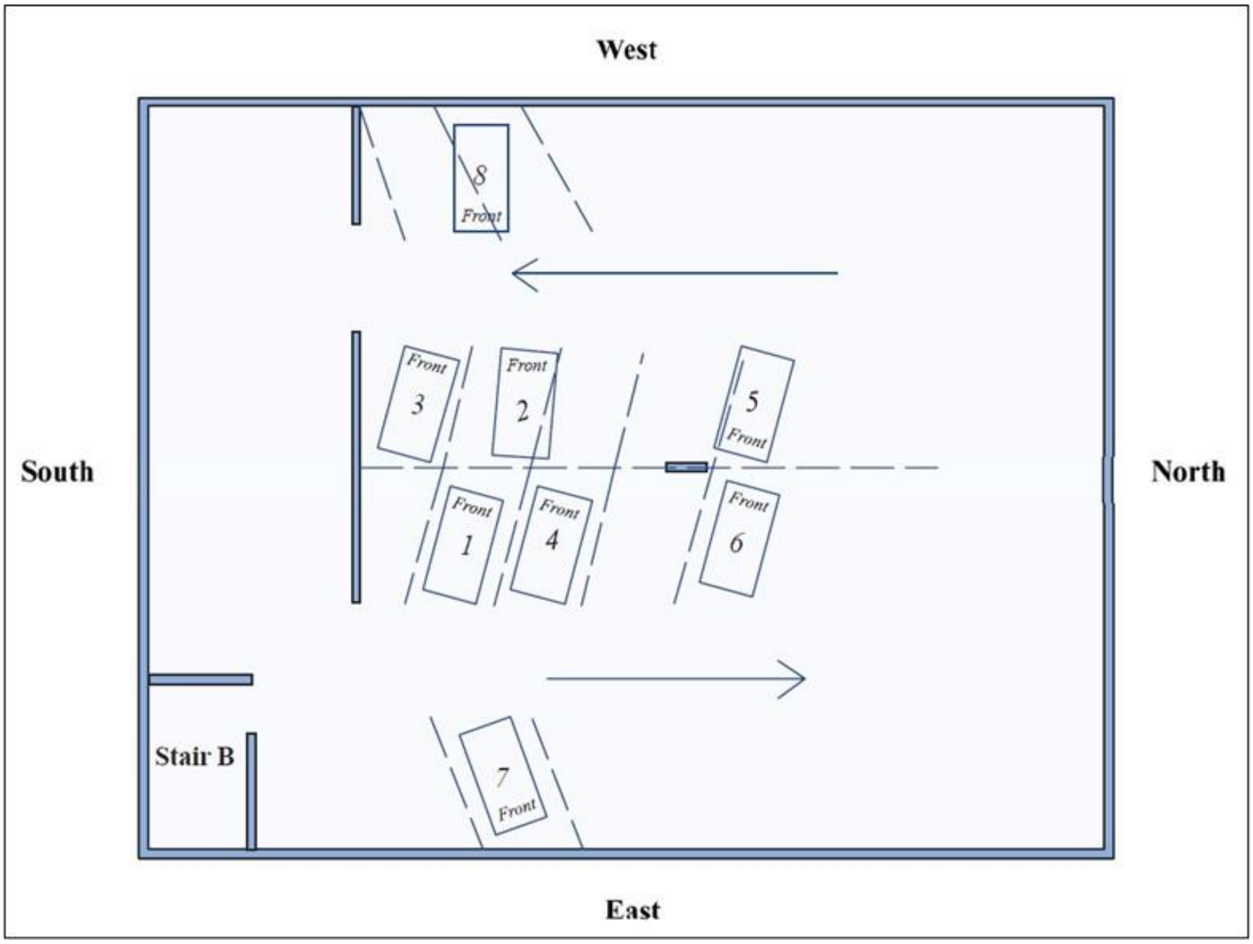

Figure 15. Vehicle locations (not to scale) during the fire. Refer to Table 2 for information about each numbered vehicle. Source (HCDFRS Investigative Report).

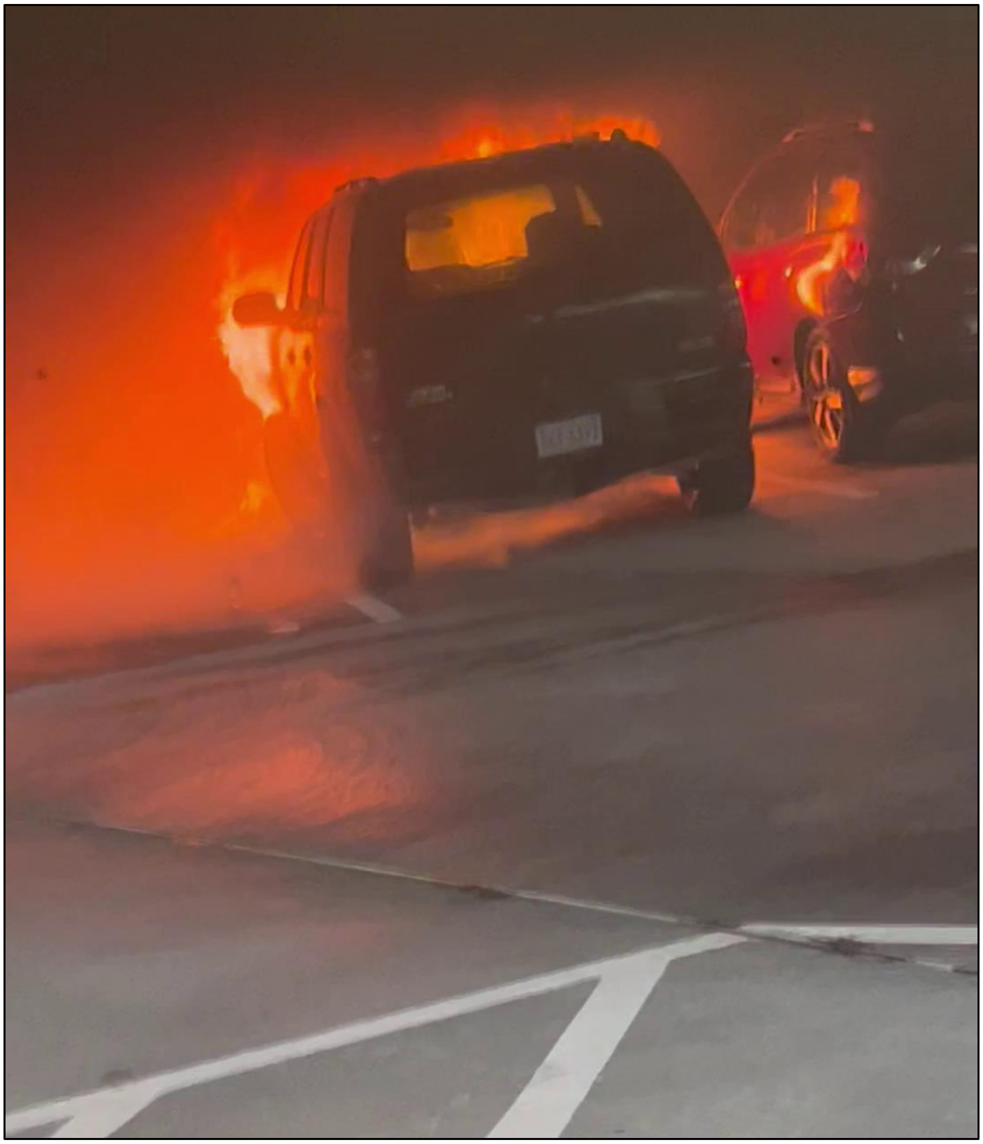

Figure 16. Snapshot from video footage taken by vehicle owner. Source (HCDFRS materials).

Upon subsequent visits to the fire scene, it was discovered that the HCDFRS diagram had a few inconsistencies with what was observed on the scene, mostly related to locations of the parking space lines. During one of the visits, the parking garage at the location of the fire was diagrammed with dimensions by CSE. This diagram of the parking space locations and dimensions can be found as Figure 17.

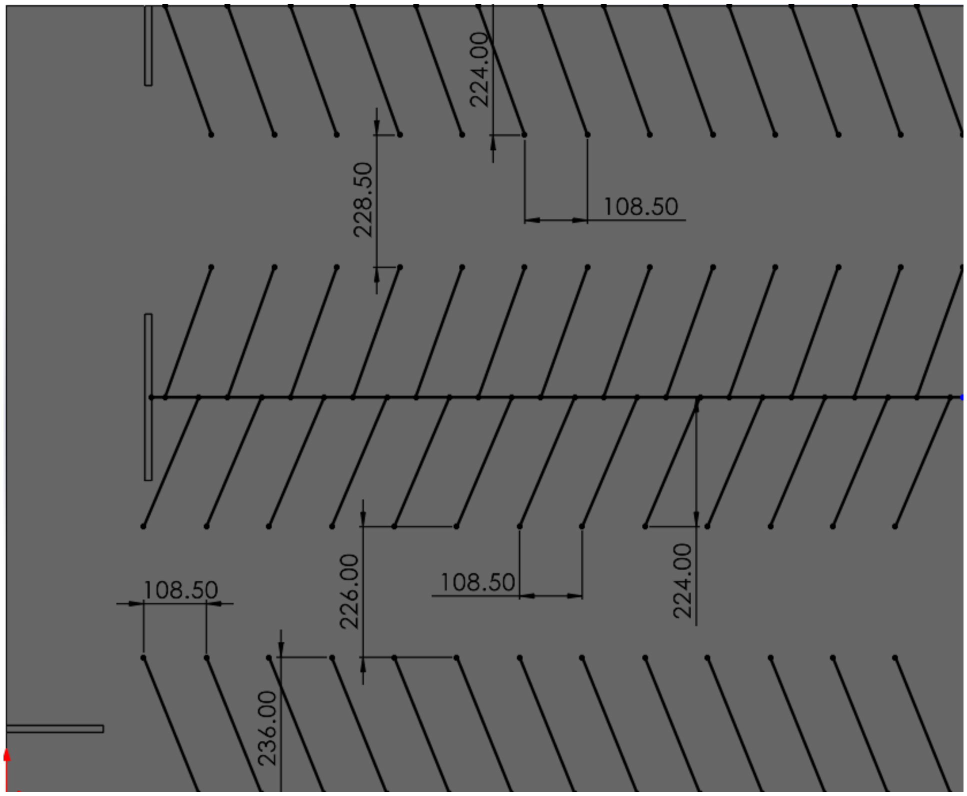

Figure 17. Scale diagram of Merriweather parking garage in the location of the fire with parking space dimensions (in inches). Source (CSE site visit).

As mentioned, the physical evidence indicated that the fire originated either in vehicle #1 or vehicle #2. Specifically, the front of vehicle #1 or the rear of vehicle #2. Witness testimony indicates that vehicle #1 was potentially seen by a bystander issuing smoke. Based on this information, the HCDFRS investigator indicated the most likely origin of the fire was the engine compartment of vehicle #1, but could not rule out the rear of vehicle #2 and therefore described the fire origin as undermined.

The parking garage was of the "open" type and presumably was built before fire codes required sprinkler systems in open-type garages. The fire was able to spread from whichever vehicle (#1 or #2) was the originating vehicle to the other. A photograph of vehicle #1 is shown as Figure 18. The vehicle immediately next to vehicle #1 (vehicle #4) also had substantial heat and fire damage and appeared to be significantly if not completely consumed. The interior of vehicle #4 is shown as Figure 19. As the distance increased from the originating vehicle(s), the damage began to lessen. Vehicle #6, which was separated from vehicle #4 by an additional empty space, showed melting damage to the side of the vehicle, as seen in Figure 20. Vehicle #7, which was across the aisle from vehicle #1, was also beginning to show some melting damage to the components on the rear of the automobile, specifically the taillight as mentioned in the HCDFRS report. A photo is included as Figure 21.

Figure 18. Fire-related damage to the interior of Vehicle #1 (source: HCDFRS photo IMG_0236.JPG)

Figure 19. Fire-related damage to the interior of Vehicle #4 (source: HCDFRS photo IMG_0114.JPG)

Figure 20. Vehicle #6 fire-related damage (source: HCDFRS photo IMG_0049.JPG)

Figure 21. Vehicle #7 fire-related damage (source: HCDFRS photo IMG_0141.JPG)

As can be seen in Figure 17, the width projection of the parking spaces in this area is approximately 9 feet 0.5 inches (2.76m). From other dimensions, the angle of the parking spaces was calculated as 67°. Referring to Figure 3, for a space with an angle between 65° and 70°, the minimum level of comfort width projection is between 8’9” (2.67 m) and 9’1” (2.77 m) and the maximum level of comfort width projection is between 9’7” (2.92 m) and 9’11” (3.02 m). This indicates that the parking spaces in this garage are within the recommended width projections based on the design vehicle, but are on the tight side with a minimum level of comfort. Therefore, this results in a relatively worst-case scenario for car to car spread for cars in adjacent spaces. As mentioned above, damage was sustained on an automobile separated by one empty space (vehicle #6). Additionally, damage was also incurred on an automobile at least 18’10” (5.74 m) away (vehicle #7), which is the equivalent of at least two empty spaces away. This behavior is consistent with the testing by BRE [18], where a fire was able to skip over an empty parking spot to ignite a vehicle after more than one vehicle was already burning. This indicates that while the spaces in this garage were on the relatively small end of the recommended range, the fire was indeed capable of spreading and was beginning to damage automobiles significantly further away than the largest recommended parking space size. The fire likely would have continued to spread to multiple vehicles and likely would have still damaged vehicles even further than one space away, possibly igniting them had the incident continued without Fire Department intervention.

The beginning of some spalling on the ceiling of level 6 was also mentioned in the HCDFRS report and some photos were included in the report. The initial spalling was still present when CSE visited the site several months later (06/2023), as can be seen in Figure 22, and some remediation had taken place when CSE re-visited the site in January, 2024, as seen in Figure 23.

Figure 22. Spalling on the upper portion of level 6 in the parking garage near Merriweather Post Pavilion. (source: CSE post-fire site visit – 06/2023)

Figure 23. Remediated spalling on the upper portion of level 6 in the parking garage near Merriweather Post Pavilion. (source: CSE post-fire site visit – 01/2024)

This case study appears to exemplify the scenario of concern in the Phase I report [1]. In an existing open garage, which was not required to have sprinklers per NFPA 88A or other codes and standards since it was built before the inclusion of sprinkler requirements for open garages, a fire ignited and grew in the origin vehicle and additionally spread to multiple other vehicles before Fire Department arrival and extinguishment. Coincidentally, a Fire Department station is at the same address as the parking garage and per the report arrived 3 minutes after being dispatched; ergo, the Fire Department arrived relatively quickly in this incident. Additionally, based on the video footage, there was a vehicle owner with a phone in the garage before the fire had spread beyond vehicles #1 and #2, yet by the time control and extinguishment of the fire occurred, vehicle #4 was almost completely consumed. It is possible the fire would have continued to have spread further had it burned for a longer duration. Indeed, it was already beginning to heat and melt fuels across open parking spaces and aisles. This behavior is consistent with that identified in the BRE testing [18] where the fire was able to spread across an empty space to additional automobiles. The spacing of the vehicles (Figure 15) indicates that this level was not fully filled with vehicles, and vehicle-to-vehicle fire spread may have been more significant had more vehicles been present. Additionally, it was beginning to spall the concrete above the fire area. It is unclear how many other automobiles were present on this level of the parking garage or nearby beyond those shown in Figure 15, but the spreading of fire to multiple cars and the spalling of the concrete indicates that had the Fire Department not arrived quickly and successfully extinguished the fire, further spread was likely involving more vehicles and potentially structurally compromising the garage.

Combustion Science & Engineering, Inc.

Incident 2: Luton Airport, London, United Kingdom

On October 10, 2023, a fire occurred in a parking garage at the Luton Airport in London, United Kingdom. The fire spread significantly and ultimately resulted in a significant structural collapse of the parking garage. Ultimately, over 1000 vehicles were damaged or destroyed in the fire, either due to the fire or due to the structural collapse. The parking garage was unsprinklered and was of the open-type construction. In addition to the sheer magnitude of the property damage, the airport itself had to restrict some flights on the day of the fire, resulting in considerable disruptions for passengers and airlines. This likely added considerable monetary damages (unspecified at this time) to the already extremely large direct property losses.

According to a news article [19], the fire started on level 3 of the parking garage. Initial reporting has indicated that the fire originated in a diesel-powered vehicle, possibly a Range Rover. There was an arrest following this incident, but news reports indicate that it is believed the arrest is just a precaution and that the initiation of the fire is believed to be accidental. It is unclear if the individual that was arrested is the owner of the initiating vehicle. A photo of the fire well after its ignition showing considerable fire involvement of an entire level of the parking garage is shown as Figure 24.

Figure 24. Luton airport parking garage fire (source: ITV News [20])

Video footage [19] presumably taken by a bystander shows the fire in its early stages with only a single car involved. It is assumed this is the diesel Range Rover. A snapshot of this video is shown as Figure 25. One initial observation from the video is that it appears that there was not a vehicle parked immediately next to the originating vehicle. This cannot be said for certain given the quality of the video and the angle it was taken from, but it appears that the nearest vehicle or secondary fuels are approximately a vehicle width away. This preliminarily analysis indicates that there does not have to be a vehicle immediately next to an originating vehicle in order for the fire to spread. This behavior was noted in the Merriweather parking garage analysis also. Additionally, in the testing by BRE [18], a fire was able to skip over an empty parking spot, but this was after more than one vehicle was already burning. Preliminarily, this may indicate that the fire was able to jump approximately the width of a parking space to the next vehicle just from the first vehicle. This would indicate that mitigation efforts based on simply spreading out vehicles may not be adequate to stop the fire spread.

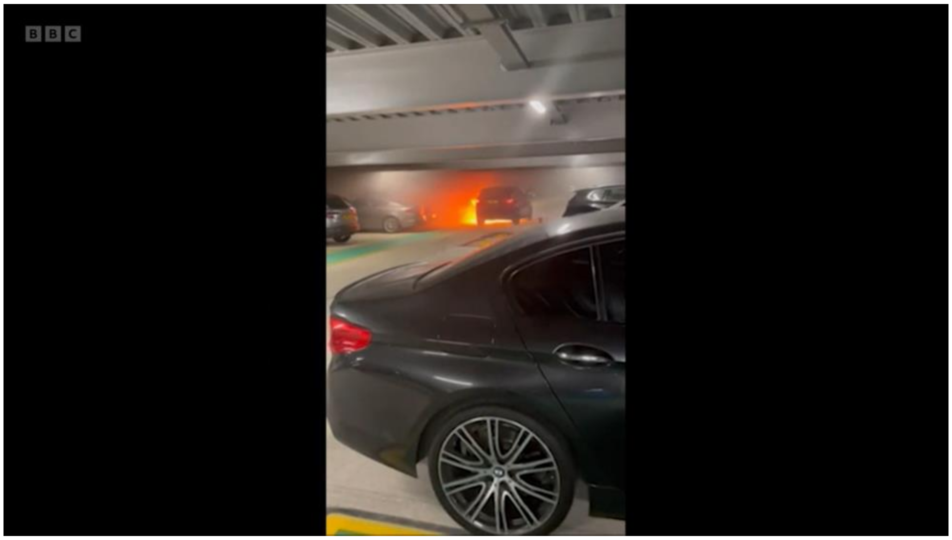

Figure 25. Snapshot of video from Luton Airport fire (source: BBC [19])

A review of photographs of the Luton airport parking garage preliminarily indicate that it was primarily a metal structure. It is unknown how it was structurally protected from fire, if at all, but it is possible that the structural design of the parking garage was contributory to why it collapsed. For comparison, the Liverpool parking garage that sustained a major incident was designed with reinforced concrete columns and beams [21] and only had localized structural failures, though it was considered a total loss and had to be torn down and rebuilt. The Stavanger airport parking garage fire, another major incident, was built in three stages, with the concrete structure portion only damaged while the steel structure portion collapsed [22]. As will be discussed later in this report, a concrete structure would be classified by NFPA 220 as Type I, with a steel-only structure classified as Type II, with a lower fire resistance rating. The number of incidents of major parking garage fires that did or did not result in collapse is relatively small and therefore sweeping conclusions should not be drawn, but the available data on these incidents does potentially indicate that the specific structural design of the parking garage, and specifically whether the metal is reinforced by concrete in the design, may have an impact on whether a significant parking garage fire can proceed further to a structural collapse. Additionally, it is unknown whether such a collapse meaningfully increases the direct property damage if the fire had already proceeded to such a large event that all vehicles are already lost and the entire structure will have to be rebuilt. Certainly, though, preventing collapse could provide safer conditions for Fire Department personnel who ultimately are tasked with suppressing these very large events.

