Modern Vehicle Hazards in Parking Structures and Vehicle Carriers

Final Report by:

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Foreword

Vehicles have changed significantly over the years. Modern vehicles present new hazards, such as due to the incorporation of larger quantities of combustible materials (e.g. fuels, plastics, synthetic materials, etc.) into their designs. As alternative fuel vehicles are popularized, concerns regarding their unique hazards, burn characteristics, and typical burn duration have been raised. Compared to older vehicles, modern vehicles burn differently. Modern parking garages have optimized space requirements for vehicle parking and storage and often implement automated retrieval features and car stacking, which presents unique hazards as well. Thus, it raises the question if the safety infrastructure of these parking structures and vehicle carriers (i.e. maritime vessels) have kept pace. This project aimed to quantify the fire hazard of modern vehicles in parking structures and vehicle carriers to provide guidance for the applicable technical committees.

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The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

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Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

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Executive Summary

Fires in vehicles are not uncommon, but the majority of these occur along the road or after collision. Vehicle fires in parking structures developing into large, out of control events are fairly rare, and civilian injuries in these types of incidents number fewer than two dozen annually in the USA. However, fires in parking structures can lead to very large economic losses, as evidenced by recent fires at Liverpool's Echo Arena (UK) and at the Stavanger Airport (Norway). These incidents involved hundreds of automobiles and resulted in severe structural damage. Fires on marine vehicle carriers or ferries are extremely challenging due to the setting and can result in injury and loss of life to passengers and crew, as well as loss of the cargo and the vessel. Data on modern vehicles imply there is a small, and shrinking, margin of error when a single vehicle fire can develop into a conflagration. It is important to understand the hazard posed by modern vehicle fires and determine if current fire codes are mandating adequate fire protection requirements.

This report details an analysis of the current scientific literature regarding the fire hazard modern vehicles represent to parking garages and marine vessels. The changes in vehicle and garage design have been documented, and the factors that most impact the fire development have been identified. Areas where current codes may be inadequate are presented and knowledge gaps and potential areas of research required to address the hazard are identified.

There has been an increase in the fire hazard from changes in vehicle design and increased use of plastics and other combustible materials in vehicle construction. The increased plastic content of modern vehicles manifests as faster flame spread within the vehicle, easier ignition and more rapid fire spread to neighboring vehicles. Modern parking garages tend to have narrower parking spaces than before, with increasing use of vertical stacker systems, leading to more densely packed fuel loads. The spread of fire between cars in a garage, especially from the initial to the second and third vehicles, is shown to be critical in determining the extent of the fire and the ability of the fire department to successfully control and extinguish it. There is limited test data available on this spread between multiple vehicles, especially on newer cars. Some testing of multiple modern vehicles has shown very rapid fire spread between vehicles in a parking garage configuration, on the order of 10-20 minutes. Based on the findings, test data from older vehicles (>15-20 years at the time of writing) should not be used as basis for development of codes and regulations.

The evaluation of modern vehicle fire hazards and current code requirements found that for enclosed parking garages and marine vessels the existing requirement for active protection systems appears adequate to control a vehicle fire until the fire department arrives, based on historical fires and laboratory testing. Open parking structures emerge as the main area of concern regarding fires in modern vehicles. The lack of any requirements for active protection systems in fire codes, and trends in both vehicle and garage design suggest that large, devastating fires in these structures could become increasingly common. Though the risk of civilian injuries will continue to remain low, these fires could cause extremely large property losses, business disruption, and adverse environmental impact. The current knowledge gaps focus on three areas; earlier detection and notification, viable sprinkler protection, and fire spread between vehicles. Focus of potential research in these three areas is proposed to better evaluate and analyze the threat of modern vehicle fires in open parking garages. This understanding is also critical to determine the best approach to reduce the risk of catastrophic fires.

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1. Introduction

The effect on fire dynamics in residential fires due to modern construction techniques, floor plans, and use of polymer materials is well studied. Less effort has focused on the impact on fire hazards from changes in vehicle design and changes in production techniques, material types and material usage in vehicle construction. Additionally, the adoption of different motor technologies and the use of alternative fuels such as battery electric vehicles and hydrogen fuel cells present different vehicle configurations and burn characteristics. Large lithium-ion batteries and hydrogen fuel cells in vehicles may represent a change in the type of hazard and required fire protection and firefighting techniques in parking structures. These developments will have significant implications touching on many different areas, such as design of parking garages and vehicle carriers, suppression systems, as well as firefighter tactics. While still low in percentage of total sales, the number of electric vehicles (EVs) on the road around the world has increased in the last few years representing 2-4% of all sales. The rate of sales growth is also rising dramatically, nearly doubling from 2017 to 2018 [IEA, 2019]. Hydrogen fuel cell vehicles are currently less developed and mainly still in the research stage, with a few thousand sold and refueling stations limited to a few test areas [Antoni et.al., 2018].

The goals of this project are to review current literature on vehicle fire hazards and protection requirements, thoroughly identify and evaluate the hazards associated with modern vehicle fires, including how, and to what degree, they may differ from older vehicles. Current design guidelines, codes and criteria for vehicle storage facilities and carriers will be evaluated, and how these structures and vehicles may be impacted by fires. Finally, guidelines and areas for further research will be discussed.

2. Identification of the Problem

There is a concern that the materials used in modern vehicles present a significant increase in energy content during a fire, both in intensity and duration, compared to older vehicles. These changes in materials may have an impact on the fire hazard posed by vehicles. Especially concerning is that many design guidelines and standards were developed using supposedly conservative values based on vehicle fire tests performed many decades ago and assume there will be limited fire spread between vehicles before suppression. The assumptions, forming the basis for the fire resistance and suppression system requirements, may in fact underestimate the hazards from a vehicle fire. If fires in modern vehicles do present a greater hazard due to the changing materials, the increased fire intensity will have an external impact on design of parking facilities, vehicle carriers, ferries, and any other facilities where a large number of vehicles are densely placed. The potential change in fire hazard associated with modern vehicles has been hypothesized due to two well-documented developments:

1. Larger vehicles with increased use of polymers and other combustible materials in construction, which are parked closer together. These materials often ignite easier, contain more chemical energy per volume, and burn more intensely and/or longer than legacy materials.
2. Rapid growth of alternative fuel vehicles replacing internal combustion engines (ICE). These include plug-in hybrid electric vehicles (PHEVs), fully electric vehicles (EVs), and hydrogen fuel cell vehicles.

Statistics on vehicle fires are published by National Fire Data Center and the US Fire Administration [2018]. These statistics do not distinguish which fires occurred in parking garages, or any other information about the location of the vehicle when the fire occurred. In total from 2014 to 2016 there were an average of 171,500 vehicle fires each year in the USA. Analyzing data for

2002-2005, Ahrens [2008] states that in the USA only 1% of vehicle fires, or 4,300 annually (with 2 fatalities annually), occurred in "storage" locations, which include those in parking garages. It is also reported that vehicle fires are involved in 18% of all US fires, and cause 13% of deaths and 10% of the direct property damage. Vehicle fires thus result in relatively fewer injuries and damage in relation to their share of total number of fires. This is likely because many of the fires classified as vehicle fires occur in a vehicle along the road, possibly related to a collision, with no spread and only resulting in the loss of a single vehicle. Evaluating data for fires occurring in commercial parking garages in the USA for the period 2014-2018 Ahrens [2020] found that on average there were annually 1,858 fires, causing $22.8 million in direct property damage and 20 civilian injuries.

2.1.   Notable Vehicle Fire Incidents

Although fires involving automobiles are not uncommon, there have been a number of incidents in the last decade that are noteworthy for the scope and severity of the event. As would be expected, significant incidents generally involve a high density of automobiles within a structure or vehicle carrier, where the close proximity of the vehicles leads to rapid fire spread.