It is expected that in the future more information will become available regarding this fire at the Luton Airport. There will likely be public sector investigative reports and photographs. In fact, this fire was significant enough that it may lead to technical papers, reports, and presentations in the fire protection industry regarding the origin and cause of the fire, as well as lessons learned. Despite the lack of definitive information regarding this fire at this time, it was included in the case studies herein because of the sheer magnitude of the fire, and the similarities it has with the parking structure fires at Liverpool and Stavanger airport., The incident at Stavanger also involved the disruption of air traffic at the airport and a partial collapse of the parking structure. As mentioned above in the general statistics, these large, outlier events are the ones that can significantly change the losses involved in parking garage fires, and are the ones that tend to shape public perception regarding parking garage fires. This clearly was a very large loss and demonstrates how a single fire incident is capable of significantly changing the annual property loss statistics if it involves damages to a large number of the vehicles and/or causes structural collapse.

Two additional related issues have been identified from this fire. The first is that a movement on social media emerged that blamed this fire on an EV [23]. As mentioned previously, per news articles quoting Fire Department officials, this fire likely started in a diesel-powered vehicle, not an EV. The car chargers the airport offered for EVs were in a different parking garage altogether [23]. Nevertheless, it demonstrates that the public may have the perception that EVs are a more dangerous type of vehicle from a fire perspective than traditional ICE vehicles. Some of the public perception may be related to the fact that the EV fires are often more difficult to extinguish. In this case, though, it is likely that many of the vehicles that burned were ICEs and many were EVs. This affirms the conclusion in the 2020 FPRF report [1] that while fires in EVs and ICEs can have different features related to their ignition, burning characteristics, and suppression, both contain a significant amount of combustibles, particularly plastics, and therefore are capable of spreading fire from a single car to a very large multi-car fire such as that at the Luton Airport. This perception of the public likely needs to be monitored by the fire protection industry to ensure that efforts to mitigate the risks related to vehicle fires in parking garages is not focused only to EVs.

A second related issue that has formed out of this fire is a potential renewed push for sprinklers in parking garages in the UK. The British Automatic Fire Sprinkler Association (BAFSA) issued a detailed statement after the fire indicating that parking garages are currently not required to have sprinkler systems and that said lack of a requirement should be revisited given the increase in plastics in automobiles [24]. Therefore, it may be that this fire, along with the Liverpool fire in the UK in 2017, may drive a requirement for sprinklers in UK parking garages in the future. If a push is made for parking garage sprinkler systems in the UK, they will likely also have to consider the economics of such a requirement. This cost/benefit analysis was addressed recently by Alimzhanova et al. [25].

Incident 3: Marienplatz, Ravensburg, Germany

In a European Fire Sprinkler Network (EFSN) position paper on sprinklers in parking garages containing electric vehicles [26], a fire is cited that involved an EV that was charging in an underground parking garage in Marienplatz, Ravensburg, Germany. The position paper mentions that the originating car was charging and caught fire and despite the presence of a sprinkler system, the fire damaged three other vehicles. A news source [27] was quoted as the source for some of the information. This news source was reviewed, along with a Facebook post by the Ravensburg Fire Department [28] and a few limited photographs from the Fire Department.

The Fire Department Facebook post indicated that the automatic fire alarm system activated as did the sprinkler system. The post indicated that upon arrival, due to the smoke, the Fire Department had to utilize breathing apparatuses in order to approach the vehicle and extinguish the fire. The post also seemed to confirm that the originating vehicle was charging at the time of the fire. Additionally, the news article indicated that the originating vehicle was a Volkswagen ID.4. A photograph of the originating vehicle and fire scene is shown as Figure 26.

A magnified view of the photograph can be seen as Figure 27, with annotations added to show the charging cable (orange arrow) and sprinkler location (green arrow).

Figure 26. Marienplatz parking garage originating vehicle and surrounding fire scene. (Source: Feuerwehr Ravensburg)

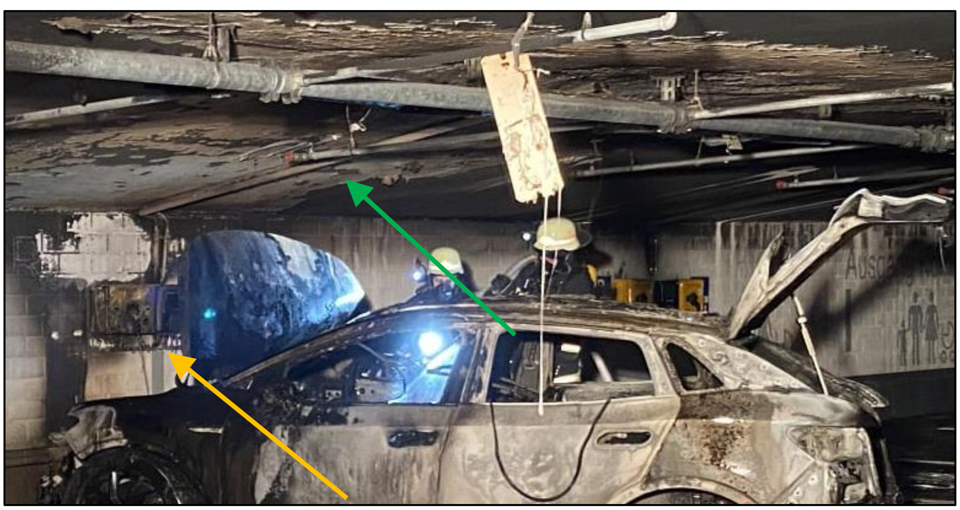

Figure 27. Magnified view of photograph of Marienplatz parking garage originating vehicle and surrounding fire scene. (Source: Feuerwehr Ravensburg). Annotations added by authors.

As can be seen in Figure 27, the sprinkler was positioned over the originating vehicle. It is unclear whether this is optimal or near-optimal sprinkler placement or not. Nevertheless, with a sprinkler directly above the originating vehicle, the originating vehicle appears to have been nearly fully consumed (see Figure 28), though some tire material and perhaps other remnants remain. Unfortunately, the other surrounding vehicles are not included in the photographs to allow for assessment of the extent of the damage. There is considerable spalling on the ceiling of the garage. It appears to be mostly over the originating vehicle, indicating that the other damaged vehicles were probably only heat damaged and did not actually ignite themselves. The spalling, which is visible in Figure 26, indicates that even with a sprinkler system present, damage to the concrete structure is possible. In sum, this incident does highlight that damage to more than one vehicle as well as damage to the parking garage structure can occur even with a functioning sprinkler system.

Regarding the sprinkler system, the EFSN position paper [26] indicates that the sprinkler system for this parking garage would have been designed in accordance with VdS CEA 4001, which applies “the same OH2 criteria as EN 12845, i.e. an application density of 5 mm/min over 144 m^2 for wet systems”. This density relates to something between light (4.1/140 mm/min/m^2) and OH1 (6.1/140 mm/min/m^2) in accordance with NFPA 13 [2022 edition] [29]. Therefore, with a sprinkler system that provides less water than that required in the United States, both prior to and after the latest changes to NFPA 13, a fire in an EV and charger was controlled until ultimate extinguishment by the Fire Department. This can be considered successful sprinkler system performance. In this case, while it appears that the sprinkler prevented fire spread or certainly significant fire spread beyond the first vehicle, the originating vehicle did burn nearly to completion with a sprinkler positioned directly above it. This behavior is in concurrence with several testing reports in the literature where, despite sprinkler activation, the originating vehicle continued to burn to completion, but further significant fire spread was successfully prevented. The originating vehicle may have continued to burn due to the shielding of the fire from the sprinkler system. It is unknown if a higher sprinkler density would have fully extinguished the fire in the originating vehicle. Conversely, it is unknown if a sprinkler in a different location relative to the origin vehicle would have continued to prevent fire spread to additional vehicles. A further consideration from this case study is that even with a functioning sprinkler system, a fire in a car can do significant damage to the structure and nearby vehicles, even if it does not ignite them.

Incident 4: Des Plaines, Illinois, United States

On July 13, 2023, a fire occurred in a parking garage on the ground floor of a 6-story apartment building in Des Plaines, Illinois. A news story for the fire [30] provided details of the incident and a corresponding Fire Department report and investigative materials including photos were obtained via a Freedom of Information Act request [31]. The vehicle was in the corner of the parking garage. Ultimately, the fire only involved the origin vehicle, which was a 2011 Lexus RX450h. The Lexus RX450h is hybrid ICE/EV vehicle. The garage would be considered an enclosed parking garage and it contained a sprinkler system. A post-fire photo of the origin vehicle is shown as Figure 29.

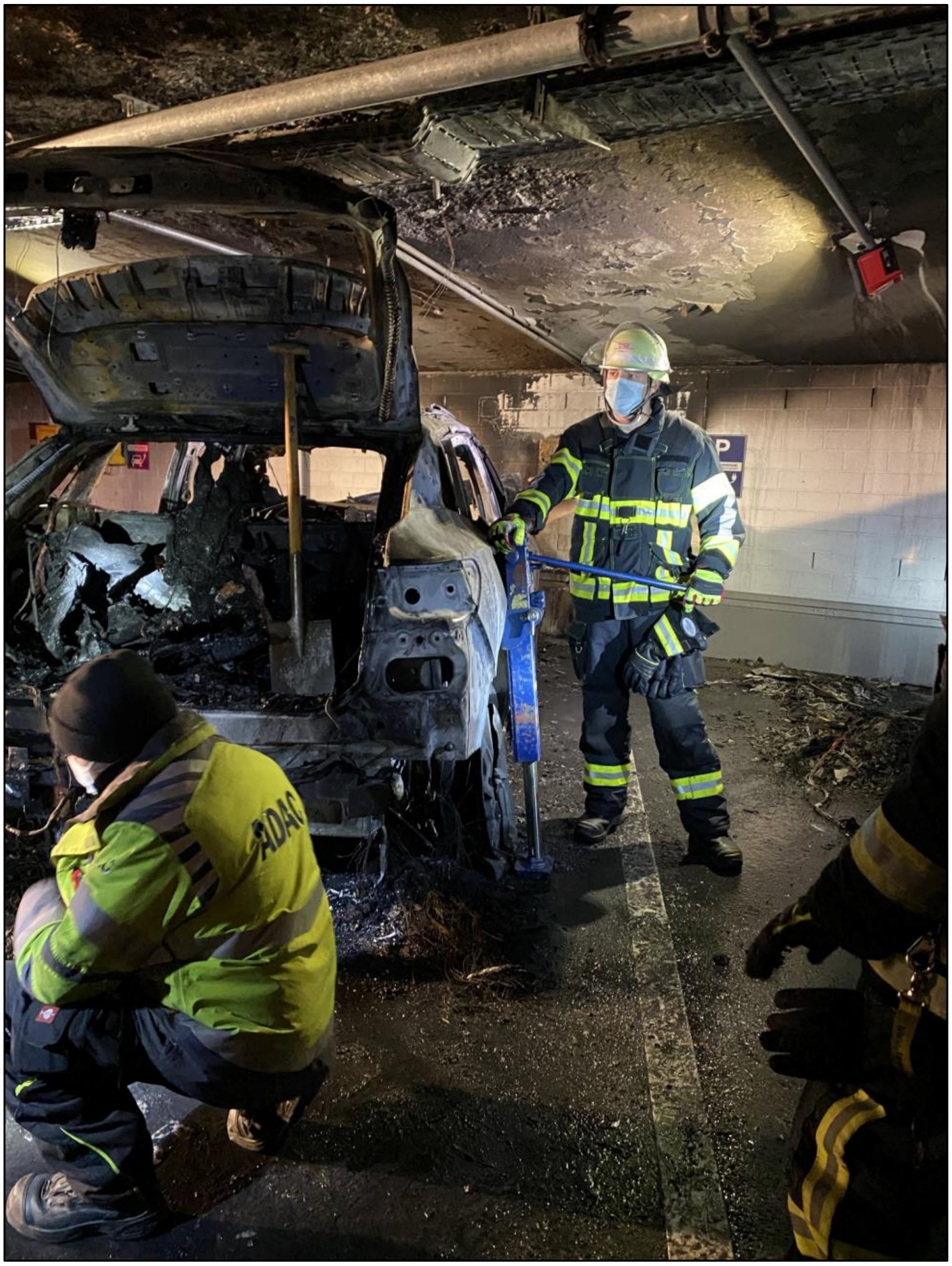

Figure 28. Marienplatz parking garage originating vehicle. (Source: Feuerwehr Ravensburg)

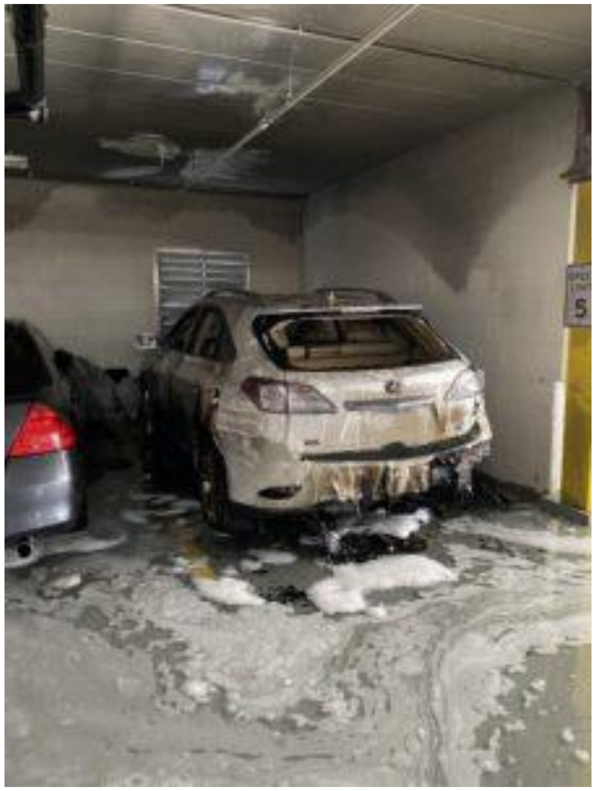

Figure 29. Des Plaines, Illinois parking garage fire (source: Festenstein, 2023 cross-referenced to Des Plaines Fire Department)

Per the NFIRS report, the Fire Department was first dispatched at 8:17 am and the first arriving units arrived at 8:21 am. The Fire Department had trouble accessing the parking garage due to a non-functioning overhead door. Upon entry, they encountered little to no visibility due to the smoke in the garage. Ultimately, they found the burning vehicle and observed heaviest burning underneath the vehicle on the driver's side and rear of the vehicle. The Fire Department suppressed the fire, and noted that re-ignition occurred multiple times after stopping water application. Ultimately, the Fire Department used a hydraulic tool to open the hood of the car and extinguished an engine compartment fire at which point the fire did not re-ignite. Investigation after the fire indicated that the fire damage was heaviest in the engine compartment and at the rear bumper. The fire did not spread to the passenger compartment, as seen in Figure 30. Interviews with the property manager by Fire Department investigative personnel indicated that this vehicle may have leaked liquid fuel at some point in the days or weeks prior to the fire. This liquid fuel was reportedly cleaned up, but this behavior may indicate a preexisting issue with the vehicle.

Figure 30. Interior passenger compartment of origin vehicle in Des Plaines, Illinois parking garage fire (source: Des Plaines Fire Department)

The parking garage had a sprinkler system, presumably designed to the OH1 design density as this was an enclosed parking garage. The sprinkler system activated, with the fire report indicating one head activated while the news article indicated two heads activated. Photographs of the incident (see Figure 29) indicate that at least one activated sprinkler head was immediately above the vehicle and hence was well-placed for activation and water delivery. The parking garage also reportedly had an alarm system. It is unclear if the alarm system included automatic fire detection or only sprinkler flow monitoring. It is also unclear if the fire alarm system resulted in automatic notification of the Fire Department or notification of the building occupants in the apartments above.

In this case, the sprinkler system controlled the fire until Fire Department intervention. Whether it was one sprinkler head or two, while the fire appears to have been shielded and not extinguished by the sprinkler system, the fire had not involved the passenger compartment where a significant amount of additional fuel would have been available. The fire also did not spread to the neighboring vehicle, which appears to be only 2-3 feet away (see Figure 29). This certainly is indicative of a successful sprinkler intervention in the fire by limiting the amount of fuel involved and preventing vehicle-to-vehicle fire spread, despite the presence of both a lithium-ion battery and liquid gasoline. This successful performance would be attributable to an OH1 designed system, though with only one or two sprinklers activating, more water was likely delivered than the OH1 design density since the whole design remote area of sprinklers was likely not activated. Additionally, photographs of the fire scene do not seem to support any significant spalling or other structural issues after the fire. In fact, it appears only to be some minor heat damage and perhaps scorched paint on the ceiling, as shown in Figure 31.

Figure 31. Ceiling above origin vehicle in Des Plaines, Illinois parking garage fire (source: Des Plaines Fire Department).

Despite the performance of the sprinkler system being considered a success, there were still some concerning aspects to this fire. First, the sprinkler system was unable to fully extinguish the fire. While total extinguishment of the fire is not the primary purpose of a sprinkler system, fire control is expected. In fact, the Des Plaines, Illinois Fire Prevention Division fire records indicate that the Fire Department initially were "having trouble getting the fire controlled due to no visibility." The fire records also note that the fire would "continually re-ignite after water was no longer applied." It is unclear if the re-ignitions were related to the presence of a lithium-ion battery in the hybrid vehicle. Additionally, photographs of the fire (for example, see Figure 29) seem to show some foam in the water. The use of foam by the Fire Department was not mentioned, but it is possible that further action by the Fire Department beyond than simply applying water was necessary to finally achieve suppression. As a hybrid vehicle was involved, the Fire Department may have decided to apply foam if they felt liquid fuel from the gas tank was involved. It certainly warrants consideration that had the Fire Department not intervened quickly and possibly with foam would the fire would have eventually spread into the passenger compartment and to other neighboring vehicles under a different timeline, for instance involving a slower Fire Department response. It also highlights the possibility that even with successful sprinkler intervention that controls the fire and prevents spread to neighboring vehicles, complete extinguishment by the Fire Department can be difficult.

Of additional concern in this fire is that smoke from the fire complicated the fire event considerably. First, the Fire Department has indicated that the enclosed garage configuration caused significant visibility issues due to smoke buildup which made identifying the burning vehicle and ultimately suppressing it difficult. Further, though, while the actual configuration of the stairwells (i.e., pressurization) and remainder of the building is unknown, the fire report indicates that smoke did penetrate the building stairwells, vestibule, and was present in light quantities on multiple floors of apartments above the parking garage. Fire Department personnel did still find some residents inside the building. Some of the residents were instructed to shelter in place due to the smoke in the stairwells. Additionally, at least two residents were evaluated for smoke inhalation and at least one of them had to be transported to the hospital for further evaluation [30]. Hence, even when a sprinkler activates and controls the fire, there is the possibility of dangerous conditions in configurations such as podium/pedestal construction where the parking garage is on a lower level and there are occupied areas, often residential, in the upper levels. General statistics, though, have not indicated a significant injury or death issue with parking garage fires to date. In 2017-2021, no deaths occurred in parking garage fires in the United States. Additionally, if evenly distributed, an injury only occurred in 1.1% of parking garage fires. It is possible some injuries in these situations are not captured by the statistics for parking garage fires if the injury occurred in the residential section, not the parking garage section. Nevertheless, this configuration of a parking garage under a residential structure is likely one of the life safety areas of concern, and led to possible injuries in this fire.

In conclusion, this fire resulted in a presumed OH1 sprinkler system controlling a vehicle fire in a parking garage, including preventing involvement of the passenger compartment and also preventing vehicle-to-vehicle spread. The fire, though, was still capable of creating challenging smoke conditions that hampered Fire Department final extinguishment efforts, and ultimately caused possible injuries and life safety concerns for residents in the apartments above.

Incident 5: Towson, Maryland, United States

On the evening of March 22, 2023, a fire incident occurred in a parking garage in Towson, Maryland. This parking garage has multiple levels under a multiple story residential apartment complex. A view of the location of the fire is shown as Figure 32.