One of the larger recent events occurred in Liverpool, England in December of 2017 in an open, 8-level concrete parking garage with 1,600 car capacity. A fire believed to have started in a 2002 model Land Rover that had been "converted to a different fuel arrangement" (the nature of the conversion is not specified), and spread throughout the parking structure, resulting in damage to over 1,400 vehicles, and structural damage so severe the building will be demolished [BBC, 2018; Kirkham, 2018]. The local fire chief claims that had the parking garage been equipped with sprinklers it would have made it easier to contain and put out the fire, by putting more water on the fire [Bona, 2018]. The fire chief also points out that when dealing with a "running fuel fire" foam is required, which the local fire department did not have access to. Once the fire fully developed, fire crews reported additional vehicles becoming involved every 30 seconds.

Another fire with very extensive impact occurred on January 8th, 2020 in an open parking garage at Stavanger airport in Sola, Norway [The Local, 2020]. The fire is reported to have started in a 2006 diesel car (Opel Zafira) [Frafjord, 2020]. A similar model car is also reported to have started a fire in an Irish parking garage, and has been subject to a recall [English, 2019]. The incident vehicle at Sola was a 2nd generation with left side steering, while the UK recall applied to 1st generation vehicles with right side steering [Karlsen, 2020]. The Norway fire destroyed 200-300 vehicles inside the building, with a further 1,300 vehicles trapped with some degree of heat and smoke damage, and part of the five-story structure collapsed (see Figure 1). The owner of the originating vehicle stated that he attempted to start it, saw smoke coming from the engine compartment, and soon after flames. News articles about the incident report that it still took the fire department approximately 19 minutes from ignition until first units arrived [Klingenberg and Ramsdal, 2020], and that the first fire fighters claimed to have seen as many as 10 vehicles burning on arrival, though this has not been confirmed. As the airport firefighters are not able to respond to non-aircraft fires while the airport is operating, the closest responding fire fighters had a travel time of up to 13 minutes (at normal driving speed).

Figure 1 – Partially collapsed parking garage at Norway's Stavanger Airport after fire in January, 2020.

While automobile fires themselves are considered among the largest causes of fatalities in the US [Diggs, 2008], most of the large, notable parking garage fires in recent years have led to large material losses but have not involved any human fatalities and few injuries [Ahrens, 2020]. A 2004 collapse of an underground parking garage in Gretzenbach, Switzerland after a fire trapped several firefighters, with seven eventually dying as a result [Firehouse, 2004]. The parking facility was underneath a playground and the fire started in a parked vehicle. After approximately 90 minutes, the concrete roof collapsed. It should be noted that the fire was described as "relatively small", and concerns have been raised about excessive load from the soil on the roof [Annerel, et.al. 2013]. Some other notable parking structure fires are summarized in Table 1. There were no fatalities in any of these fires.

Table 1 – Parking garage fires in 2019. Included is the model of the vehicle identified as the initial source of the fire.

Date	Location	# of Vehicles	Initiating Vehicle (Model)	Parking Structure Type
9/23/19	Richmond, VA	1 (2 others damaged)	Audi sedan	Parking garage (multi-use)
1/31/19	Newark, NJ	17 (2 totaled)	Dodge Durango	Parking garage roof
9/16/19	Miami, FL	1	Hyundai Elantra	Residential parking garage
4/10/19	Myrtle Beach, SC	1	-	Parking garage
4/22/19	Shanghai, China	3	Tesla Model S (EV)	Parking garage
6/29/19	Chicago, Illinois	3	-	10 story garage
5/26/19	Houston, Texas	2	-	In a parking garage
2/7/20	Gaithersburg, MD	4	"SUV"	Garage. Spread to neighbor vehicles

Likewise, fires on marine vehicle carriers or ferries can result in injury and/or loss of life to passengers and crew, as well as the property loss of the cargo and the vessel itself. Since 2014

there have also been six significant fires on marine vessels. Examples include fires on the *M/S Norman Atlantic* (2014 Adriatic Sea); *M/V Courage* (2015, English Channel); *M/V Silver Sky* (2016, Antwerp, BE); *M/V Honor* (2017, English Channel) and *M/V Sincerity Ace* (2019 Pacific Ocean). A fire occurred on June 4th, 2020 onboard the M/V Höegh Xiamen [Schuler, 2020]. The fire started on the Number 7 deck of the vessel loaded with automobiles. These may have been used vehicles with various unknown amount of fuel in the fuel tanks. The fire spread throughout the vessel and burned for more than a week and required the response of 120 firefighters. On June 5th during the extinguishment effort, an explosion occurred which injured eight firefighters. The vessel was declared a total loss, and the investigation into the cause is ongoing (at the time of this report).

2.2. Storage and Transportation of Vehicles

Parking structures for vehicles are needed in urban settings and are used for a variety of purposes. A common usage of these structures is to provide a place to store the vehicles in areas where there is high density of people living or working. Parking structures are also used to store automobiles and provide protection from weather damage (e.g. hailstorms). Parking structures can be stand-alone construction or attached to other occupancies, such as retail shops, hotels, or office buildings. Construction of most large-scale parking structures generally uses concrete assemblies, though combination of steel and concrete can also be used (e.g. Sola, Norway), and there are timber-framed garages in some locations. Fire protection measures must account for the type of construction, parking density, location of the garage (i.e. above or below grade, open or closed configuration) and proximity to other occupancies. Furthermore, some structures use car stacking mechanisms, where hydraulic systems lift two or more cars above each other, effectively inside the footprint of a single car. This placement of multiple vehicles in a vertical configuration is advantageous for rapid fire spread. Details of stacker systems will be explored further in this report.

Vessels that transport cars also can involve the storage of a large density of automobiles and must account for the fire load and fire spread mechanisms. Cars in such transport vessels are typically densely packed, and across multiple decks. Large merchant ships and ferries that transport vehicles have specific fire protection concerns, including the need to avoid accumulating excess water weight during fire-fighting actions, and limitations in availability of egress paths. Conversely, the regulation of marine vessels is more stringent as will be discussed.

3. Current Protection Requirements

In the United States, and some other jurisdictions, vehicle parking structures are governed by NFPA 88A, *Standard for Parking Structures* [NFPA, 2019]. At the time of this writing, the latest version is the 2019 edition. In NFPA 88A, the general structural fire resistance guidelines refer to requirements and categories in NFPA 220, *Standard on Types of Building Construction* [NFPA, 2018]. Also relevant are sprinkler requirements in NFPA 13 *Standard for the Installation of Sprinkler Systems* [NFPA, 2019]

Marine vessels that may transport vehicles, such as roll-on/roll-off (ro-ro) vessels and ferries are governed by numerous standards and regulations. NFPA publishes NFPA 301 *Code for Safety to Life from Fire on Merchant Vessels* [NFPA, 2018], which deals with concerns unique to marine vessels, such as water supply limitations, crowded storage compartments, limited escape paths and limited ability for outside assistance. Title 46 of the Code of Federal Regulations (CFR) also contains fire protection requirements for vessels operating in US waters. The main regulatory body for vessels that cross borders is the Safety of Life at Sea (SOLAS) published by the International Maritime Organization (IMO) [2007].

The current protection, design parameters, and codes for parking facilities, vehicle carriers, ferries etc., were evaluated, with an aim to assess the inherent assumptions about vehicle fires, and how this may be affected by the fire dynamics of modern vehicles, presence of charging and refueling equipment, or any other changes associated with modern vehicle storage and transportation systems.

3.1. NFPA 88A - Vehicle Parking Structures

The fundamental requirements for parking structures deal with two points; fire resistance, manifested as a time to failure under a standardized fire test, and requirements for sprinkler protection. There is also an interplay between the two, where if lower fire resistance materials are used, the code requires increased sprinkler protection. As the composition of vehicle construction changes, the requirements for the structures may need to be adapted to provide adequate protection.

3.1.1. Open and Enclosed Parking Garages

Throughout NFPA 88A, a distinction is made between parking structures with an *open* configuration and those with an *enclosed* configuration, as defined in section 5.5 (2019 ed). These are defined by the fraction of wall surface that is open directly to the outside. An open parking structure is one with "uniformly distributed openings on two or more sides", with at least 20% of the total area of the outside perimeter and interior walls being open. The openings also must be distributed over at least 40% of the length of the building perimeter, or on two opposing sides. The justification for the distinction is not specified in NFPA 88A, but in theory, due to the number of openings and the distribution around the building, natural ventilation will prevent or reduce the buildup of a hot layer of combustion products in the structure, and thus reduce the risk of fire spread among vehicles from radiant heat transfer from the hot upper layer. Presumably toxic gases would also be vented to the outside, allowing occupants longer time to exit the structure without risk of being exposed to fire effluents.

3.1.2. Detection, Notification and Automatic Sprinkler Systems

Open parking structures are not required to have either an automatic sprinkler system (NFPA 88A, 6.4.4) nor any fire alarm system (NFPA 88A, 6.6.3). Enclosed parking structures are required to have an automatic sprinkler system if it is located below grade or is more than 15 m high and not made wholly of noncombustible or limited combustible materials. The reasoning for the lack of protection requirements for open structures is likely one of practicality, as well as a combination of venting of hot gases slowing spread, and possibly a rapid fire department response as fires are easily noticed and accessed in the interior.

Automated-type parking structures (which includes stacker systems), are required to have a sprinkler system, but a fire alarm system is not required (Section 9.2). Though local sprinkler waterflow alarm is required in some cases. For the sprinkler system design, NFPA 13 considers automobile parking structures, i.e. garages, as an ordinary hazard (group 1) (NFPA 13, A.4.3.3). Car stacker systems are considered extra hazard (group 2) (NFPA 13, A.4.3.6) when protected only with overhead sprinklers. With sprinklers at the levels between the vehicles a lower water application density can be used. The maximum possible difference in sprinkler coverage requirements is shown in Table 2, with hydraulically calculated extra hazard system with ≥10.2 mm/min (0.25 gpm/ft^2). As can be seen, the extra hazard classification leads to stricter protection area and sprinkler spacing requirements.

Table 2 – Sprinkler coverage and spacing requirements for ordinary and extra hazard (hydraulic calculated ≥10.2 mm/min (0.25 gpm/ft²) from NFPA 13 (2019).

	Protection Area		Max Spacing	
	ft²	m²	ft	m
Ordinary hazard	130	12.1	15	4.6
Extra hazard	100	9	12	3.7

3.1.3. *Fire Resistance and Compartmentation*

Per section 5.1.2 of NFPA 88A, open parking structures shall only be constructed of materials with type I or II fire resistance, meaning only noncombustible or limited combustible materials. Unlimited height and floor areas are allowed if the structure is Type I, II (222), or II (111). This requires that the three sets of main structural elements have a 2-hour or a 1-hour fire resistance rating in standardized tests. Open parking structures can be constructed of materials of Type II (000) if they are less than 25 m (75 ft) high and the distance from any point to the exterior is less than 60 m (200 ft).

If the parking structure (open or enclosed) is below or directly adjacent to another occupancy, there shall be a barrier separating the two with at least a 2-hour fire rating, which can be reduced to 1 hour if the building is sprinklered. If the parking structure is below another occupancy, the supporting members shall have fire resistance rating equal to the above occupancy. There is a requirement for floors to be of noncombustible material, liquid tight, and be sloped and equipped with drains.

3.2.   International Parking Garage Codes

The International Building Code (IBC) [International Code Council, 2018] contains similar requirements as NFPA 88A. Open parking structures are defined as those with greater than 20% of the exterior wall area open to the outside. Like NFPA 88A, the IBC require that these openings be uniformly distributed across the wall area. The current (2018) edition of the IBC also follows NFPA 88A and does not require sprinklers in open garages. In 2018, a change was approved (as modified) for the next 2021 edition of the IBC regarding sprinklers in open garages [The Fire Code Action Committee, 2018]. The proposed (and accepted) change will require that automatic sprinkler systems be installed in open parking garages with greater than 48,000 ft² (4,459 m²) fire area or 55 ft (16.8 m) in height [National Fire Sprinkler Association, 2018].

The Eurocodes covering the states of the European Union (EU) and European Economic Area (EEA) does address general construction requirements for structures, including structural resistance to fire. But these documents do not detail the specific fire protection systems such as sprinklers and alarm systems. These requirements are specified by the individual countries' codes and can vary substantially between nations. An overview of the wide range of sprinkler requirements in car parks throughout the EU/EEA is summarized by the European Fire Sprinkler Network (EFSN) [2020]. According to the code in most EU countries, sprinklers are required for enclosed parking garages with more than one floor underground, or in some cases if the garage is larger than a certain size or vehicle capacity. Some EU states have requirements similar to NFPA 88A and have no requirement for sprinklers in open parking garages. In most of the national codes summarized by the EFSN, there is some requirement for automatic sprinklers in open garages above a certain floor area, height, or when located below an assembly or hotel occupancy. The cut-off area when sprinklers are required varies from 1,000 m² to 4,500 m², the latter a value larger than that proposed for the IBC.

3.3. Marine Vehicle Carriers Codes

The fire protection and life safety requirements for vehicle carriers are covered by multiple standards, depending on where they are built, flagged and to some extent where they enter port. The Project Technical Panel contacted operators of vehicle carrier vessels inquiring about their protection systems. The details from the five operators who responded are anonymized and summarized in Table 3.

Table 3 – Fire protection strategies from five vessel operators responding anonymously to the research panel.

Operator	Vessel Type(s)	Fire Protection on Vehicle decks
A	Vehicle Ferry	Above the vehicle deck is an enclosed passenger deck, restrooms, diet kitchens, store room, and offices protect from the vehicle deck in accordance with 46 CFR 72.05-10. Below the vehicle deck is a combination of machinery spaces, store room, engine control space, and voids, these areas are protected by structural fire protection in accordance with 46 CFR 72.05-10. [Ferry Operator A] complies with 46 CFR 76.05-20 using a fixed manual saltwater sprinkler system along with the required portable fire extinguishers required by 46 CFR 76.50-10.
B	Large Car & Passenger Ferry (Enclosed freight decks), Freight Boats (open freight decks); and Passenger ferry (no vehicles)	The fire protection for the Large Car/Passenger ferries consists of sprinkler system on the freight decks with manual control consisting of several zones. The system is a dry system and charged only when needed. The vehicle decks have freeing ports to reduce flooding of the vessel when the sprinklers are in use. The Freight boats have no sprinklers but have fire stations located on and near the vehicle decks and carry AFFF. The passenger ferry (high speed craft) does not carry vehicles.
C	Passenger/Vehicle Ferry Combo	Vehicle decks have water sprinkler systems.
D	RO/RO (Pure Car / Truck Carriers - vehicles in transit for sale)	The cargo deck areas use the following to combat fires: Fixed CO_2 Fixed Sea Water Fire Main Portable Dry Powder Fire Extinguishers Portable Foam Applicators Portable Water Fog Applicators
E	RO/RO (Military vehicles)	Fixed CO_2 is used for the Cargo Holds (vehicle decks) and Engines Room. Some vessels use the CO_2 bottles, others use the LP CO_2 tanks

3.3.1.   NFPA 301 and 46 CFR

In the USA the NFPA developed NFPA 301, *Safety to Life from Fire on Merchant Vessel*, at the request of the US Coast Guard (USCG), and the standard follows the USCG mandates. The latest edition is 2018 [NFPA 301, 2018]. The general principles governing the requirements are stated as (section 4.1):

1. Limit fire to the space and deck of origin
2. Provide for 100% self-sufficiency in extinguishing or controlling fires, protecting lives, and protecting property
3. Provide protected escape routes for egress
4. Provide areas of refuge

For the prescriptive-based option there are a range of fire scenarios that must be considered, and the standard specifies that irrelevant scenarios can be omitted. Some of the scenarios most relevant to vehicle carriers are:

- 5.5.3.6 Scenario 6: an ultrafast-developing fire in the largest possible fuel load in the vessel. In a roll-on/roll-off (known as a ro-ro) type vehicle carrier, this could mean a fire in one of the vehicles, potentially with large amounts of gasoline or diesel fuel in the fuel tank.
- 5.5.3.8, Scenario 8: fire in ordinary combustibles where fire protection system is rendered ineffective. This could include a fire in the vehicles storage area where the sprinklers are disabled, creating a potential for spread to other vehicles, and an extremely severe fire.