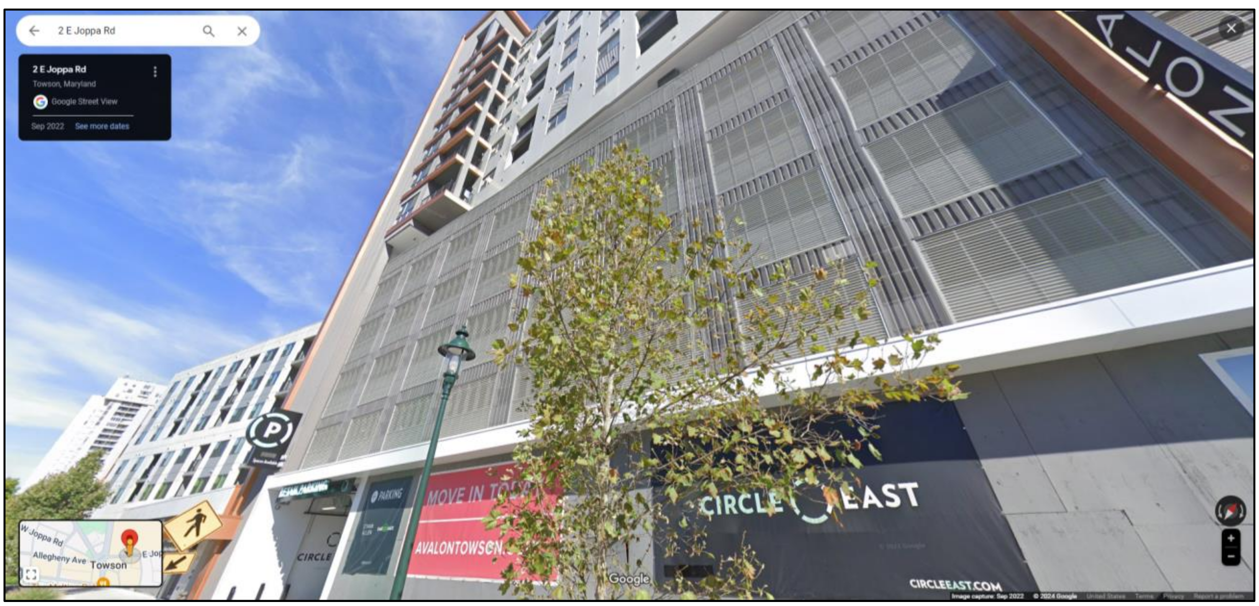

Figure 32. Parking garage location in Towson, Maryland (source: Google maps).

Incident details were obtained from a Police report (Baltimore County Police Department, 2023) and Fire Department NFIRS report [32]. No photographs were included in response to a Freedom of Information Act request. In this incident, a Police Officer was doing a foot patrol in and around the location when they encountered an individual who indicated that something was wrong with their vehicle, which was running at the time. The vehicle was a 2011 BMW X5. While the current X5 model is an EV, in 2011, the X5 was a diesel-powered ICE vehicle. The officer found light smoke in the passenger compartment and ultimately tracked it to the hatchback area in the rear of the vehicle and observed yellowish smoke coming from a small hole near the tailpipe as well as another small hole inside the rear hatch. The vehicle occupant and officer pulled her belongings (bags) from the vehicle and heard "popping" sounds and the officer notified police dispatch that the Fire Department was needed. Subsequently, the officer noticed there was a flame at the small interior hole and the plastic interior of the vehicle was melting. The officer and vehicle occupant then began to search for a fire extinguisher in the garage but then noticed that there were large flames coming from the rear of the vehicle and they were becoming more significant. The officer again contacted dispatch to notify that the vehicle was on fire and provided details on the vehicle location.

A second Police Officer arrived and attempted to use a fire extinguisher from their patrol car, but while approaching the vehicle abandoned the attempt due to the size of the fire. Shortly after this attempt, the fire alarm and sprinkler system in the garage activated, which caused a large amount of smoke to begin to quickly fill the garage. This ultimately caused the officer and vehicle occupant to leave the garage and wait outside.

Fire Department personnel ultimately relayed to the officer that they were able to extinguish the fire but that the smoke condition was persisting and that numerous vehicle owners, presumably occupants from the apartments above, were coming down the stairwells to retrieve their vehicles from the garage. It was ultimately determined through emergency personnel conversations with the property maintenance manager that the exhaust fans for the garage did not activate with the sprinklers as they were supposed to, and had to be activated manually by emergency personnel. As an additional precaution, emergency personnel had building security restrict access to the stairwells leading to the garage. Fire Department personnel also required multiple residents of the apartments above the garage to leave their residences due to smoke in the stairwells.

While the fire was contained to a single vehicle, with assistance from a functioning sprinkler system, this case study demonstrated some of the difficulties with vehicle fires in parking garages. In this case, emergency personnel received notification of the fire very early in its progression, likely earlier than on average for these incidents. In this case, it was potentially just before, flaming ignition. Despite this early warning, smoke spread ended up filling the structure, which appears to be an enclosed garage in the photos, due to the sprinkler water spray likely cooling and dragging down the smoke. As the ventilation system reportedly did not activate appropriately during the fire, this case demonstrates the holistic fire protection scheme that is necessary for the best possible outcome in a vehicle fire in the parking garage. In this case, the Fire Department received early warning, the sprinklers did activate, the fire was contained to a single vehicle, and yet with the ventilation system initial failure, smoke reportedly filled the parking garage and began migrating up stairwells towards the apartments. Perhaps luckily, the fire occurred around 6:30pm, with many residents likely awake at the time of the fire. This again shows, the difficulties not only with parking garage fires, but particularly with those in configurations where residences or other occupancies are present above the parking garage with communicating stairwells.

An additional consideration is the effect a functioning ventilation system may have on the performance of the sprinkler system. Removal of smoke and hot gases is helpful to occupants and Fire Department personnel, but the ventilation of these gases may delay or prevent sprinkler activation which could interfere with the ability of the sprinkler system to control the fire. This would constitute both a specific smoke ventilation system operating during a fire, as well as a ventilation system designed to run even during non-fire conditions to remove exhaust fumes. The best approach to balance the mitigation of smoke conditions while allowing the sprinkler system to activate and control the fire should be considered in the design of a parking structure.

Another interesting complexity to this case study is the behavior of the occupants in the residences above the parking garage. In this case, the Fire Department got early warning of the fire and apparently intervened quickly in the fire. Nevertheless, many occupants were entering a reportedly smoke-logged parking garage to retrieve their vehicles. This behavior is similar to residences that have a fire, where some occupants attempt to grab valuables instead of promptly exiting the structure [33]. In this incident, the sprinkler reportedly controlled the fire and the Fire Department was able to extinguish it. The smoke could have been hazardous, though no injuries were reported. This incident could have escalated to much more serious situation without early activation of the sprinkler, especially since individuals with vehicles in the garage did attempt to move those vehicles to avoid damage. It should be considered that, while injuries and deaths are rare in these fires, that some of these injuries could be preventable and a result of people from nearby occupancies entering the parking garage after becoming aware of the fire to move vehicles. To minimize this risk, this response may need to be considered in the building emergency plan, in the training of staff, and appropriate signs may need to be posted to prevent re-entry into parking garages with an active fire.

These case studies are only a small snapshot of the possible conditions and outcomes that can occur in a vehicle fire in parking garage. They exemplify the wide range of outcomes that can occur, from a single vehicle fire extinguished by a sprinkler system, to a catastrophic loss, to a near-miss of a much larger incident. They encompass fires originating in EVs as well as ICEs and hybrid automobiles, in open- and enclosed-type garages, and in both free-standing structures as well as separated buildings such as podium/pedestal structures. An important message from these incidents is that while sprinkler systems often contained the fire to a single vehicle, that vehicle can potentially still significantly burn, and can cause damage to nearby vehicles as well as the parking structure. In general, though, most or all vehicle-to-vehicle spread occurred in parking garages without sprinkler systems and structural collapse occurred in metal structures instead of concrete structures. Finally, the incidents indicate that without early intervention by sprinklers or fire department personnel, vehicle to vehicle spread can occur over relatively large distances, including across empty parking spaces and potentially even further including across multiple empty spaces or aisles.

Relevant Fire Protection Requirements

In the United States, and some other jurisdictions, parking garage fire protection requirements are dictated by either the International Building Code (IBC) or the primary relevant NFPA Standards, in this case, NFPA 88A and NFPA 13. There are also other codes and standards that are potentially applicable to parking garages, although in some cases they are voluntary or utilized by insurers instead of Authorities Having Jurisdictions (AJHs). These include the applicable FM Global data sheets. There are also some municipality actions that have been taken regarding specialized parking facilities, particularly those involving vehicle stackers, that have become known in the fire protection industry. Finally, different codes and standards are utilized internationally. These mandatory and voluntary requirements are summarized below.

NFPA Standards

The applicable NFPA standard for parking garage facilities is NFPA 88A, Standard for Parking Structures [34] whose most recent edition was released in 2023. The standard makes a distinction between open and enclosed parking structures based on the fraction of wall surface that directly communicates to the outside environment. As outlined in the 2020 FPRF report [1], in the 2019 edition of NFPA 88A [35] an enclosed parking structure was required to have an automatic sprinkler system if it was located below grade or if it was more than 15m high and not made entirely of non- or limited-combustible materials (6.4.2; 6.4.3). Conversely, open parking structures were not required to have a detection or automatic sprinkler system (6.4.4). Automated parking structures, including stackers, were required to have a sprinkler system (9.2.4.1). In all cases, NFPA 88A pointed to NFPA 13 [36] for the specific sprinkler system requirements. Standpipes were also required for most parking garages (6.5) and automatic detection was only required for a small subset of parking garages, specifically enclosed parking structures without sprinklers (6.4).

The 2019 edition of NFPA 13 [36], considered parking structures as ordinary hazard group 1 (OH1) (A.4.3.3) and considered car stacker systems up to 2 levels high as extra hazard group 2 (EH2) (A.4.3.6) if protected only with ceiling-level sprinklers, but this sprinkler density could be reduced by a certain percentage if in-rack sprinklers were used as well (25.2.3.2.4). Due in part to the 2020 FPRF report, as well as some high profile and high property losses, the applicable Technical Committees revised the requirements in these standards (NFPA 88A and NFPA 13) in recent editions.

In the 2023 edition of NFPA 88A, there were no substantiative changes regarding standpipes or detection, but the standard was changed to require automatic sprinkler systems in all parking structures, not just enclosed parking structures (6.4). The substantiation for the change specifically referenced the 2020 FPRF report [1]. Additionally, the 2022 edition of NFPA 13 changed the hazard grouping for parking garages from OH1 to OH2 (A.4.3.3.2). The required sprinkler densities for new systems in NFPA 13 (2022) are shown below as Figure 33 (Table 19.2.3.1.1). The substantiation for this change did mention that due to more plastics being used in automobiles and more challenges related to modern vehicles, that the higher hazard classification was warranted. It was noted that further research is needed. Additionally, while the vote was overwhelmingly for the change, it was not unanimous, with multiple Technical Committee members indicating that more information was needed. Additionally, the Technical Committee also reportedly considered increasing the sprinkler density for parking garages even further to EH1, though the support for such a measure was not as substantial. There was also specific reference in one negative vote for the OH2 increase that the 2020 FPRF report indicated that open garages, which at the time were unprotected by an automatic sprinkler system per the 2019 edition of NFPA 88A [35], were the area of concern and that the same report found that garages that were already protected, which would be enclosed garages by an OH1 sprinkler system, were adequately protected. Therefore, the comment indicated that the focus should be on protecting more parking structures with sprinklers, which has been accomplished by the 2023 edition of NFPA 88A [34], and not on increasing the design density of the sprinkler systems.

Table 19.2.3.1.1 Density/Area

Hazard	Density/Area [gpm/ft²/ft² (mm/min/m²)]
Light	0.1/1500 or 0.07/3000* (4.1/140 or 2.9/280)
Ordinary Group 1	0.15/1500 or 0.12/3000* (6.1/140 or 4.9/280)
Ordinary Group 2	0.2/1500 or 0.17/3000* (8.1/140 or 6.9/280)
Extra Group 1	0.3/2500 or 0.28/3000* (12.2/230 or 11.4/280)
Extra Group 2	0.4/2500 or 0.38/3000* (16.3/230 or 15.5/280)

*When required by 19.2.3.1.5.

Figure 33. NFPA 13 (2022) sprinkler densities as a function of occupancy hazard for new systems.

The requirements for car stackers also changed somewhat in the 2022 edition of NFPA 13 [37]. In the 2019 edition of NFPA 13 [36], stacker systems up to two (2) car levels high were required to be EH2 at the ceiling level (A.4.3.6), still with a reduction based on percentage if in-rack sprinklers were present (25.8.2.2.2.2). No requirements exist for stacker systems over two car levels high in the 2019 edition of NFPA 13. NFPA 13 (2022) still only addresses stacker systems up to two car levels high (A.4.3.5). Installation of sidewall sprinklers is now mentioned in the list of locations where they can be installed (10.3.2(9)) and mentions that they should be placed under each tier of cars. Additionally, A.10.3.2(9) indicates that if in-rack sprinkler protection is included in each tier of cars in accordance with NFPA 13, the overhead ceiling system only must meet the design density of a parking garage. In other words, the option now exists for car stacker systems to either use in-rack sprinklers and a ceiling OH2 density, or if the stacker system or configuration does not include in-rack sprinklers, a ceiling-level EH2 system is required. Again, though, this is only for stacker systems up to two-tiers high. The NFPA 13 Technical Committee has not yet acted on stacker systems more than two-tiers high. There were Public Inputs by the National Fire Sprinkler Association (NFSA) and the San Francisco Fire Department for car stackers over two levels high to have EH2 sprinklers, or to require in-rack sprinklers, respectively, but the Technical Committee did not make a revision to the standard based on these Public Inputs. The substantiation for not acting on these inputs is the lack of data on which to base requirements.

Additional NFPA Standards also apply to parking structures. NFPA 101, Life Safety Code, 2024 edition [38], considers a parking garage to be a storage occupancy and has special requirements for parking garages in Chapter 42, specifically in section 42.8. Per 42.8.3.5, an automatic sprinkler system is required in all new parking structures. This would apply both to open and enclosed parking garages. NFPA 5000, Building Construction and Safety Code, 2024 edition [39] also has specific requirements for parking structures in the storage occupancy section (Chapter 30), in Section 30.8. NFPA 88A requirements are excerpted in this section and, consistent with NFPA 88A and NFPA 101, sprinklers are required in all parking structures. As NFPA 5000 applies to construction of new structures, this would apply to new parking garages only, regardless of whether they are of the open- or enclosed-type.

NFPA 221, Standard for High Challenge Fire Walls, Fire Walls, and Fire Barrier Walls, 2024 edition [40] addresses the separation of vertical buildings, such as would be used in podium or pedestal construction where the parking garage and another occupancy are housed in the same physical structure. NFPA 221 requires that that a horizontal assembly separating the parking garage from the rest of the building have a three-hour fire resistance rating, and the lower occupancy, if a parking garage, must be sprinklered, regardless of whether it is the enclosed- or open-type.

Aside from active fire protection requirements, some of these NFPA standards also have specific passive fire protection requirements for parking garages. NFPA 88A (2023) requires that parking garages be built using one of the types of construction outlined in NFPA 220, Standard on Types of Building Construction, of which the current edition is the 2024 edition [41] (5.1.1). NFPA 88A indicates that open parking structures shall be Type I or Type II construction in accordance with NFPA 220 (5.1.2). There are no specific requirements for enclosed parking garages. Type I construction is comprised of non-combustible/limited combustible materials, typically concrete. Type II construction utilizes non-combustible/limited combustible materials, typically steel with or without fireproofing, with a lower level of fire resistance than Type I. Additionally, NFPA 88A (2023) has specific height and area limitations depending on what type of construction is utilized. The typical fire resistance ratings for the different types of construction are included as Figure 34. NFPA 101 (2024) does not have any construction fire resistance rating requirements for parking structures. NFPA 5000 has the same requirements as NFPA 88A, which were extracted from that standard. Therefore, the NFPA codes require Type I or Type II construction with the fire resistance ratings as shown in Figure 34. The very limited data from some of the more significant incidents in Europe indicated collapse occurred in steel-only structures, but generally did not occur in concrete structures. As seen in Figure 34, the steel-only structures, which would likely fall into Type II construction, would have a lower fire resistance rating than that for concrete structures, which would be categorized as Type I. The reduced fire resistance rating of steel structures may explain the collapses in the European parking structure incidents; however, the data is very limited. Additionally, it should be noted that either Type I or Type II is permissible for open parking garages per NFPA standards.

Table 4.1.1 Fire Resistance Ratings for Type I Through Type V Construction (hr)

Construction Element	Type I		Type II			Type III		Type IV	Type V	
	442	332	222	111	000	211	200	2HH	111	000
Exterior Bearing Walls[a]										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0^b	2	2	2	1	0^b
Supporting one floor only	4	3	2	1	0^b	2	2	2	1	0^b
Supporting a roof only	4	3	1	1	0^b	2	2	2	1	0^b
Interior Bearing Walls										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	2	1	0
Supporting one floor only	3	2	2	1	0	1	0	1	1	0
Supporting roofs only	3	2	1	1	0	1	0	1	1	0
Columns										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	H	1	0
Supporting one floor only	3	2	2	1	0	1	0	H	1	0
Supporting roofs only	3	2	1	1	0	1	0	H	1	0
Beams, Girders, Trusses, and Arches										
Supporting more than one floor, columns, or other bearing walls	4	3	2	1	0	1	0	H	1	0
Supporting one floor only	2	2	2	1	0	1	0	H	1	0
Supporting roofs only	2	2	1	1	0	1	0	H	1	0
Floor/Ceiling Assemblies	2	2	2	1	0	1	0	H	1	0
Roof/Ceiling Assemblies	2	1½	1	1	0	1	0	H	1	0
Interior Nonbearing Walls	0	0	0	0	0	0	0	0	0	0
Exterior Nonbearing Walls[c]	0^b	0^b	0^b	0^b	0^b	0^b	0^b	0^b	0^b	0^b

H: Heavy timber members *(see text for requirements)*.

[a]See 7.3.2.1 of *NFPA 5000*.

[b]See Section 7.3 of *NFPA 5000*.

[c]See 4.3.2.12, 4.4.2.3, and 4.5.6.8.

[**5000:**Table 7.2.1.1]

Figure 34. NFPA 220 (2024) types of construction and associated fire resistance ratings [41].

Therefore, based on the applicable code and standards revisions, more new parking garages will need to be sprinklered than previously required, and the sprinkler design density will be higher in the NFPA standards. Nevertheless, voting and commenting on the changes, particularly the change from OH1 to OH2, indicates that while there was near consensus that the increase in sprinkler density was the accepted decision, there is still a need for further data to justify and clarify the proper sprinkler density. Additionally, given that older versions of the code did not require a sprinkler system for open parking garages, there is likely a large base of open garages in the build environment without an automatic sprinkler system. Finally, there is a little clarity in NFPA 13 for stacker systems up to two-levels high, but there are still no requirements for stacker systems over two-tiers high. Regarding types of construction and fire resistance ratings, requirements exist to ensure a fire resistance rating for open parking garages.

International Building Code (IBC)

The current edition of the IBC was enacted in 2024 [42]. As outlined in the 2020 FPRF report [1], the 2018 IBC had similar requirements to the 2019 edition of NFPA 88A. The 2018 IBC [43] required a sprinkler system in an enclosed parking garage if it was of a certain size (1115 m^2) (406.6.3; 903.2.10), but has no requirements for a sprinkler system in an open parking garage. The sprinkler system is required to be installed in accordance with NFPA 13, 2016 edition, which would invoke the OH1 design density. The 2021 edition of the IBC removed the requirement that the garage be enclosed to have a sprinkler system requirement (903.2.10). Therefore, sprinklers are now required in all parking garages, regardless of configuration (i.e., open or closed), provided they meet a particular size requirement (1115 m^2 for enclosed, 4460 m^2 for open) (903.2.10). The IBC (2021) requires that the system be installed in accordance with the 2019 edition of NFPA 13, therefore the OH1 design density was still code-compliant with the 2021 IBC, though best practice would be to base a design on the latest version of NFPA 13 (2022 version), which requires an OH2 design density for parking garages. The 2024 edition of the IBC directly references the 2022 edition of NFPA 13, requiring OH2 design density.