The standard has specific requirements for vehicle spaces in section 16.3.4 (2013 ed). Covered decks must be equipped by a fire protection system, installed according to NFPA 13. The same section also required that firefighting foam hydrants or portable equipment is placed on each deck with vehicles. It's important to note that vessels with water-based protection systems, i.e. sprinklers, foam systems etc., are required to have a drainage system capable of removing the water at a rate equal or greater to the maximum water flow rate from the extinguishment system (section 9.2.4). A properly installed and functioning system should prevent any issues with listing, capsizing or sinking of the vessel due to filling with water from the fire protection equipment.

NFPA 301 also specifies in section 10.2 the requirements for separation of egress and accommodation spaced from other parts of the vessel to ensure that occupants can reach embarkation and areas of refuge without being exposed to the fire. General egress requirements also specify the number of exits depending on occupancy, travel distances and other factors. An area of refuge is required to be maintained free of smoke or flooding for at least the time for embarkation of the vessel or 1 hour, whichever is shorter.

Large goods-only vehicle carrier vessels (i.e. not ferries) typically have no passengers and a very limited crew, who are distributed through the ship, and required to have some minimal training in emergency procedures. With required detection, notification and protection systems, as well as training, a fire in a vehicle onboard therefore represents a relatively low hazard to the crew. The lack of serious accidents on these vessels resulting in injury or death to the crew bears this out. Ferries or other vessels with civilian passengers on board have more strict requirements for protection of means of egress, extinguishment equipment, and fire separation. In those situations, sprinklers and/or foam systems will be required, and the cargo and passenger areas (and areas of refuge) are separated by barriers able to withstand smoke and heat transfer for one hour.

The Code of Federal Regulation, 46 CFR, contains minimum requirements set by the US Coast Guard for all US flagged vessels. It requires, per 181.400 for example, fixed fire extinguishing systems in any vessel carrying ICE powered vehicles, (ICE greater than 50 hp, and gasoline fuel tank). If the vessels operate outside US waters, they must also comply with international regulations.

3.3.2. IMO Standards

For international shipping the main regulatory document is the International Maritime Organization (IMO); International Convention for the Safety of Life at Sea (SOLAS) Chapter II-2 [IMO, 2007]. The standard is adopted by the member countries (173 countries in 2018) and applies to all vessels registered in those countries. The rules and standards are enforced by the country where a vessel is registered. In addition, through a process of Port State Control, vessels can also be inspected in other countries they enter [ICS, 2020]. Vessels flag-registered in smaller countries with fewer inspection resources can therefore be expected to still have to comply with the IMO standards if they visit ports in larger nations where enforcement is stronger. The SOLAS standard went through a major revision in 2002, having last seen a significant update in 1974. The requirements apply to all ships built since 2002, and in addition there are requirements for certain types of existing ships and those undergoing significant renovations.

SOLAS chapter II-2 contains many requirements similar to NFPA 301, requiring protection of occupant areas, dangerous cargo, vessel integrity, extinguishment equipment etc. The fire protection requirements are relatively strict, especially compared to that seen for land-based vehicle storage. Vehicle and ro-ro spaces are specifically addressed by SOLAS Regulation 20 chapter 6, which specifies that such spaces which are able to be sealed from a location outside the space shall be fitted with a CO_2 or other inert gas systems. If that is not possible, or as an alternative, vehicle carrier spaces can be protected by an automatic sprinkler (or foam) systems installed that operate without crew interaction, and with a waterflow alarm. In addition, separate automatic detection and notification systems are required. These shall also be addressable to a detector or deck/section, so the crew can quickly locate the fire. In the event of a fire, it is therefore expected that the crew will quickly be notified and respond, in addition to the system applying water to the fire.

The SOLAS regulation also mandates drainage systems capable of removing 125% of the combined water spray capacity of the sprinklers and required fire hoses, either via scuppers or pumps in below-deck locations. This is to ensure that water used for firefighting does not compromise the stability of the vessel.

4. Modern Vehicle Fire Hazards

The protection requirements in NFPA standards that deal with vehicle fires are based on certain assumptions about the fire hazard that a burning vehicle could present. This is necessarily influenced by the results from fire tests on vehicles available at the time the standards are created. There have been little changes to the fundamental protection requirements in the NFPA 88A standard since the initial 1973 and 1979 editions. However, there have been various revisions, editorial changes, and updates throughout the years, especially to the 1991 and 2011 editions. For example, provisions for natural gas vehicles and automatic stacker systems have been added. There are many developments to modern vehicles which may increase the fire hazard, including changes to construction and use of the vehicle. In the U.S., vehicles (on average) have become larger and there has also been an increased use of plastics and polymers over the past

few decades. Furthermore, there has been a rapid growth of vehicles using different power sources, replacing the internal combustion engines (ICE).

Close examination of the test parameters must be made when comparing the measured heat release rates from vehicles. Many times, the fuel tank is drained for safety reasons when full-scale tests are conducted on ICE cars. This is not an issue when comparing modern and legacy ICE vehicles if the test parameters are the same (e.g. no liquid fuel in the system). The lack of gasoline must be considered when comparing data for EV or hydrogen vehicles if the primary energy sources (battery or hydrogen tank) are involved. The contribution to the heat release rate of a gasoline/diesel volume equivalent to the fuel tank can be added if assumptions are made for release rate, full or partial spill etc. As the rate of release can vary significantly in an actual fire, this is only useful to calculate the total potential energy in the fuel content, not the rate of heat release.

The hazards that may be present in modern vehicles compared to older ones will be discussed in this section. The extent of the hazard will be quantified, and the impact on parking facilities and vehicle carriers will be discussed in later sections.

4.1. Vehicle Sizes and Use of Plastics

As is the case with residential furnishings [Bukowski, 2008] there has been a steady increase in the use of polymeric or plastic materials in the auto industry. These materials generally represent a more severe fuel load in the case of a fire, compared to traditional construction materials. In the majority of cases, the plastics have a higher heat of combustion than the materials they replace (often metals) [American Chemistry Council, 2019]. They will therefore yield a higher fire energy per weight of material, and more potential energy in the same volume [Spearpoint, 2015]. Often, they also ignite and sustain a fire more easily, support more rapid flame spread, and produce more toxic smoke than the materials they replaced. In many markets there has also been a general shift to heavier and larger personal vehicles (though this is not the case everywhere), further increasing the potential fuel load per vehicle [Tohir, 2013]. This will lead to more severe vehicle fires, either in intensity (peak heat release rate), fire duration, or both. An example of the growth in curb weight and width from the 1970s to 2018 of the two most popular vehicles in the USA for many decades is shown in Table 4. As shown, there is a substantial increase in both characteristics over this time period.

Table 4 – Increase in body width and curb weight of the two most popular vehicles in the USA from 1970s to 2018.

	Width Increase	Weight increase
Toyota Corolla	21 cm (8.3 in)	430 kg (948 lb)
Ford F150	8 cm (3.1 in)	150 kg (332 lb)

Some data can be found on the amount of plastics used in the average vehicle fleet over time, mostly for the US market. Similar trends can be expected to apply to other Western markets, though more data should be gathered for confirmation. In developing countries, the vehicle fleet trends are likely to be somewhat different. Plastics are often used to reduce the weight of vehicles, primarily to improve fuel efficiency. But as customers have bought larger and heavier vehicles such as trucks and sport utility vehicles (SUVs), the weight of the average vehicles has remained steady or gone up in the last decade, while the percentage and absolute weight of plastics has similarly gone up. It is reported that the weight of the average light vehicle in 1976 was 1,618 kg (3,567 lb), which had risen to 1,805 kg (3,979 lb) in 2018, an increase of about 12% [American

Chemistry Council, 2019; Dai, Kelly, and Elgowainy, 2016]. In this context, and throughout this report, "light vehicle" or "light-duty vehicle" denotes passenger vehicles, excluding trucks. The Environmental Protection Agency (EPA) classifies these as having a Gross Vehicle Weight Rating of less than 8,500 lbs (3856 kg) [EPA, 2020].