Stacker systems are referred to as mechanical-access parking systems in the IBC. Initially, in the 2018 edition of the IBC, there was only a definition for a “Mechanical-Access Open Parking Garage” and no corresponding definition for a mechanical-access enclosed parking garage (Chapter 2). Likewise, there were no specific sprinkler requirements for a mechanical-access open parking garage. Therefore, the sprinkler requirements were simply as they were for non-stacker garages in the 2018 edition. Open garages did not require a sprinkler system at that time, while closed garages did. The sprinkler systems would still have to be installed in accordance with NFPA 13, 2016 edition [44]. Presumably, a stacker system in an enclosed garage would have had to be EH2 with the percentage reduction for in-rack sprinklers, but no sprinkler system would be required at all for an open stacker parking garage. Therefore, it is possible there are currently stacker systems in open garages that, if they only followed the 2018 IBC and not NFPA 88A, do not have a sprinkler system at all.

The 2021 edition of the IBC [42] has changed as it relates to stackers. Mechanical-access enclosed and mechanical-access open parking garages are now both defined (Chapter 2). Since the 2021 edition of the IBC requires sprinkler systems for both open and closed garages in accordance with NFPA 13, 2019 edition [36], this will invoke an EH2 sprinkler density for all stacker systems up to two-levels high with a percentage reduction for in-rack sprinklers. Additionally, there is a specific requirement that the entire building with a mechanical-access enclosed parking garage shall have automatic sprinklers and the portion containing the mechanical-access enclosed parking garage will be protected with a specially engineered sprinkler system (903.2.10.2). This requirement goes beyond that for the NFPA 13 EH2 requirement by requiring a specific engineered solution, which presumably has been tested and demonstrated to the satisfaction of an AHJ to be adequate to control and/or suppress a fire in a stacker system. The 2021 IBC [42] has also added in requirements for fire barrier separation, smoke removal, fire department access doors, and a required fire control equipment room for mechanical-access enclosed parking garages (406.6.4). It should be noted that while enclosed stacker parking garages require a specially engineered sprinkler system, an open parking garage with a stacker system simply needs to follow NFPA 13 (EH2 with percentage reduction for in-rack sprinklers) and there are no requirements in NFPA 13 (2022) for stacker systems over two-levels high. All of these requirements that changed in the 2021 edition of the IBC are still in effect in the 2024 edition of the IBC [42].

Neither the 2018 nor the 2021 or 2024 IBC require detection systems for parking garages of any style. Both editions of the IBC do require standpipes, with the 2018 requirement for a system and the class of the system depending on the presence of an automatic sprinkler system, the height of the building, and whether the garage is open or closed (905.3.1). As the 2021 and 2024 versions of the IBC requires sprinkler systems in all garages, the requirement for standpipes is now simplified to class I in all parking garages (905.3.1).

Regarding types of construction and the associated fire resistance ratings, the 2024 edition of the IBC requires open parking garages to be Type I, II, or IV with different height and area restrictions based on the type of construction (406.5). There are no specific requirements for the type of construction for enclosed garages, presumably because a sprinkler system is required regardless of the floor area or height of the enclosed parking garage. Types I and II use non-combustible materials while Type IV utilizes mass timber or non-combustible materials with the fire resistance ratings as shown in Figure 35.

TABLE 601 FIRE-RESISTANCE RATING REQUIREMENTS FOR BUILDING ELEMENTS (HOURS)

BUILDING ELEMENT	TYPE I		TYPE II		TYPE III		TYPE IV				TYPE V	
	A	B	A	B	A	B	A	B	C	HT	A	B
Primary structural frame[f] (see Section 202)	3[a, b]	2[a, b, c]	1[b, c]	0[c]	1[b, c]	0	3[a]	2[a]	2[a]	HT	1[b, c]	0
Bearing walls												
Exterior[e, f]	3	2	1	0	2	2	3	2	2	2	1	0
Interior	3[a]	2[a]	1	0	1	0	3	2	2	1/HT[g]	1	0
Nonbearing walls and partitions Exterior	See Table 705.5											
Nonbearing walls and partitions Interior[d]	0	0	0	0	0	0	0	0	0	See Section 2304.11.2	0	0
Floor construction and associated secondary structural members (see Section 202)	2	2	1	0	1	0	2	2	2	HT	1	0
Roof construction and associated secondary structural members (see Section 202)	1 1/2[b]	1[b, c]	1[b, c]	0[c]	1[b, c]	0	1 1/2	1	1	HT	1[b, c]	0

For SI: 1 foot = 304.8 mm.

a. Roof supports: Fire-resistance ratings of primary structural frame and bearing walls are permitted to be reduced by 1 hour where supporting a roof only.
b. Except in Group F-1, H, M and S-1 occupancies, fire protection of structural members in roof construction shall not be required, including protection of primary structural frame members, roof framing and decking where every part of the roof construction is 20 feet or more above any floor or mezzanine immediately below. Fire-retardant-treated *wood* members shall be allowed to be used for such unprotected members.
c. In all occupancies, heavy timber complying with Section 2304.11 shall be allowed for roof construction, including primary structural frame members, where a 1-hour or less fire-resistance rating is required.
d. Not less than the fire-resistance rating required by other sections of this code.
e. Not less than the fire-resistance rating based on fire separation distance (see Table 705.5).
f. Not less than the fire-resistance rating as referenced in Section 704.9.
g. Heavy timber bearing walls supporting more than two floors or more than a floor and a roof shall have a fire-resistance rating of not less than 1 hour.

Figure 35. IBC (2024) types of construction and associated fire resistance ratings [42].

In sum, the 2024 IBC [42] is now also requiring more parking garages have automatic sprinkler systems (enclosed and open). The 2021 IBC was still only mandating the OH1 design density, but only because of the version of NFPA 13 (2019) that is referenced. When the 2024 IBC was released that updated the reference of NFPA 13 to the 2022 edition, OH2 became the required hazard classification for all parking garages. Finally, the IBC has upgraded the sprinkler protection for stacker systems by now requiring it for all stacker systems in accordance with NFPA 13, which will require an EH2 design density. They have also required a specially engineered system for stacker systems in enclosed garages. The IBC, though, points to NFPA 13 for all stacker systems where NFPA 13 only has requirements for stacker systems up to two-levels in height.

FM Global Data Sheets

While not usually codified into law, FM (Factory Mutual) Global Property Loss Prevention Data Sheets provide property loss prevention recommendations often used by the insurance industry. These data sheets were not initially considered in the 2020 FPRF report [1].

FM Global Data Sheet 7-15 (2021) [45] is the applicable data sheet for parking garages. Regarding detection and standpipes, there are no requirements for standpipes nor detection systems, though small hose stations or portable fire extinguishers are required (2.1.1.3).

Regarding sprinklers, FM Global Data Sheet 7-15 (2021) [45] indicates that all parking garages need to have automatic sprinkler systems per FM Global Data Sheet 3-26 [46] in accordance with a Hazard Category 3 occupancy (2.1.1.1). The July 2023 interim revision to this data sheet clarified the scope of the document to indicate that these requirements apply to garages with ICE vehicles as well as EV vehicles, including the presence of charging stations. FM Global Data Sheet 3-26 (2021) [46] indicates that for a Hazard Category 3 occupancy, depending on the ceiling height, the required sprinkler design density varies from 0.3-0.6 gpm/ft^2 (2.3.1.10). Relating this back to NFPA 13 (2022) [37], this is basically an EH1 design density which could expand into EH2 or beyond if the ceiling height is particularly high (NFPA 13, 2022 19.2.3.1.1). Stacker systems are not specifically addressed or mentioned in the FM Global Data Sheet.

Additionally, FM Global Data Sheet 7-15 (2021) [45] indicates in the revision history that in January, 2021, two significant changes were made (Appendix B). First, an option to omit sprinklers in open parking garages was deleted. Additionally, the hazard category for parking garages was raised form Hazard Category 2 to Hazard Category 3. Per Data Sheet 3-26 (2021) [46], a Hazard Category 2 occupancy requires 0.2-0.6 gpm/ft^2 depending on the ceiling height (2.3.1.10). This ranges from OH2 to EH2 per NFPA 13 (2022) (19.2.3.1.1). Therefore, similar to the NFPA standards and IBC codes, the applicable FM Global Data Sheets have changed to require sprinklers in all parking garages, not just enclosed garages. Additionally, they have increased the sprinkler design density for all parking garages, though while NFPA 13 increased from OH1 to OH2, even at the lowest ceiling heights, the FM Global Data Sheet increased from OH2 to EH1.

San Francisco Fire Department

NFPA 88A (2023) [34] and NFPA 13 (2022) [37] now address up to two-level stacker systems as a situation requiring an EH2 density for ceiling sprinklers, but this can be reduced to OH2 if in-rack sprinklers are installed. The IBC similarly takes this approach by referencing NFPA 13 for open stacker garages. Enclosed stacker garages required a specially engineered system per the IBC. Regardless, there are some jurisdictions, though, that are going beyond these requirements. The City of San Francisco (CA), for example, through its Fire Department (SFFD) Administrative Bulletin 4.25 [47] has additional guidelines for sprinkler protection of car stackers. The SFFD Bulletin 4.25 currently (2022) does not apply to enclosed stacker parking garages that are required to have a specially engineered sprinkler system per the IBC (adopted as the California Building Code in San Francisco), but did apply to enclosed stacker parking garages in the 2019 edition of the Bulletin [48]. But for stacker systems in open garages (and all stacker garages before 2022), SFFD Bulletin 4.25 requires an EH2 design density for a maximum of two cars stacked vertically with an option ("shall be acceptable") for in-rack sprinklers designed to an ordinary hazard occupancy (does not specify OH1 or OH2). The in-rack sprinklers are not required to be included in the hydraulic calculation. Stacker systems above two cars stacked vertically also require an EH2 design density at the ceiling and while in-rack OH2 sprinklers "shall be acceptable" for each level, at least six (6) must be included in the hydraulic calculation so they are required. These requirements are slightly more stringent than NFPA 13, as racks with two cars still require EH2 at the ceiling, but there is no reduction in the SFFD Bulletin to OH2 if in-rack sprinklers are present. Additionally, San Francisco has requirements for stackers over two cars, which has not been acted on by NFPA 13 to date. These requirements are EH2 at the ceiling and OH2 in-rack sprinklers. It should be noted that one of the Public Inputs to NFPA 13 to include requirements for car stackers higher than two-tiers was submitted by the SFFD, but was resolved (i.e., rejected) by the Technical Committee with a reasoning that there was not data to support requirements for these parking systems. This is an indication that some local jurisdictions have looked to the NFPA Technical Committees for requirements for car stackers over two-levels, but based on a lack of data, no requirements have been established in the NFPA standards. This has caused some local jurisdictions to act on their own as they see appropriate.

In sum, San Francisco has slightly more stringent requirements for two car level stackers and has specified requirements for stackers with over two car levels. There may be other jurisdictions that have similarly created more stringent requirements for two car level stackers and have created their own requirement for stackers over two-levels where NFPA 13 has not. The lack of guidance for multi-tier (3+) stacker systems may be creating a patchwork of disparate requirements across the United States for stacker systems.

European Codes and Standards

As mentioned in the 2020 FPRF report [1], the Eurocodes do address general construction requirements across the entire European Union (EU), but do not detail fire protection system requirements including sprinklers. Therefore, these requirements vary from each individual country. It was beyond the scope of this project to investigate each individual EU country's requirements and throughout the world. Nevertheless, as mentioned in the 2020 FPRF report, an overview of sprinkler requirements in parking garages throughout the EU is summarized in a document by the European Fire Sprinkler Network (EFSN) [49]. The requirements in the EU are basically unchanged from the description in the 2020 FPRF report. Some countries (e.g., Serbia) require sprinklers only in particular sized parking garages and only if enclosed, while others (e.g., Spain) only require sprinklers in automatic parking garages. The specific design densities are not listed in the summary, but just based on location alone, given the NFPA 88A now requires sprinklers in all parking garages, it does not appear that any EU country has more stringent requirements than those in the NFPA codes. The area restrictions in the 2021 edition of the IBC that invoke the requirement for a sprinkler system (1115 m^2 for enclosed garages, 4460 m^2 for open garages) are also similar (with some variability) to most of the countries that have a requirement for sprinklers based on area.

One notable European standard is EN 12845, Fixed Firefighting Systems – Automatic Sprinkler Systems – Design, Installation, and Maintenance. This standard is the one generally indicated in several literature tests with sprinklers as well as in the description of the Marienplatz incident, and is used in several countries in Europe. In general, older versions of the standard only required 5 mm/min (European OH2) in parking garages, though the UK version of EN 12845 was updated recently (2023) to increase the protection for parking garages from European OH2 (5 mm/min) to European High Hazard, Process Group 3 (HHP3), requiring 12.5 mm/min in parking garages, equivalent to EH1 in NFPA 13.

To summarize the current code and standards, fire protection requirements for parking garages are more stringent than those outlined in the 2020 FPRF report [1]. Per NFPA standards and the IBC, sprinklers are required in more parking garages than before. Additionally, the sprinkler density has generally increased as well. Requirements for stacker systems have generally increased moderately, with an engineered fire protection solution now mandatory for enclosed stacker systems in the IBC. But there are still some potential current weaknesses in the codes and standards related to fire protection of parking structures. Stacker systems over two-levels high are not addressed in the NFPA standards and are not addressed in the IBC if the garage is not enclosed. Some municipalities, such as San Francisco, have acted on their own since NFPA 13 did not include requirements for stacker systems over two-levels. This may lead to disparate requirements across different municipalities if national codes do not have requirements addressing these taller automated parking systems. There is a gap in the testing- and knowledge-base on stacker systems over two-levels, and therefore codes and standards do not address this issue since no data exists (e.g., nationally in NFPA 13). Some municipalities have invoked standards based on their best judgement on what requirements should exist but without adequate data or foundation. This can lead to inconsistency of the requirements across different enforcement areas. Finally, codes and standards in Europe appear at least generally be in agreement with those in the NFPA standards and the IBC, though there is also considerable variability between the sprinkler requirements in any given individual EU country.

Literature review

A literature review was performed to accumulate recent publications that include fire tests of modern-day vehicles using various fuels. The vehicle power types included were internal combustion engine vehicles (ICEVs) burning gasoline or diesel fuel, battery electric vehicles (BEVs or EVs), plug-in hybrid electric vehicles (PHEVs), natural gas vehicles (NGVs), propane vehicles (LPGVs), and hydrogen fuel cell vehicles (FCEVs). Sixteen such recent publications were identified from research performed around the world relating to modern vehicle fires. The thirteen publications are briefly summarized as follows:

Arvidson and Westlund (Sweden) studied the effects of water spray fire suppression on ICEVs and BEVs [50] . Two tests were performed on each type of vehicle and data recorded included heat release rate (HRR) calculated from calorimetry data (oxygen depletion), heat fluxes (HFs) at different targets, and temperatures at different locations and mass loss rate (burn rate). Sprinklers were used for fire suppression in all four tests to study the effects on vehicle fire growth rate. The authors concluded that the fires in BEVs and ICEVs were somewhat different but did have similarities and a BEV fire was not more challenging for a sprinkler system then an ICEV fire.

Cui et al. (China) studied the characteristics and hazards of a fire involving a plug-in hybrid vehicle where the fire was initiated in the electric battery in the vehicle [51]. In this study two PHEVs were tested. These tests were performed outdoors and only HF and temperature data was recorded. The authors noted that PHEV fires can result in an explosion of combustible gases, pool fires due to molten materials, and fire whirls which need further exploration through testing.

Kang et al. (South Korea and United Kingdom) performed fire tests involving BEVs, an ICEV and a FCEV [52]. For these tests, a large outdoor calorimeter was built and six total tests were performed on three different EVs (one vehicle battery and body were tested separately), one ICEV and one FCEV. The data published in the paper includes HRR, total heat release (HR), HFs, mass loss, and temperatures measured inside the vehicles and at various distances away from the burning vehicle. The study found that most of the heat released in BEV fires was due to the body components, with the battery pack contributing a smaller amount. The burn rate of a BEV is much faster if the jet flames from the battery are present during a given test. The peak HRRs for BEV tests were slightly lower than those in ICEV tests.

Another publication by Cui et al. (China) included the study of fires involving a BEV and a PHEV [53]. One of each type of vehicle were tested outdoors positioned in parallel (side by side) to study the fire spread to the PHEV from a fire was started in the BEV. Only heat flux and temperature data were recorded. The study found that the external and internal peak flame temperatures were similar for both BEVs and ICEVs and the presence of a battery pack or fuel tank did not factor into the maximum temperature characteristics. The spewing flames from the battery compartment led to faster flame spread in the BEV fire as compared to PHEV or ICEV fires.

Lam et al. (Canada) performed seven different fire tests of ICEVs and BEVs [54]. These tests were performed under a large hood calorimeter and HRR, total HR, mass loss, and HFs were measured. The tests were run using the guidance from UL2580 and the fire in each test was extinguished by firefighters after 30 minutes. The study found that the fire spread in BEVs depends on the vehicle model, battery design and the amount of battery charge. The overall results were similar for PHEVs, BEVs and ICEVs.

A study by Lecocq et al. (France) included fire testing of ICEVs and BEVs from two different manufacturers [55]. These tests were performed in a tunnel-like setup where all of the exhaust gases were analyzed for various species. HRR, HF, mass loss and temperature data were included as part of the test results. The study concluded that the general behavior of BEVs and ICEVs in fires was similar when exposed to similar external heat stress. Analysis of the combustion exhaust gases showed similar results for CO_2, CO, total hydrocarbons, NO, NO_2, HCl and HCN for both types of vehicles.

Hynynen et al. (Sweden) published results of fire testing that included results from two different studies performed at different times [56]. The publication includes results for six (6) different tests performed on ICEVs and BEVs including one fire test of an EV where the battery was removed. The primary purpose of the fire testing was to study the exhaust for toxic gases. The data in the publication include HRR, total HR, concentrations of various gas species in the exhaust, and temperatures measured inside the vehicles and at various distances away from the burning vehicle. The study determined that the peak heat release rate (PHRR) and the total heat released were affected by the fire scenario and the vehicle model but not significantly by the type of powertrain. Analysis of the combustion gases showed a large difference in the presence of hydrogen fluoride as compared between BEVs and ICEVs. Battery specific metals including manganese nickel, cobalt and lithium were found in higher amounts in the BEV tests.

Tramoni et al. (France) published a study of fire tests on vehicles tested in pairs [57]. In each test, one diesel vehicle (ICEV) was paired with another vehicle including an ICEV, a PHEV, a NGV, a LPGV, and a BEV. In each test the secondary vehicle (ICEV) was present to study the fire spread while the fire was initiated in the primary vehicle. The testing was performed in an underground plane hangar to study the effects of vehicle fires on steel members of the structure. Temperatures were measured at various locations on the steel beams and pillars of the testing rig manufactured inside the hangar for this particular testing. The testing results showed that the stability of the steel structure was not adversely affected during the fire, regardless of the type of vehicle.

Strum et al. (Austria) presented a study that included five different fire tests performed on BEVs and ICEVs [58]. The objective of this testing was to study the behavior of vehicle fires in road tunnels. Five (5) fire tests were run on various sized vehicles and gases produced by fire were analyzed. The fires were suppressed by firefighters except for one test where a fire blanket was used to control the fire. HRR and temperature data is included in the report. The study found that hydrogen fluoride was the most critical combustion exhaust gas released by BEV fires but the levels exceeding the critical threshold for humans were only found in the smoke layer. Alternative firefighting methods were tested and it was determined that the fire blanket was not effective once the battery was involved in a BEV fire. The use of a fire lance to inject water into the battery housing was very effective. The internal battery cooling systems were very effective in delaying the involvement of battery in fires unless the fire started in battery. The water used to fight BEV fires showed a presence of metals in concentrations high enough to require special treatment in post-fire cleanup efforts.

Funk et. al. (Denmark and Sweden) published a study that included nine (9) different fire tests in open ended enclosures performed on BEVs built by three different manufacturers [59]. Each vehicle where fire was started was surrounded by eight (8) other vehicles, one on each side and three each in the front and the back. This setup was used to study a roll-on /roll-off (ro-ro) setup typically used for shipping vehicles. The testing structure was built with three shipping containers with the short ends removed and the vertical walls removed from the middle container. Different firefighting techniques were used to suppress the fire once the fire had spread to the neighboring vehicle(s). These techniques included fire blanket, an extinguishing lance, a piercing device, a water curtain Joni, a low-pressure water mist, a water curtain, both a water mist and lance, both a fire blanket and lance, and both a water curtain and lance. The test time varied during each experiment and the time to spread the fire to next vehicle varied between about 3 to 46 minutes. The study found that the detection times were affected by the wind direction due to the openings on the ends of the enclosures. A rapid increase of hydrogen fluoride was detected in the boot (trunk) of the BEV vehicles when thermal runaway was initiated which can possibly be used as a detection tool. Direct cooling methods were more effective in BEV fires while indirect cooling methods prevented fire from spreading to the adjacent vehicles.

Watanabe et. al. (Japan) conducted a study involving one each of an ICEV and BEV [60]. A total of two (2) tests were performed outdoors where the mass loss was measured during the fire test of each vehicle. HF and temperatures were recorded and HRR was calculated from the mass loss data. The study concluded that the maximum values of HRR and heat flux were higher for the BEV fire tests as compared to the ICEV fire test.

A publication by the British Research Establishment (BRE) in the United Kingdom included a study of vehicle fires [18] involving ICEVs situated in varying configurations, including some tests that involved multiple vehicles to study the fire spread from vehicle to vehicle. In the final fire test for this study, two vehicles were used on a stacker where the fire was ignited on the driver side seat of the bottom vehicle with the window open. In two other tests, simulating an arson fire, a fire was started on the driver side seat in the car with closed windows and the door was closed after the fire was established. The fire self-extinguished once the oxygen was consumed. Additional tests were run by starting a fire on the driver side seat with the windows open. In two of the tests, the fire was initiated in the engine compartment. In test number 2, three vehicles were tested where two vehicles were parked next to each other and the third vehicle was located with an empty parking spot in between. An OH2 sprinkler system was used and activated at 4 minutes after ignition but did not extinguish the fire on the initial vehicle which reached a HRR of 7 MW. Despite not achieving full extinguishment, the sprinkler performance was successful as the sprinklers did control the fire from spreading to the other vehicles.

BRE Global performed [61] a vehicle fire test to study the effect of sprinklers on a stacker fire involving two vehicles as shown in Figure 37. The setup and ignition were similar to the stacker test as described in [18]. Each vehicle was protected with four sprinkler heads, located near each corner of the vehicle. The fire spread to the under carriage of the upper vehicle from the bottom vehicle and did not spread into the passenger compartment as it was controlled by the sprinklers. The bottom vehicle suffered damage to the entire passenger compartment. As found in the first multi-vehicle test series [18], this test demonstrated that the sprinklers, as situated in this test, were effective in controlling the fire.

Okamoto et. al. [62] performed four (4) vehicle fire tests on ICEV passenger sedans. Two different ignition scenarios were used to ignite the vehicles, including three tests where right-rear of the vehicle was ignited and one test where fire was started on the left front seat. All tests were run until the fire burned out (80 to 110 minutes) and all major events for the fire spread were noted. Thermocouples were placed at various locations inside and on the vehicle body for each test. Mass loss rate was recorded during each test and heat of combustion of 22 MJ/kg was used to calculate HRR. Maximum HRR was calculated to be 3 to 3.5 MW for three of the tests while one test only had maximum HRR of 2 MW. The total mass lost during the fire was similar for all four tests and total heat released was about 5 GJ for each test. The study concluded that the burning behavior was greatly affected by the window breakage and the amount of gasoline in the tank.

A second study by Okamoto et. al. [63] performed four (4) vehicle fire tests on ICEV minivan passenger cars. Four different ignition scenarios were used to start the vehicle fire including rear splash guard ignition, right front bumper ignition, center of 2nd row seats and the center of the back row seats. Similar instrumentation and measurements were taken during these test as in the first study. Fires were burned to completion (80-100 minutes) for three tests and in one test where fire was started at the center of the second-row seats, the fire self-extinguished after 20 minutes of ignition due to closed windows. The maximum HRR was between 3 to 4 MW for the three tests where fire burned to the end. The authors concluded that like the first study, the breakage of the windows greatly controlled the fire spread and the fire self-extinguished in the case where windows were closed.

Li et. al. [64] performed on test on two (2) ICEVs parked side by side in reverse direction to study to fire spread to the adjacent vehicle. Plume temperature was measured and a heat flux gauge was placed 5 meters from the initially ignited vehicle. The fire was started in the engine compartment for first vehicle and the second vehicle ignited at about 20 minutes later and both vehicles became fully involved at about 30 minutes. Peak temperatures inside the vehicles reached 900°C, with the passenger compartment becoming involved in the fire, while the plume temperature above the vehicles was measured at 90-295°C.

Database

A Microsoft Access database was created to tabulate the information available in the publications involving fire tests of vehicles and to allow for easier data searching and analysis. The specific information selected to be included in the database is shown in Table 3. It should be noted that not every publication included information for each of the data fields covered in the Table 3. As an example of data gathered, Table 4 shows the data from testing by Arvidson and Westlund in Sweden [50]. The vehicle fire tests included in the selected publications were performed in various settings including outdoors, indoors under large calorimetry setups, in enclosures, in built-up settings to simulate parking garages etc. Only a few of the tests included use of sprinkler systems to control the fire spread. Most of the tests included heat flux measurements at targets away from the burning vehicles to access the potential for fire spread to neighboring vehicles where vehicles are parked near each other, such as in a parking garage. If possible, graphs were added to the database for easier viewing. Nevertheless, not all information from every single test could be effectively included in the database. A user of the database should be able to search the data and find specific tests that are of interest, along with basic details on those tests. Ultimately, the database user will want to consult the actual technical reference to obtain more detail about a particular experiment.

Publication Information	**Testing Information**
Title	Extinguishment
Author(s)	Extinguishment Start Time (min)
Organization(s)	HRR Chart
Testing Location	HRR Measurement Method
Journal	Peak HRR (kW)
Publication Date	Time to Peak HRR (min)
	Total Heat Released (MJ)
	Initial Mass (Kg)
	Mass Loss Total (kg)
Vehicle Information	Heat Flux Target Distance (m)
Vehicle Info Table	Heat Flux (at Targets)(kW/m2)
Vehicle-Power Type	Heat Flux Table/Chart
Manufacturer	CO Curve
Vehicle ID in Paper	Oxygen Curve
Model	CO2
Manfactured Date	Other Species
Fuel Type	Temperature Curve
Weight (kG)	Temperature Location
Vehicle Type	Flame Height (m)
Transmission	Sprinklers
EV Battery Capacity (kWh)	Sprinkler Flow Rate (LPM)
Amount of Fuel (L)	Sprinkler Density

Table 3. Information (where available) included in the Microsoft Access database from each of the publications.

ID	1	2	3	4
Reference No	1	1	1	1
Number of Tests	4	4	4	4
Testing Facility Information	RISE	RISE	RISE	RISE
Objective	Water spray fire suppression comparrison of gasoline fueled and electric vehicles involved in fire			
Vehicle ID	1	2	3	4
Fuel Type	Gasoline	Electric	Gasoline	Electric
Vehicle Condition	New	New	Used	Used
Ventilation Conditions	Large Scale Calorimeter Lab			
Target Vehicles	Heat Flux and Temperature			
Number of Target Vehicles	Sensors on all 4 sides			
Ignition Type	Fuel Leak-Ignited	Battery Damaged-Ignited	Fuel Leak-Ignited	Battery Damaged-Ignited
Ignition Location	Leaked Fuel on the Floor	At the Battery	Floor	At the Battery
Ignition Source	Electronic	Electronic	Electronic	Electronic
Explosion	No	No	No	No
Burn Time (Minutes)	90	90	90	90
Extinguishment	Sprinklers	Sprinklers	Sprinklers	Sprinklers
Extinguishment Start Time (min)	1	13	1	17
HRR Chart	Link	Link	Link	Link
HRR Measurement Method	Calorimetry-Oxygen Depletion			
Peak HRR (kW)	7978	2944	5324	1975
Time to Peak HRR (min)	3	20	4	17
Total Heat Released (MJ)	5241	4510	4765	4474
Initial Mass (Kg)	1614	2120	1295	1598
Mass Loss Total (kg)	-	-	-	-
Heat Flux Target Distance (m)	-	-	-	-
Heat Flux (at Targets)(kW/m^2)	98-138	6-7	44-59	5-6
Heat Flux Table/Chart	Link	Link	Link	Link
CO Curve	-	-	-	-
Oxygen Curve	-	-	-	-
CO2	-	-	-	-
Other Species	-	-	-	-
Temperature Curve	Link	Link	Link	Link
Temperature Location	Gas Temp-above			
Flame Height (m)	-	-	-	-
Sprnklers	Yes	Yes	Yes	Yes
Sprinkler Flow Rate (LPM)	372	372	372	372
Sprinkler Density (mm/min)	10	10	10	10

Table 4. Example of data extracted from one of the publications (Arvidson and Westlund [[50]]) and presented in the database. Similar data (where available) was included into the database from the publications summarized above.

Data Analysis

Some of the general findings and observations from the experiments in the publications included in the database are presented. The ignition method and location on the vehicle varied across studies. Arvidson and Westlund [50] ignited ICEVs by puncturing the fuel tank and then igniting the fuel on the ground below vehicles which lead to a very high HRR at the start of the test. Conversely, many BEVs were ignited inside the battery compartment which led to a lower initial heat release rate. Therefore, ICEVs often produced much higher peak HRRs but the total HR for a comparable ICEV and BEV was similar in magnitude. The study by Arvidson and Westlund [50] was conducted where sprinklers were activated after a short period from the start of the test which may have affected the HRR. In a study by BRE [18], vehicles were burned with the ignition location at the driver side seat or in the engine compartment. In the tests with ignition at the driver side seat and with windows open as well as with the fire initiated in the engine compartment, the fire was able to build to a size that allowed spread to the nearby vehicles. In the scenario where the fire was ignited at the driver side seat and windows and doors were closed, the fire burned for a period of time but ultimately self-extinguished due to lack of oxygen. Several of the studies included different ignition scenarios for vehicle fire tests and the ignition mode and location appeared to be important factors in the growth of the fire and the resulting heat release rate, which impacts the propensity of the fire to spread to nearby vehicles. In other words, with the same exact experimental setup (same model vehicles and same distance to neighboring vehicles) but a differing ignition scenario and/or variables in terms of the condition of the vehicle (windows open/closed etc.), different results in terms of heat release rate and fire spread can and did occur.

A number of the studies examined the effects of vehicle fires on the neighboring structures. BRE [18] studied the effects of vehicle fires on concrete structures similar to parking garages. Several of the vehicle fire tests in this study led to extensive spalling of the concrete at the surfaces of the testing facilities. Strum et. al. [58] performed five vehicle fire tests in a road tunnel. They concluded that “the heat release rate of a BEV is higher than that of conventionally fueled vehicles. However, how much additional heat is released depends very much on the extent to which the battery is involved in the fire.” These tests were not run to completion as the firefighting efforts were initiated 10 minutes after the start of each fire test (replicating a typical fire department response time), but they stated that numerical simulations of such tests for longer periods showed that the tunnels can experience significant structural damage due to fire. Tramoni et. al. [57] studied the effects of vehicle fires of unprotected steel members of a parking garage. They tested an ICEV, a BEV, a LPGV, a NGV, and a FCEV. The highest temperatures at the steel members were measured during the testing of the FCEV and the LPGV and were slightly above 900°C. The study concluded that “These tests suggest that the stability of the structure is not adversely affected by the type of vehicle” as far as the steel members are concerned in their testing setup. Several other studies included the temperature measurements of the plume above the fire as included in the database.

Several of the studies measured heat flux during the vehicle fire testing at multiple targets away from the burning vehicles to better understand the effects of the fire on the surroundings including fire spread to other vehicles. The BRE [18] study stated that a heat flux exceeding 25 kW/m^2 is “in excess of critical irradiance of most combustible materials”. This value is generally consistent with the critical ignition heat flux for many plastics [65]. As provided in several of the publications [[50], [52], [54], [60], and [18], the vehicle fire tests for both ICEVs and BEVs produced heat fluxes at nearby targets greatly exceeding 25 kW/m^2 . The targets were placed

0.5 to 1.5 meters (1.64 to 4.92 ft) from the vehicle in most studies, which is in line with the distances between parked cars using the guidance for parking structure design.

Another piece of data that was commonly reported across studies was determination of peak HRR and total heat released (HR) of fires either by calorimetry or using the mass loss rate of the vehicle being burned. The peak HRR varied across studies but most of the studies showed that the EVs produced higher peak HRR in more cases as compared to ICEV but in the study by Lam et. al. [54] where all of the vehicles were tested for the same length of time (30 minutes), ICEVs produced higher peak HRR. Since the test conditions (ignition type and location) and burn duration varied across studies, peak HRR may not be a good comparison point between studies. A few of the studies documented total heat released during each fire test as well the total mass loss as shown in Table 3. Heat released per unit mass across all three studies reported similar values when comparing ICEVs against BEVs. Kang et. al. [52] also tested an EV battery by itself which demonstrated a higher heat released per unit mass as compared to other vehicles in the study including the test using only the body of the same EV from which the battery was removed. The total HR numbers from the Lam et al. study are lower because the vehicle fire tests were only run for 30 minutes each before extinguishment. They also tested two PHEVs that show comparable values for HR/kg.

Reference	Fuel Type	Total Heat Released (MJ)	Mass Loss Total (kg)	HR/mass (MJ/kg)
Kang et. al.	Electric (Bat. Only)	1300	28	46.4
	Electric (Body Only)	7530	262	28.7
	Electric	8450	284	29.8
	Electric	9030	296	30.5
	Gasoline	8080	314	25.7
	Hydrogen	10820	397	27.3
Lam et. al.	Gasoline	3290	274	12.0
	Electric		333	
	Electric	4910	295	16.6
	Gasoline	4950	336	14.7
	Electric	4660	363	12.8
	Hybrid	4630	308	15.0
	Hybrid	5850	445	13.1
Lecocq et. al.	Electric	6314	212	29.8
	Gasoline	6890	192	35.9
	Electric	8540	278.5	30.7
	Gasoline	10000	275	36.4

Table 5. Total hear released and mass lost for the duration of the test during the vehicle fire testing by Kang et. al. [52], Lam et. al. [54] and Lecocq et. al. [55]. Shading denotes type of vehicle.

Some of the studies ([50], [55], [56], and [58]) were performed to analyze the production of toxic gases during the fire testing of various vehicles. Included in the components of the fire exhaust included metals such as cobalt, lithium, manganese, and nickel. The fire plumes were also analyzed for compounds including carbon monoxide, carbon dioxide, hydrogen fluoride, hydrogen chloride, hydrogen bromide to name a few. The overall assessment of the fire exhaust indicates that many compounds are released during a vehicle fire, likely due to the synthetic nature of the combustible plastics used in the vehicle, and that many of these chemical components have toxicity implications to occupants and firefighters.

Sprinklers were included in very few vehicle fire tests. Arvidson et. al. [50] used a sprinkler system that operated manually at 372 l/min during all four tests for the ICEVs and BEVs with a sprinkler density of 10 mm/min. The water spray system was activated when the fire reached between 1 to 1.5 megawatts, which was about 1 minute into the ICEV tests. For the BEV tests, the water spray was activated later as fire growth rate was slower as compared to the ICEV tests. The peak heat flux measured during each test was 44-138 kW/m^2 for ICEVs, measured on each side of the vehicle at 500 mm (19.7 inches) and at about door handle height of the vehicle, which would simulate the approximate distance to a neighboring vehicle. The peak heat flux for the BEVs was only 5-7 kW/m^2. Since the fuel tanks for ICEVs were punctured and the fuel was leaked on the floor and ignited (large pool fire under the vehicle), a large spike in HF occurred which was also seen in the HRR. Meanwhile, BEVs burned slower and the sprinkler spray controlled the radiant heat to the targets. The water spray did not suppress the fire during any of the tests. BRE [18] performed one test where OH2 sprinklers were used as designed in accordance with British Standard EN 12845:2004 [66]. OH2 in the BRE study is 5 mm/min sprinkler density or light hazard/OH1 per NFPA 13 [29]. Three vehicles were included in the fire test where two vehicles for were parked next to each other and one vehicle had a gap of a parking spot from the pair. This scenario was also tested without the sprinklers and the fire eventually spread to all three vehicles. For the test with the sprinklers, the vehicle where the fire was initiated continued to burn reaching a HRR of 7 MW but the sprinkler performance was successful as it controlled the fire and prevented spread to any other vehicles.

Figure 33 from NFPA 13 ([29]) shows the sprinkler densities as related to the hazard categories. The limited number of tests included the reviewed literature that involved sprinklers, used sprinklers densities that were either between light and OH1 (5 mm/min) or slightly higher than OH2 (10 mm/min) when converted to the NFPA 13 densities as presented in Figure 33. In both tests by BRE, one involving three vehicles and one involving two vehicles in a stacker configuration, OH2 (equivalent to between light and OH1 in the United States) sprinklers were able to control the fire from spreading, though the fire was not extinguished by the sprinklers.

BRE [18] performed one fire test that involved two vehicles (ICEVs) in a stacker setting, as shown in Figure 36, where the objective was to observe the fire spread from the lower vehicle to the upper vehicle. The fire was ignited on the driver side seat of the lower car with windows open to observe the fire development and HRR of the fire. Figure 36 shows the test setup and the fire in progress. The fire burned for about 25 minutes without sprinklers and was extinguished by the fire service.

Figure 36: Test 11 as published in BRE report [18]. First image (left) shows the setup of the stacker test. The second image (right) shown is 10 minutes and 10 seconds after the fire was started at driver side seat of the bottom car with the windows open.

The stacker fire reached a peak HRR of 8.5 MW after just 12 minutes from the start of the fire. The total HR reached about 6000 mega joules (MJ) before the fire was extinguished.

A similar stacker test was repeated in 2009 by BRE Global [61] with eight (8) quick response sprinkler heads (Tyco TY363-1-11). Four sprinkler heads were installed above each vehicle. The sprinklers were designed to be OH2 per BS EN 12845 [66]. The setup was similar to the non-sprinklered test, though the vehicles were different models but arranged the same way as seen in Figure 37. The vehicles, both ICEVs, had 20 liters of fuel in the tanks. The fire was started at the driver side seat of the bottom vehicle with a No. 7 crib and driver side window was open.

It should be noted that the BRE stacker test with sprinklers utilized a 1992 diesel-powered Land Rover Discovery and a 2001 gasoline-powered Ford Mondeo hatchback. Meanwhile, the BRE stacker test without sprinklers utilized a 2001 gasoline-powered Land Rover Freelander and a diesel-powered 2001 Peugeot 406 Estate. All of these automobiles are older and hence may have quick different compositions compared to modern vehicles. For instance, while these vehicles were only a little bit older than the oldest vehicle involved in the Merriweather parking garage fire (see Table 2), the vehicle trends contained in Figure 10 indicate that vehicles between 1992 and 2001 contain, on average, anywhere from 100 to 140 kg of plastics, while a modern vehicle, on average, contains 160 – 200 kg of plastics. While this test data is certainly useful, it does warrant consideration of whether these tests are representative of modern vehicles in a stacker configuration.