The Economics & Statistics Department of the American Chemistry Council released a report "Plastics and Polymer Composites in Light Vehicles" [2019] analyzing the material composition of light vehicles assembled in the NAFTA countries (USA, Mexico, and Canada), representing 16.8 million vehicles produced in 2018. Annual plastic content by weight is provided for 2008 to 2018. A report by Argonne National Lab [Dai, Kelly, and Elgowainy, 2016] similarly analyzed the US light vehicle fleet providing annual data for 1995 to 2014. A government steel industry report from 1991 gives some 5-year average data for material content of US vehicles for the years 1976-1990 [Brunsdale et.al., 1991]. Combining these data sources, the weight of plastics in the average US/NAFTA vehicles from 1976 to 2018 can be plotted in Figure 2, in kilograms and as percentage of average vehicle weight.
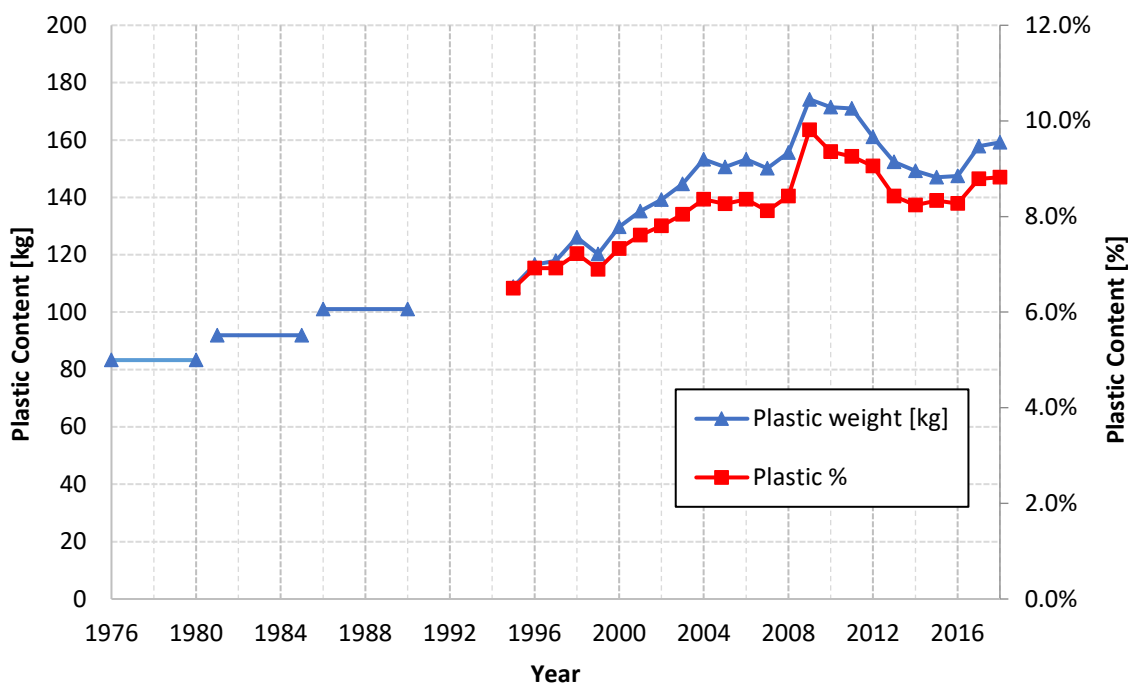
Figure 2 – Amount of plastic in average US light vehicles in weight (kg), and as percentage of vehicle curb weight.

In large part plastic materials have replaced metal in vehicle construction. For example, from 1970 to 2004, the average steel content per vehicle dropped by 458 kg (1,010 lb), a 32% reduction [Buckingham, 2006]. Many different types of plastic are used in vehicle interiors, cushions, panels, wiring, etc. Three types represent over two-thirds of the total plastic by weight in US light vehicles: polypropylene (PP), polyurethane (PU) and polyvinyl chloride (PVC). The percent of total plastic weight and heat of combustion for these are shown in Table 5 [American Chemistry Council, 2019]. Heats of combustion are from Khan, Tewarson, and Chaos [2016]

Table 5 – Most common plastic types used in US vehicles.

Type	%-weight	Heat of Combustion [kJ/g]
Polypropylene	32%	43.4
Polyurethane	17%	25.3
PVC	16%	16.4

4.2.   Plastic Fuel Tanks

Another development is the increasing use of plastic fuel tanks in vehicles, which have largely replaced metal tanks. The share of cars built in Europe with plastic fuel tanks is reported to be over 85% today [Merseyside Fire & Rescue Service, 2018]. It was estimated to be around 75% for US cars in 2010 [Vanderwerp, 2010], and has likely risen since then. As discussed above, this will increase the amount of plastic in the vehicle on the order of 8 to 10 kg (18-22 lb) per tank (1995 numbers) [Rowand, 1995], by replacing a non-flammable, metal fuel tank with high-density polyethylene (HDPE) plastic. This could also potentially result in the earlier release of fuel from the tank, in the case of fire in the vehicle, or in adjacent vehicles. If, for example, fuel leaks from a vehicle and ignites, the fuel could run under several neighboring vehicles in a garage, ferry or transport vessel, and melt the fuel tanks of those vehicles. This could result in more rapid fire spread to multiple vehicles in short order.

The heat transfer through the tank into the fuel inside is faster with a metal tank, which can lead to pressure increase and potentially leaking out of fittings. But testing showed that this occurs slower than the melting of a plastic tank [Alvarado, 1996]. However, with a sufficiently severe thermal exposure, both plastic and metal fuel tanks will eventually leak or rupture.

4.3.   Future Developments

The plastic industry is optimistic about further increasing use of plastic in passenger vehicles, mainly as a weight reduction measure to comply with increasingly strict fuel economy requirements [Oliver, 2014]. Future uses of plastic may include [Brady and Brady, 2008]:
- Replace body panels (typically aluminum)
- Plastic windows and panoramic roofs
- Replace metal parts in cooling or other under-hood systems
- High-strength plastic in transmission or drivetrains

These developments will further increase the plastic content available as a fire fuel, especially as many of these replace non-flammable metal components. In addition, the potential future use of plastic materials to the exterior of the vehicle, which is still limited, has the potential to lead to more rapid fire spread between vehicles. As most vehicles still have exterior body panels primarily made of metals, the fire cannot readily spread to these areas. Instead, fire spread relies on conductive and radiative heating of the interior of the vehicle [BRE, 2010], where there are large amounts of readily flammable materials.

4.4.   Alternative Fuel Vehicles

Increasing usage of alternative fuel vehicles such as electric vehicles, hydrogen fuel cells and LNG powered vehicles present different fuel types and configurations, sometimes resulting in dramatically altered fire characteristics.

Lithium-ion batteries used in modern EVs present a different fire hazard than traditional ICE vehicles [Mikolajczak et.al., 2011]. Fires in lithium-ion batteries are more difficult to extinguish than gasoline or diesel fires, requiring large amounts of water to fully contain and mitigate the hazard. Even if there is no immediate fire following a collision, damage to the integrity of the battery pack can result in thermal runaway with later ignition and reignition which has proven difficult to contain [Livescience, 2018]. Fire crews are required to apply water to the exterior of the battery pack for hours, while continuously monitoring the temperature [FireRescue1, 2017]. The best-selling EV brand in the US, Tesla started installing a metal plate under the vehicle floor pan to protect the battery after fire incidents involving EVs, where it was suspected that impact damage to the battery caused thermal runaway and a fire [Musk, 2014].

The main hazard from a hydrogen fuel cell vehicle is rupture of the hydrogen storage tank and release of the gas. As hydrogen is much lighter than air, leaking or burning hydrogen would quickly travel upwards in a column, as opposed to a gasoline-fueled car where the spilled fuel gathers underneath the car, as shown in the test in Figure 3 [Greenway energy, 2009]

Figure 3 – Test demonstrating the difference between hydrogen and gasoline fires.