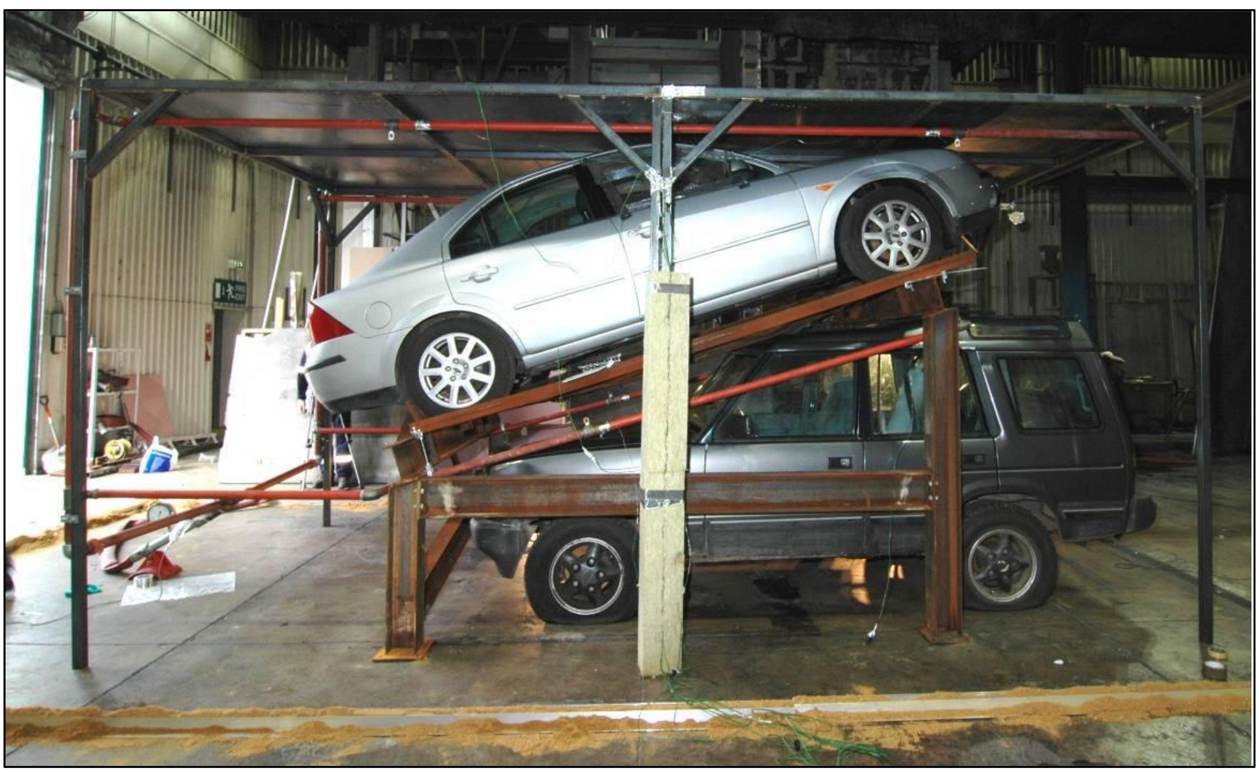

Figure 37: BRE [61] (Figure 3 in the publication) test setup for the stacker vehicle fire test with sprinklers. Eight automatic sprinkler heads (60°C) were installed, one near every corner of each vehicle.

It should also be noted that while the BRE study indicates that the system “was to be designed to be as consistent as possible with an ‘Ordinary Hazard’ risk system, the sprinklers in the test were K-80 sprinklers, operating at approximately 15 psi, as opposed to K-80 sprinklers operating at approximately 5 psi at the remote sprinkler, as is typical for EN 12845 OH2 systems. This threefold increase in pressure results in approximately 75% more water being delivered than a European OH2 system. Therefore, instead of 5 mm/min, approximately 8.66 mm/min was likely delivered, which more closely resembles the NFPA 13 OH2 density, or even a little higher.

As the fire grew in the BRE stacker test, the flames reached outside of the window of the bottom vehicle at about 4 minutes of the start of the fire. At about 11 minutes, the fire was seen at the under carriage of the upper vehicle. The sprinklers activated between approximately 13 minutes to 22 minutes after the start of the fire. The test continued for one hour after the activation of the first sprinkler. During this time fire continued to burn inside the bottom vehicle and underneath the top vehicle. At this point, the sprinklers were turned off for 10 minutes to see the effect on the fire and the fire started to grow under the top vehicle. The sprinkler system was turned back on and the fire was controlled again. The test was stopped at 1 hour and 40 minutes after the start of the fire with the residual fire extinguished by the fire department. After the test, a majority of the combustibles inside the bottom vehicle were consumed by the fire. The top vehicle suffered significant damage to the engine compartment but the fire did not reach the interior (passenger compartment) of the vehicle. Figure 38 shows the tests in progress, performed by BRE, after about 21 minutes from the ignition of the fire inside the bottom vehicle for both un-sprinklered (left image) and sprinklered (right image) tests.

Figure 38: The stacker test images shown are at about 21 minutes after the start of the fire at the bottom vehicle driver side seat for both tests as performed by BRE [18] [61], no sprinklers (left) and with sprinklers (right). (Images taken from Figures 27 and 28 of BRE [61]). The sprinklers activated (right image) starting at about 13 minutes after the start of the fire.

The literature reviewed included a limited number of vehicle fire tests that included the use of sprinklers to control the fire [[50], [56], [18]] and evaluate if the fire was capable of spreading beyond the first vehicle. Arvidson and Westlund [50] used sprinkler systems designed with the density of 10 mm/minute, which is between an OH2 and EH1 design density in the United States. They measured heat flux (HF) at targets 500 mm for four tests involving two ICEVs and two BEVs, all tested individually. HF data for BEV tests showed that the fire will not spread to the neighboring vehicles. BRE [18] performed a test that used an OH2 (British Standard) sprinkler system (between light and OH1 in the United States) and the fire did not spread to the other vehicles parked nearby. A test with a similar test setup that included three vehicles also was previously run by BRE without the sprinklers and the fire spread to all three vehicles while starting on the driver seat of the first vehicle. There is very limited data available to assess the effect of sprinklers on vehicle fires and what the effective density needed to prevent fires from spreading to other vehicles in parking garages. Nevertheless, this limited data does indicate that the presence of sprinklers can control the fire and limit it to the initial vehicle, but the necessary design density to accomplish that control is still relatively unknown. More research is needed to properly design the sprinkler systems to prevent vehicle to vehicle spread in parking garages.

Gap Analysis

After the review of parking structure design principles and guidelines, representative incidents, relevant codes and standards, and the anthology of published literature which includes full-scale experimental tests with modern vehicles, the data was considered holistically to identify knowledge gaps regarding the fire hazard of modern vehicles in parking garages. As was described initially in the FPRF 2020 report [1], the principal concern in parking garage fires is vehicle-to-vehicle fire spread. This is the mechanism whereby a fire in a parking garage can escalate into a conflagration that possibly endangers Fire Department personnel and building occupants and may threaten to render the building and contents a total loss. Therefore, the knowledge gap analysis and resulting proposed research plan focuses on the factors that directly affect the fire spread mechanism.

Sprinkler Hazard Classification

Sprinkler usage has been mandated for enclosed garages for many years and was recently included in NFPA 88A for open garages. Additionally, NFPA 13 has migrated the hazard classification from an Ordinary Hazard 1 (OH1) design density to an OH2 design density for parking garages. However, as several members of the NFPA 13 Technical Committee have indicated, there is a lack of data supporting this increase from an OH1 to an OH2 design density. Clearly, this indicates that there is a level of concern from code- and standard-making bodies that there is insufficient technical data to justify moving from OH1 to OH2, let alone if this design density is sufficient to prevent fire spread in some situations.

The few incidents reviewed for this project indicate that when sprinklers are present, the fire was either suppressed outright, or was at least controlled with no significant fire spread to neighboring vehicles, including conditions where a vehicle was in the immediate next neighboring space. Conversely, in the fire incidents without sprinklers usage, the fire did spread to neighboring vehicles on occasion, and in some cases was able to ignite vehicles more than one (1) empty space away and even across distances over two empty spaces away. This indicates that the presence of sprinklers appears to change the outcome as it relates to fire spread to neighboring vehicles, even if it does not necessarily alter the outcome for the originating vehicle. The sprinklers in garages in the US presumably used the OH1 design density (6.1/140 mm/min/m^2). At least one, though, was at the European OH2 design density (5/144 mm/min/m^2). This is between the light (4.1/140 mm/min/m^2) and OH1 design density in the U S. And while this fire in Germany did do considerable damage to the origin vehicle, damaged three other nearby vehicles to an unknown magnitude, and did some damage to the garage structure, the fire still was reportedly controlled by the sprinkler. This incident involving a sprinkler system with the European OH2 design density controlling a fire raises the question of the necessity of an OH1 (or OH2) design density. The use of OH2 may be an overdesign and potentially unnecessary and unwarranted requirement in NFPA 13. Recall, the Technical Committee for NFPA 13 was and still is considering a further increase to an EH1 water density, which would further increase the water density and would require different equipment than current OH systems. At this time, there is no clear data available to use for examining this question of what sprinkler design density is appropriate.

The database compiled of recent vehicle fire studies was analyzed to examine the range of outcomes that can occur as a function of sprinkler design density. This is shown graphically as Figure 39. As can be seen in Figure 39, any time sprinklers were utilized in an experiment, the fire failed to spread to a second vehicle and the data (e.g., peak heat flux, etc.) indicated that spread would not occur had a second vehicle been present. This data with sprinklers, though, only encompasses five tests, which is a relatively small data set and did not evaluate factors which may affect sprinkler effectiveness (e.g., wind). It should also be noted that the two tests in Figure 39 with a sprinkler design density over 6.1 mm/min (NFPA 13 OH1) where the heat flux exceeded 10 kW/m^2 were tests where the liquid fuel of an ICE was initially leaked under the vehicles and ignited, leading to a large, albeit short-duration, fire with a higher, though short, peak heat flux. In these tests, though, ignition of neighboring vehicles still did not occur.

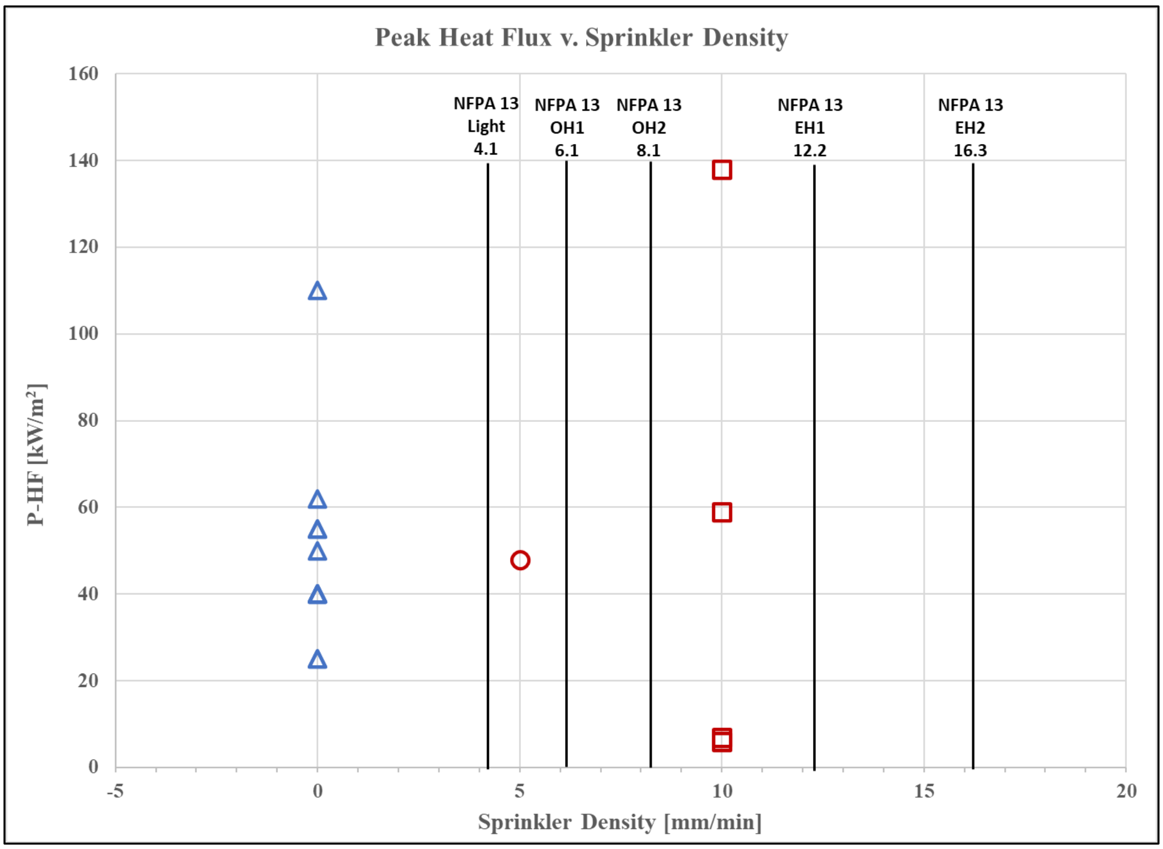

Figure 39. Peak heat flux at the neighboring vehicle location in testing documented in the literature database as a function of the sprinkler density. Blue triangles represent vehicle fire tests with no sprinklers, red circles represent tests with a sprinkler density of 5 mm/min and red squares represent tests with a sprinkler density of 10mm/min.

The control of the fire to a single vehicle, even at sprinkler design densities lower than the United States OH1 levels, confirms what was found in the limited number of fire incidents that were analyzed. The sprinkler water density necessary to control a fire to a single vehicle and prevent vehicle-to-vehicle fire spread is relatively unclear and may be lower than the currently mandated OH2 sprinkler design density in NFPA 13. But again, this is based on a very limited data set with very little consideration of the range of possible critical variables. Additionally, most of this very small data set was conducted at a sprinkler density above the NFPA 13 OH2 water density, and therefore there is still the question of whether an OH2 density would control the fire and prevent fire spread if all critical variables are set to a reasonably foreseeable worst-case value. Further testing is necessary to quantify exactly what design density is necessary to contain a fire to a single vehicle, even under worst-case conditions. The Technical Committee would then have actionable data to support requirements in NFPA 13 that, with an appropriate safety factor, would reliably control a vehicle fire in a parking garage without spread to neighboring vehicles.

Fire Growth Critical Variables

Based on the current literature, it is not known what exactly is the worst-case fire scenario for a modern vehicle in a parking structure. Requirements in codes and standards should generally be based on reasonably foreseeable worst-case scenarios. This scenario would include not only the ignition scenario, but other critical variables such as type of vehicle, ventilation paths (windows open or closed), etc. With a modern vehicle in a parking garage, though, the ultimate outcome of the fire is highly dependent on the particular conditions of the vehicle and the ignition scenario.

A review of the tests in the literature indicates that a BEV can have a jet flame originating from the battery that can directly impinge on a neighboring vehicle. This type of situation may ignite the neighboring vehicle regardless of whether sprinklers are present or not. An ICE vehicle can have a high initial heat release rate from a release and ignition of the contents of a fuel tank which could ignite neighboring vehicles regardless of the presence of sprinklers as the burning liquid fuel under the vehicles is shielded from the water.

Both types of vehicles, BEV and ICE, can also have ignition take place in the passenger compartment where there is a large amount of readily-consumable fuel. The state of the vehicle windows during the test also appears to be an important variable, as when the windows are up and sealed, it becomes harder for heat to reach the sprinklers for activation and for water to reach the seat of the fire. Conversely, though, the fire often self-extinguishes due to a lack of oxygen if the windows are closed. Meanwhile, if the windows are open, it becomes easier for heat to escape and activate the sprinkler system, and easier for sprinkler water to reach the passenger compartment and control the fire. But with the windows open, oxygen is more readily available for the fire and it can continue to grow without self-extinguishing. As can be seen in Table 6, a wide range of resulting fire conditions can result from the vehicle variables and ignition scenarios. The table is sorted based on the peak heat release rate. While there does appear to potentially be some relationship between a higher heat release rate and the windows being open as well as the fire starting in the battery or under the vehicle (liquid fuel), the relationship is not very strong with some high heat release rate fires occurring in vehicles with closed windows and/or ignited in the passenger compartment. Therefore, while there is some data in the literature about these variables and their outcomes, it is still unclear what exactly is the reasonably foreseeable worst-case vehicle condition and ignition scenario that could highly challenge building safety and sprinkler and fire protection system performance.

Ref. No	Vehicle Type	Ignition Location	HF Target Distance (m)	Peak HF (at Targets)(kW/m2)	Peak HRR (kW)	Sprinklers	Sprk Density (mm/min)	Windows (Opn/Cld)	Pass. Comp. Ign.
12	ICEV	On the Front Seat			100	No		Closed	Fire set inside
12	ICEV	On the Front Seat			100	No		Closed	Fire set inside
3	BEV	Battery Compartment and Propane Burner under Vehicle	0.89	-	1540	No		Open	Yes
1	BEV	At the Battery		5-6	1975	Yes	10	Closed	Yes
14	ICEV	Right Rear Splashguard			2000	No		Closed	Yes
11	ICEV	Left-rear splash guard	0.5-1.0	31-40	2100			Closed	Yes
9	ICEV	Inside the engine compartment			2300				
1	BEV	At the Battery		6-7	2944	Yes	10	Closed	Yes
14	ICEV	Left Front Seat			3100	No		Open	Yes
15	ICEV	Right Rear Splashguard			3100	No		Closed	Yes
15	ICEV	Front Bumper			3100	No		Closed	Yes
12	ICEV	Engine Compartment			3800	No		Closed	Yes
14	ICEV	Right Rear Splashguard			3800	No		Open	Yes
14	ICEV	Right Rear Splashguard			3800	No		Closed	Yes
15	ICEV	Third Row Seats-Middle			4000	No		Open	Yes
6	BEV	On the Front Seat	5, 8	Not Provided	4200			Open	Yes
6	BEV	On the Front Seat	5, 8	Not Provided	4700			Open	Yes
6	ICEV	On the Front Seat	5, 8	Not Provided	4800			Open	Yes
12	ICEV	Engine Compartment			4800	No		Closed	Yes
9	ICEV	Inside the Vehicle			4900				
12	ICEV	On the Front Seat		48	5000	Yes	5	Open	Fire set inside
1	ICEV	Leaked Fuel on the Floor		44-59	5324	Yes	10	Closed	Yes
5	BEV	Under the Vehicle	3.1-3.9	20-40	5900	No		Closed	Yes
3	FCEV	Propane Burner under Vehicle	0.89	-	5990	No		Open	Yes
5	BEV	Under the Vehicle	3.1-3.9*	20-40	6000	No		Closed	Yes
5	PHEV	Under the Vehicle	3.1-3.9*	20-55	6000	No		Closed	Yes
9	BEV	Under the Vehicle			6100				
6	ICEV	On the Front Seat	5, 8	Not Provided	6100			Open	Yes
11	BEV	Rear bumper	0.5-1.0	32-62	6400			Closed	Yes
3	BEV	Battery Compartment and Propane Burner under Vehicle	0.89	-	6510	No		Open	Yes
5	BEV	Under the Vehicle	3.1-3.9	20-40	6900	No		Closed	Yes
9	BEV	Liquid NaCl inj. Into battery			7000				
5	ICEV	Under the Vehicle	3.1-3.9	20-40	7100	No		Closed	Yes
3	BEV	Battery Compartment and Propane Burner under Vehicle	0.89	40-110	7250	No		Open	Yes
3	ICEV	Propane Burner under Vehicle	0.89	30-50	7660	No		Open	Yes
3	BEV	Battery Compartment and Propane Burner under Vehicle	0.89	-	7810	No		Open	Yes
5	PHEV	Under the Vehicle	3.1-3.9	20-55	7900	No		Closed	Yes
1	ICEV	Leaked Fuel on the Floor		98-138	7978	Yes	10	Closed	Yes
12	ICEV	On the front seat of Bottom vehicle			8500	No		Open	Yes
9	BEV	Liquid NaCl inj. Into battery			8600				
5	ICEV	Under the Vehicle	3.1-3.9	20-40	10800	No		Closed	Yes
12	ICEV			25	11000	No		Open	Yes
12	ICEV			25	16000	No		Open	Yes
15	ICEV	Middle Row Seats-Middle				No		Closed	Yes/ Went Out
16	ICEV	Engine Compartment				No		Closed	Yes

Table 6. Database testing sorted minimum to maximum peak heat release rate with test scenario details.

Stacker Systems and Automated Parking Systems

Currently there is a dearth of technical information on the performance of fire protection systems and combustion characteristics of modern vehicles in stacker systems and/or other automated parking systems. In general, all data sources provided very little guidance and justification, if any at all, on the recommended fire protection scheme for these types of parking systems. Regarding automated parking systems, there are no known published experiments, no known incidents from which to compare performance, and no known code requirements. In other words, if an automated parking system was constructed today, the AHJ would have no knowledge base to draw from to ensure a reasonably safe design of the parking system. The AHJ would likely be forced to require a performance-based design and still would have no data or metrics by which to ensure said performance-based design is adequate.