In an open space without a ceiling, the vertical flame can be a benefit, but a powerful hydrogen jet flame could present a new, unexpected hazard in an enclosure such as a parking facility, multi-level vehicle storage, or bulk carrier ship. Enclosures designed to expect a slow-flowing pool fire might not be equipped to deal with such a jet flame and could cause failure of overhead load-bearing members or sprinkler system components. When sprinklers do activate, they would cool the flame and vehicle, but interaction between the sprinklers and these jet flames may need further study. This could result in rapid fire spread and/or potentially building collapse, which is typically a major concern for firefighters who enter the building during the fire. A hydrogen fire can also be virtually invisible to the naked eye [Cheng, 2005], which poses a large risk to first responders, and possibly to certain visual fire detection systems. Currently hydrogen fuel cell vehicles are still in a very limited test phase, estimated at about 6,000 vehicles in the USA, and a total of 12,000 worldwide (2018) [Antoni et.al., 2018]. These vehicles typically operate in small test areas with a few refueling stations. Toyota on their website currently shows about 40 hydrogen fueling stations mainly around the areas of Los Angeles and San Francisco, and a few scattered around elsewhere in central California. Stations in development are also shown, and none are outside this area [Toyota, 2019].

Issues with hydrogen-fueled vehicles will certainly be a concern in the future and the development should be monitored and the fire hazards further studied at some point. They are not yet close to widespread adoption so the specific hazards from hydrogen vehicles will not be further discussed in this analysis.

It is important to note that even though hydrogen fuel cells and large battery packs in EVs potentially represent very high-density fuel sources, they are replacing the gasoline stored in ICE vehicles. (An exception being hybrid vehicles). The degree to which the fire hazard is increased with an alternative fuel vehicle compared to a traditional vehicle, or simply changed, needs to be established, and can depend on the environment where the fire occurs.

4.5. Modern Parking Structures

There have been changes in parking garage configurations, often driven by the high cost of property and lack of space in urban environments. This has led to multi-level parking garages, often integrated with other buildings or with shopping or restaurant venues [Albery, 2020]. Many new parking garages include photovoltaic panels and electric charging stations.

Vehicle stacking systems and similar methods for more dense space usage pack large vehicle fire loads into smaller areas and to greater heights. An example is shown in Figure 4.

Figure 4 – Example of car stacker system.

Fully utilizing all available area also leads to parking spaces being placed on access ramps between levels of parking garages. This may present a hazard in the case of gasoline leak (either from a fire or some other cause) as the gasoline will run down under other vehicles, potentially spreading the fire to multiple neighboring vehicles very rapidly making multi-vehicle conflagrations more likely. Fires in parking garages are typically relatively rare events, with the fire frequency lower than in other occupancies [Li, 2004], but still account for over 4,000 fires per year in the USA.

4.5.1. Building Design

The goal when designing commercial parking structures is to minimize the amount of area used by each vehicle to make the use of space as efficient as possible. Typical parking structures are designed with each individual space requiring around 30 m^2 (322 ft^2) [Ison and Mulley, 2014], which includes the space needed for maneuvering in the garage. The area of the parking space is much smaller, typically less than 18.5 m^2 (200 ft^2), with widths typically less than 3.05 m (10 ft). As cars have become larger and wider the distance between adjacent vehicles has shrunk. With

vehicles parked in close proximity, fire spread from vehicle to vehicle is more likely. The geometry of the parking structure will have a large influence on fire spread. Even in an open garage there are beams and walls, resulting in a hot upper layer of gases which heat the surrounding vehicles and igniting exposed combustibles such as tires, window seals, etc. Access to fresh air may be limited, potentially stagnating overall fire growth, but possibly promoting incomplete combustion and more toxic fire products (e.g. high levels of CO). Open structures will in theory allow the fire products to vent, but there will be ample fresh air to sustain burning and environmental factors such as wind can affect fire spread. The ventilation can also be compromised, as was noted in the report after the Liverpool car park fire in 2017; several sides of the parking garage were almost completely covered in plastic advertising posters, which severely reduced the airflow [Merseyside Fire & Rescue Service, 2018].

Stacker systems are required to have an automatic sprinkler system per NFPA 13, but with the upper vehicle obstructing the water spray is only expected to control the fire and limit spread until the fire department arrive. The increased application density and reduced protection area associated with extra hazard 2 classification is intended to ensure this is successful. To reduce the density requirements sprinklers can also be placed between each of the vehicles where they would have a greater chance of fully extinguishing the fire. Testing of a two-car stacker system, without sprinklers, by Building Research Establishment (BRE) in the UK [BRE, 2010] found that the fire quickly (within 10 min) reached 8 MW and was difficult to extinguish due to the orientation of the fuel packages and ability to preheat and ignite the vertically adjacent vehicles.

Some tall multi-use buildings constructed in heavy timber also contain parking areas. If the parking structure is also constructed of wood members, this will not comply with the noncombustible requirement for non-sprinklered structures in NFPA 88A. Unless the parking area is constructed using different materials, a combination of sprinklers, detection and notification, and exhaust systems will therefore be required in these areas, depending on NFPA and local codes.

5. Modern Vehicle Hazard Assessment

The hazard associated with modern vehicles was analyzed from both sides of the issue:

1. Impact of changes to vehicle design and fuels, and installed charging and refueling equipment.
2. The design of fire protection systems used by parking garages and vehicle carriers.

This information established a picture of to what degree the various types of modern vehicles represent a changed fire hazard compared to legacy vehicles. The changes to modern vehicle construction and materials that was discussed in Section 4 have an effect on the fire behavior in several ways including; peak heat release rate, fire duration, and heat flux to nearby objects.

5.1. Vehicle Design

5.1.1. Heat Release Rate

As described in Section 4, the total amount of plastics and polymers used in vehicles has increased over the years, and these materials have typically replaced non-flammable materials such as steel or aluminum. The total fire energy from a vehicle generally scales with weight. Thus, it can be assumed that the change in available chemical energy is directly equal to the weight of plastic added, multiplied by the appropriate heat of combustion for the material.

Overall, there is not a substantial amount of heat release data for burning automobiles and the data that is available is not consistent in how the tests were configured, such as ignition sources and other variables. This leads to scatter in the measurements, making it difficult to make any definitive conclusions. A number of full-scale fires tests were evaluated, and the measurements most relevant for this analysis are presented below.

5.1.2. Vehicle Fire Tests

Tohir and Spearpoint [2013] gathered and summarized a large amount of data on vehicle tests up to about 2002 model years, including where available; model year, curb weight, mass loss, peak heat release rate (HRR) and total heat released. The authors attempted to establish a correlation between vehicle model year and peak HRR but found it difficult due to limited number of tests of similar size vehicles across several decades. The data shows a wide range of peak HRRs, making it difficult to establish clear correlations. The vehicle sizes corresponding to the curb weight defined by ANSI are shown in Table 6.

Table 6 – ANSI classifications of vehicle [Tohir and Spearpoint [2013].

Classification	Curb weight	
Passenger car: Mini	1500 – 1999 lbs	680 – 906 kg
Passenger car: Light	2000 – 2499 lbs	907 – 1134 kg
Passenger car: Compact	2500 – 2999 lbs	1135 – 1360 kg
Passenger car: Medium	3000 – 3499 lbs	1361 – 1587 kg
Passenger car: Heavy	≥3500 lbs	≥ 1588 kg
Van/MPV	Not defined	
SUV	Not defined	

As the data from multiple sources presented below shows, there are light vehicles with over 8 MW, and medium and heavy vehicles with less than 3 MW HRR. Analyzing this data and looking at the mass loss as a percentage of vehicle weight, it is found that there is a wide range in this value, from 13% - 25%, and this correlates with the peak heat release rate. Some tests had, for various reasons, more complete burning of the vehicle than others. In general, the tests with a mass loss percentage about 16% or lower show a much lower peak HRR compared to other tests of similar size vehicles. A selection of fire test results was chosen based on having a higher mass loss percentage, from about 17 to 25%, indicating more complete burning of the vehicle, and a higher peak HRR. Details of the tests are shown in Table 7. The data is from Tohir and Spearpoint (T&S), Lam et.al. [2016] and BRE [2010]. There is no clear correlation between either HRR, weight, or mass loss percent, but the table has been sorted by increasing mass loss percentage as it is generally associated with larger fires.