Stacker, or vertical parking, systems only have marginally better information available. Aside from some computer fire modeling and reduced-scale tests [67], only two known tests exist in the published literature, that being a sprinklered and an un-sprinklered test by BRE ([61], [18]). As noted previously, these tests were conducted with vehicles having a model year in the 1990s or early 2000s, and therefore there is a question of whether these vehicles really represent modern vehicles. The available fuel in a vehicle, particularly plastics, is continuing to increase and has increased significantly since the year 2000. The unsprinklered stacker test demonstrated that a fire in the lower vehicle can easily spread to the upper vehicle without the presence of a sprinkler system. The sprinklered test was reportedly designed to a European OH2 density of 5/140 mm/min/m^2, which is between the NFPA 13 light and OH1 design densities, but the pressure was far higher resulting in a sprinkler density of approximately 8.5 mm/min, which is slightly higher than the NFPA 13 OH2 water density. The sprinklers were both in-rack and at the ceiling level (i.e. immediately above both vehicles). The fire on the lower vehicle was not extinguished, but it was controlled with only minor fire spread to the bottom of the vehicle on the second level. This suppression system configuration is different than that currently mandated for a two-level stacker system in NFPA 13. NFPA 13, allows in-rack sprinklers with an OH2 density at the ceiling, or simply an EH2 density at the ceiling without the in-rack sprinklers. The OH2 density above both vehicles would be similar to that tested by BRE. Therefore, two knowledge gaps are identified here. First, will an EH2 design density at the ceiling without in-rack sprinklers above the lower vehicle prevent fire spread to the upper vehicle and nearby vehicles? Secondly, there is no data at all regarding vertical stacker parking over two-levels high. This void explains why there are no requirements in NFPA 13 for stackers over two-levels high and, ergo, municipalities are having to make requirements on their own. The data available is very limited and likely outdated. Obviously, stacker tests are expensive as they may require two or more vehicles per test, and an installed sprinkler system. However, it is not desirable to rely on a limited, dated set of experiments to set code requirements for modern vehicles.

Finally, there are no known incidents regarding stacker systems, both in the United States and abroad. This lack of stacker incidents was confirmed by RISE [17]. This is potentially fortunate as it may indicate that stacker systems are not resulting in a significant number of fires. It also may indicate that perhaps any stacker systems in use have suppression systems either mandated by NFPA 13 (2 levels or less), municipalities, specially engineered systems, or just AHJ requirements for performance-based design, that are adequately controlling and/or suppressing the fire. Conversely, it may simply mean that there are not that many stacker systems in use currently and that as their use potentially increases, fires may become more prevalent. The data on past incidents in stacker systems is currently lacking, which makes a test series with controlled parameters important for setting standards and requirements.

Therefore, in sum, three major knowledge gaps have emerged when evaluating the fire safety of modern vehicles in parking garages:

1. The appropriate NFPA 13 hazard classification for the sprinkler system
2. The reasonably foreseeable worst-case scenario based on vehicle characteristics (windows, etc.) and fire ignition scenario
3. The appropriate fire suppression system characteristics for stackers and automated parking structures

Research Plan

Based upon the identification of knowledge gaps, a research plan for full-scale fire tests of modern vehicles is proposed. The ultimate goal of the research plan is to test a range of vehicle types under conditions that are determined to represent reasonably foreseeable worst-case scenarios. The results would provide actionable technical data that code- and standard-making bodies can use to create, justify, and implement fire safety requirements and recommendations.

One of the primary issues with full-scale testing of vehicles in parking garages is the expense and scale of the tests. Modern vehicles are expensive and the test facilities required for detailed experimental work are extensive, so just a single test requires considerable resources, and consequentially the cost for a single data point is significant. One possible way to minimize said cost is to explore cost-effective methods to obtain the vehicles or utilize surrogate methods to approximate the burning behavior of a vehicle. For BEVs, these vehicles may be difficult to obtain in a cost-effective manner as the installed base is lower than for ICEs. For ICEs though, it may be advantageous to try to obtain vehicles that were damaged in the field to the point that it was considered a total loss despite still being acceptable for fire testing. One possibility is water damaged vehicles which are no longer considered road-worthy, but as long as they are complete, would be acceptable for fire testing. Nevertheless, as will be explained below, a proposed financially-feasible fire testing matrix is included that will provide full-scale test data, but has some drawbacks regarding repeatability and number of tests. Additionally, an alternative approach is proposed that may offset some of the drawbacks of the full-scale vehicle test matrix. Finally, a combination of both approaches could also be utilized.

Methodology and Experimental Setup

The goal of the proposed research is to provide detailed information concerning fire protection issues of vehicle fires in parking structures, with an emphasis on preventing vehicle-to-vehicle fire spread. The testing should target the identified knowledge gaps. Therefore, it is recommended that all tests have, at a minimum, mass loss measurements to approximate heat release rate. Certainly, if large scale calorimetry is possible during these tests, it should be utilized. But there are a number of tests in the literature, both indoors and outdoors, that have determined the heat release rate of modern vehicles, reducing the need for this data from this test series. Of more paramount importance is a determination of the heat flux and/or direct flame impingement to a neighboring vehicle or to a surrogate to determine if the fire can spread.

Sprinkler Density Experiments

The objective of this set of experiments is to better determine the sprinkler design density necessary to control and/or fully suppress a vehicle fire while preventing fire spread to the neighboring vehicle. Additionally, these tests will potentially help better define what conditions represent a reasonably foreseeable worst-case scenario. These experiments should be conducted in a mock-up parking garage geometry (i.e., a ceiling should be present), but the sides can be open simulating an open-style parking garage. Mass loss should be recorded so an approximation of the heat release rate can be calculated (if not measured directly), assuming much of the heat release after the initial battery or liquid fuel fire is a generic plastic.

The type of vehicle to be tested (or utilized to develop a surrogate burner as will be discussed) may be dependent on availability and cost, but should be a relatively new vehicle (built within the past five years and of a size near that of the design vehicle described in the first Section of this report). While utilizing more than one vehicle in a test is certainly preferred, given that the cost of each test is expected to be significant, limiting each test to a single vehicle and then utilizing heat flux gauges and a target plastic and/or mock-vehicle to mimic the neighboring vehicle(s) is likely a much more cost-efficient way to run the tests with less expense and yet still obtaining the data desired from this testing. The proposed distances for the targets are shown in Figure 40. The parking spaces should be 8'3" (2.51 m) wide, which is the minimum spacing as determined from parking structure design references (see Figure 2), and the distances are based on the design vehicle 6'7" (2.00 m) wide. The first target is selected to be 6" (0.15m) away, which would represent both automobiles parked on the very edges of the spaces, to the point where one would not even really be able to open the door the vehicle to get in or out. This spacing would also potentially have applicability to a situation where a collision has occurred in a parking garage, resulting in a fire with the vehicles involved in the collision positioned very close together. The second target is 10" (0.25 m) away, which would represent one vehicle right on the line of the space, and the other centered in the space. The third target is 1'8" (0.53 m) away, which would represent both vehicles centered in the spaces. Finally, the last target is 9'11" (3.02 m) away, which would represent one vehicle centered in the space, and a vehicle two (2) spaces away but right on the edge of the space. These target distances should represent the range of expected heat fluxes to nearby vehicles for a burning design vehicle and a worst-case, but reasonably foreseeable, parking space size.

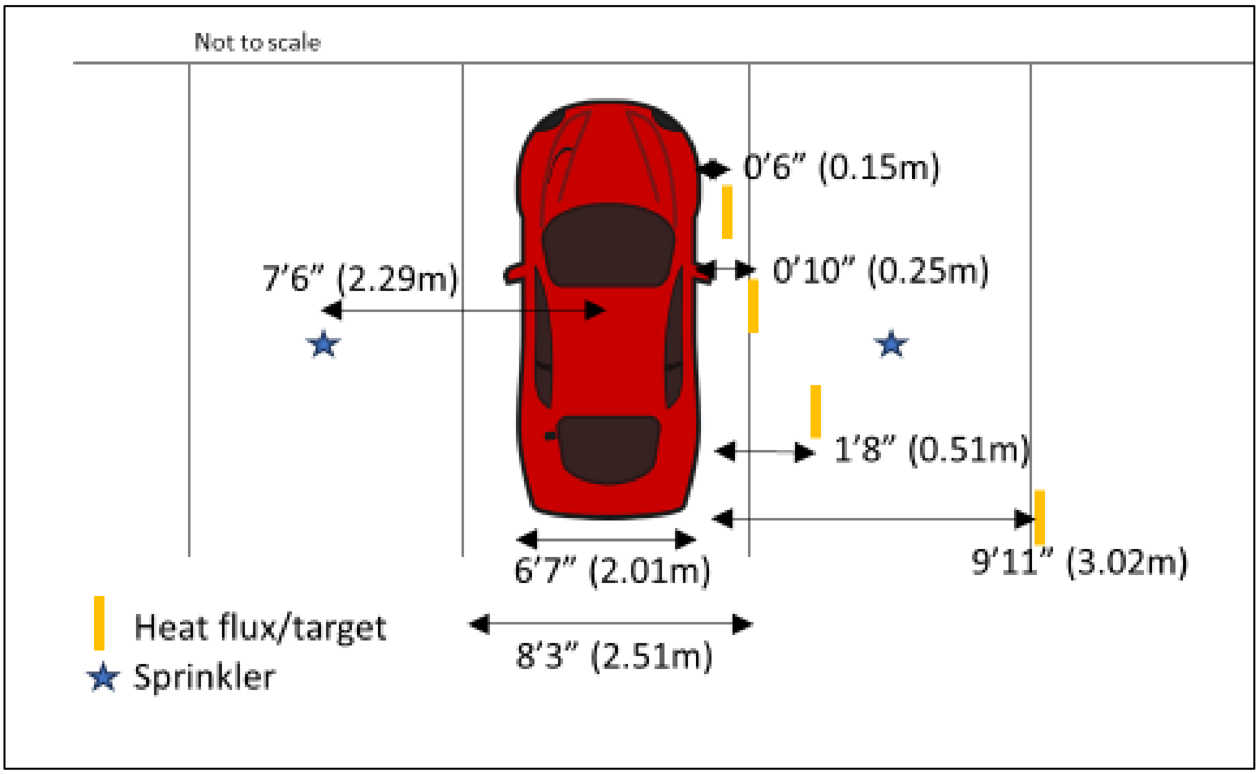

Figure 40. Proposed reasonably feasible test layout of sprinklers and heat flux targets.

In addition to the target heat fluxes (and target fuels), heat flux and temperature should be measured at the ceiling immediately above the vehicle for potential structural exposure considerations.

A number of the tests should include sprinklers. The sprinkler design density will be varied. The sprinklers, though, should not be manually activated, but should be automatically activated as would occur in the field. According to NFPA 13 [37], the maximum spacing for ordinary hazard sprinklers is 15 feet but can be as high as 20 feet for ordinary hazard extended coverage sprinklers. It is unknown, though, what sprinkler positioning represents a worst-case scenario. A sprinkler over the origin vehicle may better control the fire in the vehicle and may reduce the fire size and, consequently, the resulting heat flux, depending on the fire location on the origin vehicle, but may result in less water over the neighboring vehicles and therefore may be less effective in preventing vehicle-to-vehicle spread. Conversely, sprinklers spaced as far from the origin vehicle as possible may provide more water to the neighboring vehicles impeding vehicle-to-vehicle fire spread, but may therefore allow the origin vehicle to have a higher heat release rate and resultant heat flux, which would aid in possible vehicle-to-vehicle fire spread. Obstructions will also have to be considered, with appropriate spacing from them in accordance with NFPA 13, particularly for extra hazard sprinkler densities. Therefore, the location of the sprinklers is a variable that will have to be considered and is part of the knowledge gap regarding the variability of outcomes based on the fire scenario. Furthermore, since many of these fire suppression systems will be exposed to cold environments, a dry-pipe system should be used with a delay in water flow after activation, which would be a worst-case situation.

The exact sprinklers and sprinkler system characteristics to use in the testing will have to be a consideration. While the desired sprinkler water density is defined in the test matrix, the exact sprinklers to be used with their k-factor and associated water pressure to achieve that sprinkler water density needs to be considered. As the sprinklers should be activated by the fire (i.e., not manually), the temperature rating and thermal sensitivity (RTI), and the resulting activation time of the sprinkler also requires consideration and selections should be consistent with NFPA 13 and current typical parking garage installations. The duration of the water flow should be in accordance with the minimum NFPA 13 requirements for the sprinkler water density being tested (e.g. 60 to 90 minutes for ordinary and extra hazards respectively).

The two primary variables that should be tested are differing ignition scenarios and sprinkler densities. As it relates to variables and ignition scenario for a worst-cast fire, both BEVs and ICEs should be tested. A review of the literature points to a relationship between open vehicle windows and a higher heat release rate of the fire. Therefore, the windows should always be open or somewhat open as this seems to be a worst-case condition. In the BEV tests, the battery should be punctured to cause a jet flame out of the side of the vehicle where the heat flux gauges and target fuels are located. In the ICE tests, the fuel tank should be punctured and the liquid fuel ignited under the vehicle. These are two unique and likely potentially worst-case failures in each type of vehicle. Then both vehicles should also be ignited in the passenger compartment on one of the seats. This will allow comparison of the ICE and BEV with identical ignition scenarios. Additional considerations when establishing the potential worst-case scenario are whether a slope to the floor should be used to allow liquid fuel from ICEs to potentially travel from the origin vehicle towards the instrumented targets and target fuels, as well as whether an airflow should be implemented to simulate the airflow in a parking garage under high wind conditions. Such an airflow could be capable of tilting the flame towards a neighboring vehicle. Previous testing of airspeeds in parking garages has shown that while the speed of the wind slows inside an open-style parking garage compared with the wind speed outside, it does not completely diminish [68] and therefore may need to be considered in the testing.

Regarding the role of sprinkler water density, a review of a single test in the literature and a review of incidents indicated that the European OH2 design density of 5/144 mm/min/m^2 controlled the fire. This value is between a light and OH1 design density per NFPA 13. Nevertheless, NFPA 13 already mandates an OH2 sprinkler density and the Technical Committee was reportedly considering even increasing further to an EH1 density. A change from OH1 to OH2 does not require significant changes in sprinkler system equipment, but a change to EH1 does. Based on these considerations, it is proposed that an unsprinklered test should be conducted as a baseline, followed by a combination of OH1, OH2, and EH1 densities. If any of the scenarios results in conditions that would result in vehicle-to-vehicle spread, even at an OH2 design density, the test should be repeated one more time with an EH1 design density. This will determine both the difference in performance when sprinklers are present versus when they are not, as well as what density, if any, is capable of controlling the fire and preventing spread to neighboring vehicles.

Based on the data in the literature, if the vehicle windows are open, a fuel tank rupture in an ICE appears to be a potential worst-case scenario for fire spread due to the large initial heat release rate from the burning liquid fuel. Therefore, this scenario is tested without sprinklers and at an OH2 water density. If the OH2 water density controls the fire and prevents conditions considered capable of vehicle-to-vehicle fire spread, the second test could either repeat the OH2 density or be reduced to OH1. If the OH2 water density does not prevent conditions deemed capable of vehicle-to-vehicle fire spread, the water density should be increased to EH1 for a second test. However, given that there are several parameters that can influence fire spread and may not be included in a test, and that NFPA 13 already mandates an OH2 density, the second test may want to focus on a repeat of the OH2 design density test or an increase to an EH1 design density to maximize the information gained.

Continuing through the matrix, a BEV ignited with a battery puncture is only tested without sprinklers and with whatever the maximum necessary density was necessary to control the ICE fuel tank puncture test (OH2 or EH1) to confirm that that design density can control the failed BEV battery vehicle fire as well and prevent fire spread. The process is then repeated with a fire ignited in the passenger compartment of a BEV, with one test unsprinklered, and a second test at an OH2 water density. Depending on the results of the OH2 test, a second test could be conducted at EH1, OH1, repeated at OH2. Similar to the ICE fuel tank rupture test, given that NFPA 13 currently mandates an OH2 water density, the second test may want to focus on a repeat of the OH2 density or an increase to an EH1 water density to maximize the information gained. Finally, one test in an ICE vehicle ignited in the passenger compartment without sprinklers should be conducted to confirm similar behavior between ICE and BEV fires ignited in the passenger compartment. The entire test matrix is shown below as Table 7.

This test matrix is designed to provide data on what NFPA 13 hazard classification is appropriate for modern vehicles in a parking garage, and also will provide some data on the full-scale fire behavior of modern vehicles as a function of different variables and fire scenarios. The test matrix, as outlined, would require 9 vehicles. While this is likely still a large undertaking from a financial and experimental equipment standpoint, this very limited number of tests would provide some useful data to fill some of the identified gaps. Upon completion of test matrix, data will be available for code- and standard-making bodies to justify a particular sprinkler design density as well providing better data on what the worst-case ignition scenarios are. It will also provide data for fire spread potential in non-sprinklered situations. These non-sprinklered situations, while not allowed by current codes anymore for new construction, still represent a large portion of the built environment due to open-type garages not being required to have sprinklers until very recently.

Vehicle Type	Ignition Scenario	Sprinkler Density (mm/min)
ICE	Fuel Tank Rupture	0
ICE	Fuel Tank Rupture	8.1 (OH2)
ICE	Fuel Tank Rupture	6.1 (OH1) or 12.2 (EH1)
BEV	Battery Puncture	0
BEV	Battery Puncture	8.1 (OH2) or 12.2 (EH1)
ICE	Compartment	0
BEV	Compartment	0
BEV	Compartment	8.1 (OH2)
BEV	Compartment	6.1 (OH1) or 12.2 (EH1)

Table 7. Test matrix of ignition variables and sprinkler densities.

This approach, though, does have some drawbacks. First, there are concerns about the lack of repeatability of the testing. Each test is a single test scenario with a single sprinkler density and is only conducted once. If the test were conducted again, it will provide some idea of the variability of testing and fire scenario. Without any repeated testing, it will be difficult to assess the reliability of the results. Secondly, the testing will not answer every possible question regarding worst-case fire scenarios and configurations. Each test will be dependent on the make and model of the vehicle used for that test and will be dependent on the configuration of that test and vehicle (i.e. window position, sprinkler position, battery size, fuel tank size, etc.). Therefore, the data may have limited application to the landscape of modern vehicles in a parking structure as a whole and may require some extrapolation to other scenarios and conditions. Finally, the data will also be a temporal snapshot in time to answer these knowledge gaps. The testing will provide data on modern vehicles and sprinkler densities at the time of the testing. As was discussed, modern vehicles are continuing to evolve with more and more plastics and combustible fuels being used, as well even new propulsion technologies (hydrogen, fuel cells, etc.) Therefore, the long-term applicability of the test results may also be a concern. But the tests described in the test matrix would provide some data to answer the knowledge gaps regarding the necessary sprinkler water density and worst-case fire scenarios and configurations.

Standardized Mock-up / Surrogate Vehicle Fire

A concept introduced during the discussions with the technical panel reviewing this project was the development of a standardized surrogate or mock-up fire to replicate the characteristics of a modern vehicle fire. The idea of a mock-up fire is to replace the burning of an actual vehicle with a burner that can be controlled to mimic many of the burning and flame characteristics (e.g., HRR, flame height, radiative transfer properties, etc.) of a vehicle fire. There are several reasons that make the development of such a standardized mock-up attractive from a testing standpoint which address many of the perceived areas of concern regarding the full-scale vehicle tests:

Repeatability. Vehicle fires are notoriously unrepeatable, in that even if ignition scenarios, vehicle models, weather conditions are quite similar if not exact, the fire growth and fire characteristics can be different. This can be due to a number of different variables (e.g., reliability of the ignition method, path of fire growth, etc.) which adds to the uncertainty of the data and conclusions determined. Replacing an actual vehicle fire with a surrogate fire that can be more closely controlled will aid greatly in providing some repeatability of the results, evaluating the variability in the test results, and would provide more reliability in the findings since the variability related to the fire source would be significantly reduced, allowing only other factors (sprinkler location, water density) to be the primary variables controlling the results.

Cost of Testing. Since the vehicle is damaged greatly during a given test, every test requires a new vehicle as the fuel source. Furthermore, if vehicle-to-vehicle fire spread is under consideration, multiple vehicles may be required. For the full-scale vehicle testing described above, only a single vehicle is necessary, but this is a huge expense which can limit the size of the test series and the number of variables that can be considered. Only 7 to 9 tests are envisioned in the full-scale vehicle test matrix for this reason. Development of a vehicle mock-up fire will reduce the cost of testing by removing the need for a new vehicle(s) for each test, allow for quicker turnaround between tests (i.e., less clean up and set up time) reducing labor costs and producing more information for a given test series. This would, for instance, allow for many more tests to be conducted for a given financial budget. Therefore, other variables such as larger fires (mimicking a larger vehicle with more plastic), differing sprinkler locations, different vehicle configurations (windows, etc.), could be considered without always utilizing another full vehicle per test. Indeed, many of these variables are unknowns and if full-scale vehicle testing is only conducted with vehicles near the size the design vehicle, they may not capture the worst-case scenario of a larger vehicle with more fuel or with a worst-case ignition scenario and configuration. Use of the standardized mock-up could allow for additional tests with higher heat releases to mimic these larger vehicles with bigger fuel tanks and/or batteries, and could better isolate these variables in the testing to better test and establish worst-case conditions.