Table 7 – Select vehicle fire test results from several sources.

Source	Test	Year	Curb Weight [kg]	Peak HRR [kW]	Total Heat Release [MJ]	Mass Loss %
T&S	L4	1970	1,102	1,972	3,900	16%
T&S	C4	1970	1,360	3,633	4,860	16%
T&S	C3	1990s	1,360	3,560	4,950	17%
T&S	L7	1985-93	975	8,872	4,132	17%
T&S	M3	1994	1,454	9,854	6,806	18%
T&S	M2	1994	1,382	8,283	7,000	18%
T&S	C2	1995	1,303	8,188	6,670	21%
Lam	ICE-A	2015	1,096	7,100	3,290	25%
Lam	ICE-B	2013	1,344	10,800	4,950	25%
T&S	L3	1970-80s	1,067	4,470	8,000	25%
BRE	Test 7	2001	1,163	4,790	-	-

As the table indicates, there is no obvious correlation between peak HRR and neither age of vehicle, nor curb weight. If the mass loss percentage is high (20%+) both older and smaller vehicles can yield high peak HRRs and total heat released. It is important to note that the mass loss percentage is of total mass, not combustible mass. As the percentage of vehicle weight that is made up of plastic (replacing non-combustible items) has increased since the 1970s, it has thus become increasingly likely that a higher percentage of the vehicle weight is consumed in a fire. It is shown that both older and newer vehicles are able to produce large fires (7 MW+), but it is possible that it is *more likely* to occur with modern vehicles. This data is not conclusive in supporting this hypothesis however.

Five HRR curves, representing each of the decades from 1970s to 2010s are shown in Figure 5. The curves for 1970s, 80s and 90s are all via Tohir and Spearpoint [2013], originally from Steinert [2000], Van Oerle, Lemaire and Van de Leur [1999], and Joyeux [1997], respectively. The 2000s data is from BRE test number 7 [BRE, 2010]. The BRE report does not specify mass loss percentage, but the description and photos indicate a fully involved car fire, though as in all tests in that series, there was a long incipient stage. The 2010s data is taken from [Lam et.al., 2016].
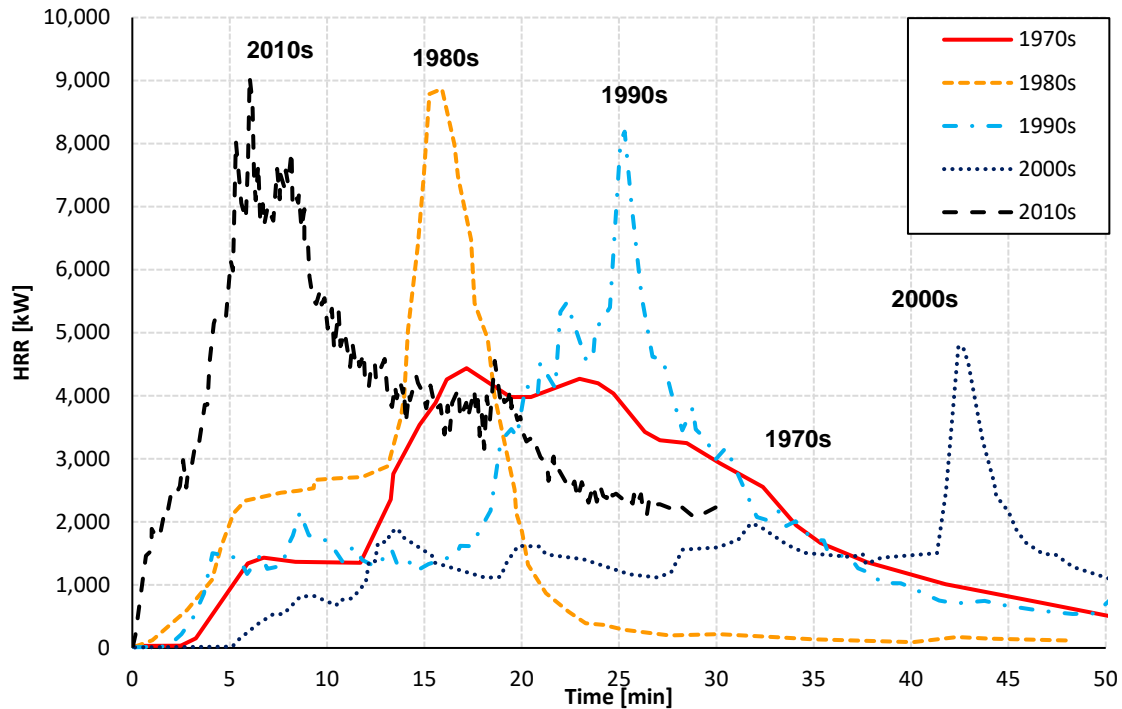
Figure 5 – Select heat release rate curves for vehicles from each decade.

The plot shows that the lowest peak HRRs are found in the 1970s and 2000s vehicles, but as seen in Table 7, there were also recorded fire tests from the 1970s with HRRs over 7 MW. The 2010s test yields a significantly faster HRR growth, but the placement and method of ignition, as well as ventilation and other environmental factors, has a large impact on how vehicle fires develop. The 2010s test plotted above used a larger ignition source than the other tests; a gas burner under the vehicle, simulating a pool fire. The 2000s test on the other hand had a smaller external ignition source which lead to slower fire spread. The test conditions and ignition sources for all the tests shown are noted in Table 8.

Table 8 – Ignition source and test conditions for the five tests in Figure 5

Test	Ignition location	Test Conditions
1970s	Front seat	Window gap
1980s	Front seat	Front windows open
1990s	Front seat	*unknown*
2000s	Engine	Windows closed
2010s	Engine, pool fire	Windows closed

Although the fire sizes used as the basis for parking garage fire codes is not explicitly stated, there are design fire scenarios for tunnel fires where values such as peak HRR is provided. For example, Ingason [2009] summarized several HRR values provided as guidelines for tunnel design. This included a car fire scenario of 4 MW peak HRR, proposed by Ingason in 1995. Reference is also made to French regulations, where a design fire with peak HRR of 8 MW is associated with "2-3 cars, tunnel height 2.7 m". Comparing this to the HRR data for a single car fire shown in both Figure 5 and Table 7, it is clear that these proposed design fires for tunnels will underestimate the peak HRR for a single car fire in many instances. Another document on tunnel design fires published by National Cooperative Highway Research Program (NCHRP) in 2011 [National Academies of Sciences, Engineering, and Medicine, 2011], references a number of

vehicle HRRs from different sources. As in the Ingason article, several specify design fires around the 5 MW range. For example design fire for tunnels in Germany, and a reference for "absolute minimum water requirements" that specifies a car fire as 5 MW. The article does reference the NFPA document "Standard for Road Tunnels, Bridges, and Other Limited Access Highways (2008)", which specify a car fire as 5-10 MW. This range does encompass the peak HRR of the majority of single car fire tests reviewed here, but with such a wide range it leaves important decisions up to the discretion of the designer.

5.1.3. *Plastic Fire Energy*

In addition to looking at fire testing of actual vehicles, the plastic content can be analyzed by itself. Using the data documented in Section 4.1, an estimate of the increase in heat release rate associated with the growth of plastic use can be calculated if some assumptions are made regarding the heat of combustion for the plastics. This will vary with the type of plastic, from about 15 to 43 kJ/g [Khan, Tewarson, and Chaos, 2016] and [Lyon and Janssens, 2005]. Heats of combustion were found from the literature for all but four of the plastics, which represent a total of 10.1% by weight. The weighted and absolute average heat of combustion for the remaining 90% were both around 30 kJ/g (30.3 and 29.5 kJ/g respectively). Evaluating the changes in plastic content over time shows that for the three 5-year periods 1976 to 1990 the total heat content (i.e. fire energy) from plastic content increased by an annual average between 47 – 52 MJ per year. Noting that there is a data-gap from 1991-95, the increase in plastic energy content from 1995 onwards was an average of 65.5 MJ/year. There were fairly large variations from year to year, from a decrease of 300 MJ, to increases of 300 MJ. The total increase in energy content from plastics in the average vehicle (in the USA/NAFTA area) from 1976 to 2018 was 2,298 MJ, a total increase of 91%. The increase in average vehicle curb weight and plastic fire energy content is plotted in Figure 6.