Existence of Similar Mock-ups. Other testing standards utilize surrogate or mock-up fuel sources to test specific systems or situations. For example, the International Maritime Organization (IMO) has issued a test method for fixed water-based fire-fighting systems used in roll-on / roll-off (Ro-Ro) spaces (IMO MSC 1430) [69] This test method simulates a passenger car fire (among other fire scenarios) utilizing wood pallets as the fuel source arranged inside a passenger vehicle mock-up. A schematic of the standardized mock-up fire source is shown as Figure 41. Therefore, this approach does already have industry acceptance. Development of a vehicle mock-up for a parking structure testing appears feasible and has a number of positive attributes. However, significant work and research must be put into developing the proper fuel package to simulate ICE and BEV vehicle fires.

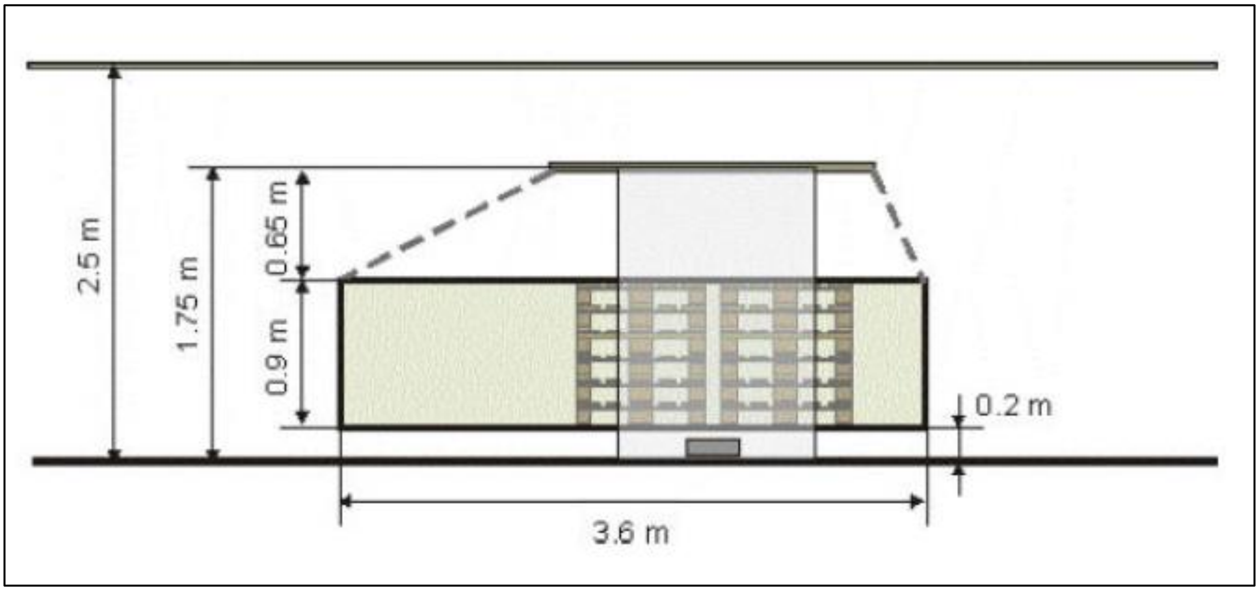

Figure 41. Side view of the standardized mock-up passenger vehicle fire source utilized in the IMO ro-ro vessel standard [69].

Computer Modeling Data. With considerably more test data and a standardized (i.e., known) fire source, computer models such as Fire Dynamics Simulator could be used to first model the testing to provide an understanding of anticipated outcome. After confirming that the computer model is accurately simulating the fire and potential for vehicle-to-vehicle fire spread using experimental data, even more cases could be modeled without the need for extensive full-scale experimental testing, again allowing the extension of the data to other heat release rates (i.e. bigger origin vehicles), different parking garage configurations, different sprinkler locations and densities, etc.

For modern vehicles in parking garages, the approach would be to utilize some vehicles, possibly a similar number to those in the test matrix for full-scale vehicle testing, to establish the appropriate standardized mock-up for ICE and BEV vehicles, as well as establish any other variables that may be critical to the testing. Therefore, the need for actual vehicles does not necessarily decrease. Instead, though, by utilizing the vehicles to establish the standardized mock-up, future tests would not necessarily require as many, vehicles. Therefore, this approach many not actually require lower financial and equipment resources in the short-term, but may provide significantly more data and testing flexibility in the future for those resources.

Full-scale Vehicle/Standardized Mock-up Combination

The use of full-scale vehicles or a standardized mock-up for the testing of modern vehicles in a parking garage do not need to be mutually exclusive. Initial testing with full-scale vehicles could be used to establish the standardized mock-up fire source, including considerations of worst-case fire scenarios and conditions. The standardized mock-up fire source could then be used to test any number of combinations of fire sizes, fire conditions, ceiling heights, sprinkler locations, sprinkler densities, etc. The standardized mock-up, though, could occasionally be replaced with a full-scale vehicle as a validation test. For instance, after a few tests with the standardized mock-up fire source, a worst-case fire size, sprinkler locations, ceiling heights, etc. could all be established and an appropriate sprinkler density to control the fire and prevent vehicle-to-vehicle fire spread could be established. An actual full-scale vehicle could then be substituted for the standardized fire source and tested under these worst-case conditions with established sprinkler water density to ensure fire control and lack of vehicle-to-vehicle fire spread. This combination full-scale vehicle/standardized mock-up fire source approach would still provide valuable data toward answering the established knowledge gaps, but would also utilize validation tests to provide actual vehicle fire burning behavior data and to enhance confidence that the results obtained with the standardized mock-up are valid.

Stacker Experiments

The second set of experiments that should be conducted are tests utilizing stacker systems. The knowledge gaps regarding stackers revolve around whether an EH2 sprinkler system at the ceiling alone can control a two-tiered stacker fire. Limited testing from BRE has already demonstrated that a water density of approximately an NFPA 13 OH2 density (after consideration of the higher water pressure) with sprinklers above each tier will control the fire and limit fire spread to the upper vehicle. Also of interest is what configuration will result in acceptable performance for stacker systems higher than two-tiers. With a stacker system experiment, the expense of the test is even further magnified as multiple vehicles become necessary for the test and is unlikely to be able to be accomplished with the use of cheaper fabricated “target” vehicles as the geometry of a full vehicle with the ability to ignite is important in the stacker tests since the upper vehicle will effectively shield the lower vehicle and, ergo, the geometry of the upper vehicle is critical. Therefore, two or more vehicles are required for each test.

Therefore, it is proposed that two tests be undertaken, requiring a maximum of five (5) vehicles total. The fabricated parking garage geometry should again be used, with the ceiling higher, if necessary, to fit the stacker system. All vehicle fires should be conducted at the worst-case ignition and vehicle condition scenario. This likely means open windows and a full fuel tank and/or battery, etc., but will be determined by the previous test series. It is certainly expected that if stacker systems are in use, they could be side-by-side and therefore the heat flux gauges and target plastics should be used in these tests as well, on all levels, to provide more data regarding side-by-side vehicle-to-vehicle fire spread.

The first test should entail a two-tiered stacker system, igniting the lower vehicle, with only EH2 sprinklers at the ceiling. No in-rack sprinklers should be used. This will determine if the fire can spread from the lower vehicle to the upper vehicle. It will indicate whether requirements for stacker systems should always include in-rack sprinklers, or whether sprinklers only at the ceiling with the high EH2 water density are sufficient.

The second test should entail a three-tiered stacker system, igniting the lower vehicle, with OH2 sprinklers at the ceiling and in-rack above levels 1 and 2. This will determine if, under this scenario with a higher stacker system, whether the fire can spread from the lower vehicle to the upper vehicles when there is an in-rack sprinkler system with an OH2 system at the ceiling. By conducting the test with three levels, this will inform the requirements for a three (or more) tiered system, and will also provide a second data point on in-rack sprinkler system performance for stacker systems.

A final test that could be considered, especially if the previous two tests resulted in performance that did not ignite the top vehicle, is a test with an engineered stacker system suppression system. If the previous two tests did not result in significant ignition of the top vehicle, provided those vehicles can be properly rehabbed, they could be reused for this third test. It is unknown what testing exists for these engineered systems and what their performance is and what it is based on. But such a suppression system could be installed in the stacker system to access their performance as well. One such stacker system and associated suppression system can be found in [70].

As an additional consideration for the stacker testing, if a standardized mock-up approach is utilized for the non-stacker tests, it is possible such a setup could be used for the stacker tests as well. Given that the worst-case scenario is very likely a fire ignited on the lowest vehicle in the rack, the lowest vehicle could be replaced with the standardized mock-up fire source. While the upper vehicles likely should be complete vehicles due to the complex geometry involved not only in their ignition from below, but also their ability to shield the lower vehicle fire, the use of the standardized mock-up fire source could replace at least one vehicle in each test (i.e. the lowest vehicle), possibly reducing the number of vehicles needed for these proposed stacker tests from five vehicles to three, while still obtaining a similar amount of data.

Evaluation Criteria

The data obtained from the testing should provide great insight on the fire behavior of modern vehicles in parking structures. While undoubtedly the data will have the ability to inform many different scientific inquiries, the most paramount concern is vehicle-to-vehicle spread, and objective evaluation criteria need to be established to allow analysis of the data.

For the stacker tests, the evaluation criteria includes ignition of the vehicles above the origin vehicle and the extent of fire spread on the upper cars. While this is a somewhat subjective evaluation criteria, video and photograph footage will provide an indication of whether the fire was controlled (i.e. no second vehicle spread), suppressed, or neither.

For the heat flux targets in both the stacker tests and in the sprinkler/ignition scenario tests, an objective pass/fail criteria is needed to infer whether fire spread to the neighboring vehicle is possible. BRE [18] determined approximate critical heat fluxes and times to ignition in a cone calorimeter on standard external vehicle component materials to. Their tests and calculation results are shown as Figure 42 and Figure 43. As can be seen, the lowest critical heat flux (for a Mohair soft top) was found to be 8 kW/m^2, though that particular material did not ignite in an actual test at 10 kW/m^2. The PVC soft top did ignite in approximately a minute at 10 kW/m^2 and had a critical heat flux of 9 kW/m^2. The mud flap had a similar critical heat flux and also ignited in just over 5 minutes at 10 kW/m^2. Therefore, it is proposed that a heat flux of 9 kW/m^2 at the target location for over 1 minute be considered a condition that could ignite shielded (i.e., dry) plastics on neighboring vehicle at that location.

Sample	Time to ignition (Seconds) (NI = no ignition) Irradiance level 10kW/m²	20kW/m²	30kW/m²	40kW/m²
Hubcap	NI	205	58	28
Mud flap	380	57	29	16
Bumper grill	NI	114	44	19
Fuel tank	NI	354	114	59
Roof box	NI	121	61	35
Wheel arch	NI	81	44	25
Bumper	NI	450	89	43
Bumper trim	415	83	30	16
Mohair soft top	NI	51	28	19
PVC soft top	67	27	13	7

Sample	Irradiance level 10kW/m²	12kW/m²	15kW/m²	20kW/m²	25kW/m²
Tyre	NI	1100	597	240	140

Figure 42. BRE time to ignition tests of vehicle components [18].

Sample	Critical Irradiance Level (kW/m^2)
Hubcaps	17.5
Mud flaps	10
Bumper grill	17.5
Fuel tank	16.5
Roof box	12.5
Wheel arch	12
Bumper	18.5
Bumper Trim	11.5
Mohair soft top	8
PVC soft top	9
Tyre	11

Figure 43. BRE critical heat flux calculations based on a thermally thin assumption [18].

The critical heat flux for these target plastics, though, is likely much higher if the fuel is being pre-wetted and dynamically cooled by the sprinkler system. Therefore, it is recommended that each target location contain a thermally thin PVC swatch at each target location to see if the plastic ignites, compared to just the heat flux measurement that is based on un-wetted plastic samples. Additionally, if any of the samples do ignite during any of the tests with the sprinklers, the heat flux and temperature at the time of ignition can be compared to the values from BRE to see how much higher that heat flux has to be to ignite a pre-wetted fuel at that sprinkler design density.

The critical heat fluxes and times to ignition detailed in Figure 42 and Figure 43 were obtained in 2010, and raises concern about whether these values are reflective of the materials used in modern vehicles. Therefore, these critical heat flux and times to ignition tests may need to be repeated with materials from modern vehicles. If this work is conducted, values should be obtained not only for dry materials, but also pre-wetted and continually wetted samples for better comparison to heat flux values obtained in the full-scale testing when evaluating the potential for vehicle-to-vehicle fire spread.

In sum, should these tests be undertaken, several of the identified knowledge gaps would be partially, if not, fully addressed. The proper sprinkler density to prevent vehicle-to-vehicle fire spread would be known. The reasonably foreseeable worst-case scenario for a vehicle fire in a parking garage that can spread to neighboring vehicles would also become clearer. Finally, the necessary suppression system locations and water density for a stacker system, including above two-tiers, would also be better understood. This would provide actionable data for code- and standard-making bodies to implement or adjust requirements to provide the desired level of safety for modern vehicles in parking structures. Three options for achieving this data in non-stacker tests are possible, one with full-scale vehicles only, one with the development and use of a standardized mock-up fire source, or a combination of the two. The stacker tests will likely require some use of full-scale vehicles, though use of the standardized mock-up fire source may reduce the total number of vehicles needed.

Conclusions

The report details an updated and expanded analysis to the 2020 FPRF report [1] about the current landscape of fire safety issues related to modern vehicles in parking structures. The analysis detailed characteristics of parking structure design, several representative fire incidents, codes and standards, and the published literature on full-scale fire testing with modern vehicles. Additionally, parking garage fire statistics and modern vehicle compositions were also examined. Knowledge gaps were identified and a testing program was proposed to fill these knowledge gaps, all with the goal of preventing vehicle-to-vehicle fire spread in parking garages whereby a fire in a single vehicle becomes a large conflagration involving many vehicles.

The characteristics of parking structures were examined though a review of parking structure design guides. The guidelines that are used for the design of parking structures as it relates to parking space widths were described. A design vehicle, based on the size of vehicles on the market, is used to develop these parking space sizes. Parking structures are continuing to evolve, with newer vertical stacker parking systems and even more automated parking systems. Even self-parking vehicle parking garages are being conceptualized for the future. These parking structure developments are leading to even more dense parking arrangements, which while important from a financial consideration for the garage owner, do add to the potential fire hazards of the space.

Overall, statistics in the United States for parking garage fires, including injuries and fatalities, have continued to remain relatively unchanged from those reported in 2020. The composition of vehicles, though, has continued to change with vehicles continuing to get heavier despite using more plastic components. Additionally, as battery electric vehicles (BEVs) have continued to grow in market share, the size of the battery in these vehicles has grown significantly and is expected to continue to grow in the near future as the travel range of a BEV is an important consumer purchase factor.

Representative fire incidents involving modern vehicles in parking garages were identified. Five such incidents were chosen for further analysis. The incidents were selected for their variety in type of vehicle involved, presence or lack of sprinklers, magnitude of the fire, and whether other occupancies shared the structure with the parking garage (i.e., pedestal or podium construction). It was found that in fires where sprinklers were present, the fire was controlled, though significant damage was still possible. Two fires were described where sprinklers were not present and the fire spread from the origin vehicle to other nearby vehicles, including one where the incident involved hundreds to thousands of vehicles and led ultimately to a collapsed parking structure. It was additionally found that even in podium/pedestal construction, smoke from the fire was able to migrate to the other occupancy sharing the structure, posing a potential life safety issue. Re-entry into the parking garage by vehicle owners to retrieve vehicles during the fire was also identified as a possible life safety issue. A search was conducted to find any incidents involving vertical car stacker systems, but none were found.

The codes and standards related to parking garage fire protection have evolved. Sprinkler protection is now required in all parking structures, not just enclosed parking garages. Additionally, many codes and standards have increased the required sprinkler water density, and most notably NFPA 13 has increased from OH1 to OH2. The review of the codes and standards, though, revealed that there are very few national requirements for fire protection for automated parking structures or vertical stackers over two-tiers high. This has led some municipalities to enact their own to create local fire protection requirements for these types of parking structures.

The published literature was examined for full-scale fire test data with modern vehicles. Sixteen such references were identified and the relevant test details were entered into a database. The testing detailed in the literature did provide full-scale data, often heat release rates, for a range of different types of vehicles. The testing, though, often were conducted with differing informational emphasis, such as toxic gas measurement, heat release rate measurement, etc. Other variables were often measured, but with differences, such as heat fluxes at a range of distances, which made comparisons between different tests difficult. It was also found that only a very limited number of tests utilized sprinklers. There also were only two tests with a vertical stacker system found in the literature, one with sprinklers, one without, and both were conducted with older vehicles that may not be representative of current vehicles.

Based upon the analysis of the issues at hand and the available literature, three primary knowledge gaps were identified. First, the proper NFPA 13 hazard classification for modern vehicles in a parking garage is unclear. While codes and standards have evolved to require sprinklers in more new parking garages and have also increased the necessary sprinkler water density, the technical justification for selection of the water density is lacking. Code- and standards-making bodies have indicated uncertainty about what the proper sprinkler water density should be to prevent fire spread in parking structures. The review of the literature and incidents has indicated that, in general, if water is applied by sprinklers, the vehicle-to-vehicle fire spread does not occur. But there is a question of whether that is just because a worst-case scenario has not yet been encountered. The technical justification for the proper sprinkler water density in parking structures should be based on testing or data.

A second knowledge gap is the conditions that would lead to the actual reasonably foreseeable worst-case scenario for a parking garage fire are also unknown. The specific size and type of vehicle, location of the ignition point of the fire, location of the sprinklers (if present) relative to the vehicle, position of the windows (open or closed), and other configuration-specific details all can affect the development of a fire in a modern vehicle. These variables can influence the ability of a fire to spread from the origin vehicle to neighboring vehicles, which is the outcome of concern. In other words, any of the testing reviewed in the literature appears to be dependent on these variables, and exactly what combination of variables is the reasonably foreseeable worst-case scenario is unknown.

There is also a knowledge gap regarding the best protection options for vehicles in parking facilities utilizing vertical stackers and automated parking machinery. The available data and guidance regarding fire safety in these types of parking structures is extremely limited. There are no known incidents regarding these types of parking facilities, and there is no data either except for two stacker tests with older vehicles. Even some of the codes and standards do not address all configurations of these types of structures (i.e. stacker systems over two-tiers high). Therefore, there is a considerable dearth of knowledge regarding fire protection practices for these types of parking facilities as they begin to be used and/or conceptualized.

A testing plan was formulated to address the identified knowledge gaps. The test matrix would entail a combination of ICE and BEV testing with different sprinkler densities and differing ignition scenarios. The testing could be implemented with a limited number of full-scale vehicle tests or with the creation of a standardized mock-up fire source. A hybrid approach, where some vehicles are used as data for creation of the standardized mock-up fire source and others are used as validation tests is also a possibility. The standardized mock-up fire source approach may allow for more tests to be performed without the need for expensive test resources such as a vehicle for each test, and may provide flexibility to test more variables and to continue to test as vehicles, parking structures, and fire protection in parking structures continue to evolve. A large number of sensors is recommended to gather as much relevant data as possible so an array of gauges and target materials to measure incident heat flux and simulate the possible ignition of a neighboring vehicles was developed. The distances between vehicles are based on the smallest parking space sizes outlined in the parking structure guides with vehicle size based on the design vehicle. Ignition potential can be deduced from measured heat flux data which can be compared to literature values for critical heat flux and times to ignition of plastics used on vehicles, though the literature data may need to be updated as it is almost 15 years old. Additionally, that data would only simulate the ignition of those materials when dry, but not when protected by sprinkler water. These tests would provide information regarding the modern vehicle in parking structures NFPA 13 hazard classification for sprinklers, as well as would provide data regarding the knowledge gap of what variables can lead to a reasonably foreseeable worst-case fire scenario in a modern vehicle in a parking garage.

A small number of vertical stacker tests is also proposed to address the lack of experimental data in this area. The testing would address whether in-rack sprinklers are necessary, and what sprinkler water density should be used for stacker systems. Additionally, the tests would explore a stack system over two-tiers high. If the standardized mock-up fire source approach is developed, it may also be able to be used in the stacker testing to replace one of the vehicles (the lower origin vehicle) in the tests.

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