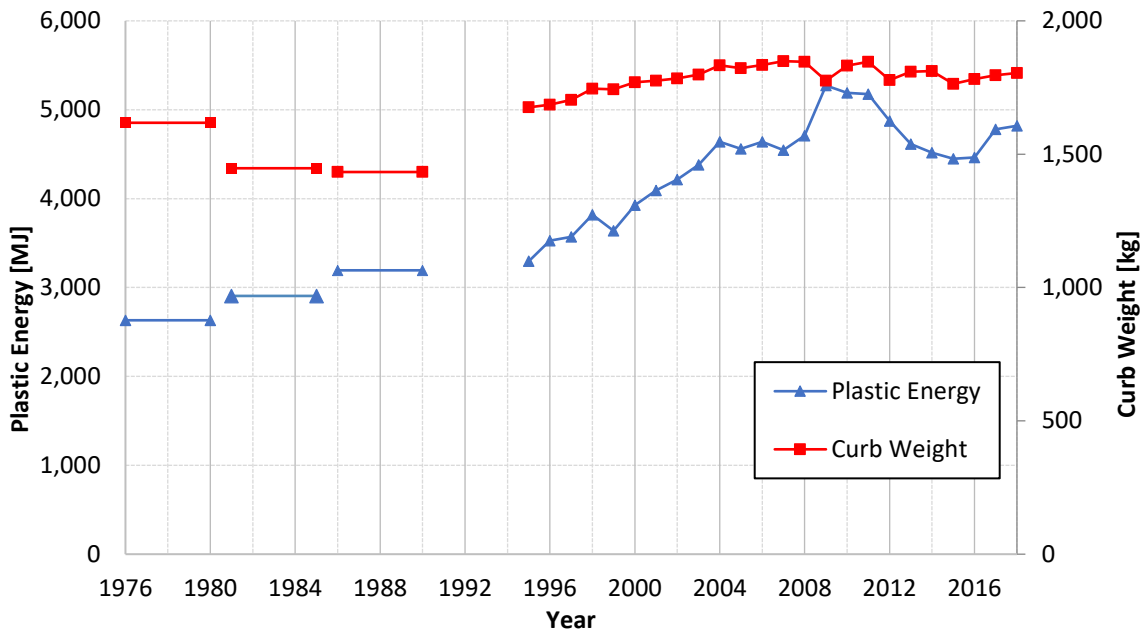**Figure 6 – Curb weight and plastic content potential fire energy from average north American vehicles from 1975 to 2018.**

Tests show great variations in total fire energy released from a full vehicle fire. A series performed on vehicles from the 1970s [Mangs, J., Keski-Rahkonen,1994] gave an average value of 3,300 MJ over three vehicle tests. Using this value, the 2,298 MJ increase in potential fire energy from the

plastic content up to 2018 represents a 6.7% increase in total fire energy from a full vehicle fire from 1970s. This is clearly a major increase in potential fire energy. Other factors may be important to the fire dynamics as well, such as easier ignition of plastics, and more rapid fire growth rate.

5.1.4.   Fire Spread

When used externally on the vehicle to replace previously non-flammable metal components, usually steel or aluminum, plastic components can contribute to faster fire spread. For example, when a fire that starts in the engine or passenger compartment is able to migrate to the exterior of the initial car, to the exterior or neighboring car, to the inside of that car and so on.

There is also an increasing amount of plastics in the engine compartment of modern vehicles. A test series reported by the Motor Vehicle Fire Research Institute (MVFRI) found that in the case of post-collision fires, the plastics and flammable fluids in the engine were able to sustain a fire large enough to penetrate into the passenger compartment [Tewarson, Quintiere and Purser, 2005]. In addition to threatening the occupants, the passenger compartment is where the largest amount of flammable materials are located. The interior materials can sustain a fire with a much larger potential to spread beyond the vehicle of origin. Fires that don't spread into the passenger compartment are typically much less severe, or may even burn themselves out before spreading to adjacent vehicles [BRE, 2010].

Tohir [2015] provides a summary of the multi-vehicle full-car fires that have been performed with adequate details to make a reasonable analysis on fire spread. Three studies have been identified as the most detailed and reliable [Joyeux, 1997; Steinert, 2000; and BRE, 2010]. These studies had vehicles spaced between 0.4 to 0.8 m (1.3 to 2.6 ft) apart. As detailed in the studies, ignition of the second vehicle took place between 5 to 28 minutes after ignition of the first vehicle, typically due to radiative heating of rubber components of the adjacent vehicle. As can be seen from the dates of these test, most of the cars utilized in the testing were older, indicating the need for more updated testing with more current vehicles.

Most flammable materials will ignite when exposed to a heat flux of 25 kW/m^2 [Tewarson, 2016]. Testing by the BRE in the UK on flammable exterior materials for vehicles found a critical heat flux range of 11-18.5 kW/m^2, with most plastic components at the upper end of the range; bumpers at 17.5 kW/m^2, fuel tank at 16.5 kW/m^2, and the tires near the bottom at 11 kW/m^2. An upper layer temperature of 500-600°C is typically associated with the 20-25 kW/m^2 criteria where most ordinary flammable materials will ignite [Karlson and Quintiere, 2000]. As discussed in Section 3, parking garages often have limited ceiling heights, due to cost and space concerns, or to conform to apartment or retail ceiling heights for surrounding occupancies in multi-use buildings. The buildup, and trapping, of hot gases is therefore critically important when considering fire spread.

5.1.5.   BRE (UK) Vehicle Fire Tests

A test series by BRE involved several multi-vehicle, full car fires in a parking garage mockup [BRE, 2010]. The tests found that with the second vehicle involved, the ceiling temperatures reached 1100°C, and a third car that was separated from the two others by an empty parking spot quickly ignited. The BRE test series involved a "car park enclosure", not a fully open garage. There was extensive ventilation around the vehicles, approximately 10 m^2, including a fully open wall. The NFPA 88A definition to consider a parking garage open is if interior walls are at least 20% open and uniformly distributed (section 5.5.2 and 5.5.5). In the BRE testing two of the sides were 25% open, but the third was solid, thus the testing space is not considered open per NFPA 88A. As shown in Figure 7, the openings were also low to the ground, only supplying air to the

fire, not venting hot gases as might be the case with a fully open configuration. Note that NFPA 88A does not have requirements for vertical placement of the openings but does state that openings shall be uniformly distributed.

Figure 7 –Configuration of openings in BRE test [BRE, 2010].

Large beams and beam pockets are also common in multi-level parking garages which can trap hot gases. As Figure 7 shows the beams were relatively shallow in the garage mockup. The BRE tests can therefore be considered somewhere between an enclosed and fully open garage; the ventilation area is more than is expected in for example a small underground garage but venting of hot gases is more restricted than in a code-defined open configuration. How much the beam pockets contribute to trapping hot gases, and whether it's sufficient to ignite neighboring vehicles should also be established. This has been done for compartment fires (e.g. [Floyd, Gottuk and Mealy, 2008]), but it is not obvious that the dynamics of vehicle fires are the same. Vehicle fires are typically larger and faster growing, and the fuel package is larger and taller than in most compartment settings.

5.1.6.   Fire Resistance Rating Time-Temperature Requirements

The fire resistance ratings employed by the NFPA standards (i.e. NFPA 220) are based on resistance to a fire exposure described in ASTM E119 [ASTM, 2014], specifically a time-temperature curve, shown in Figure 8.
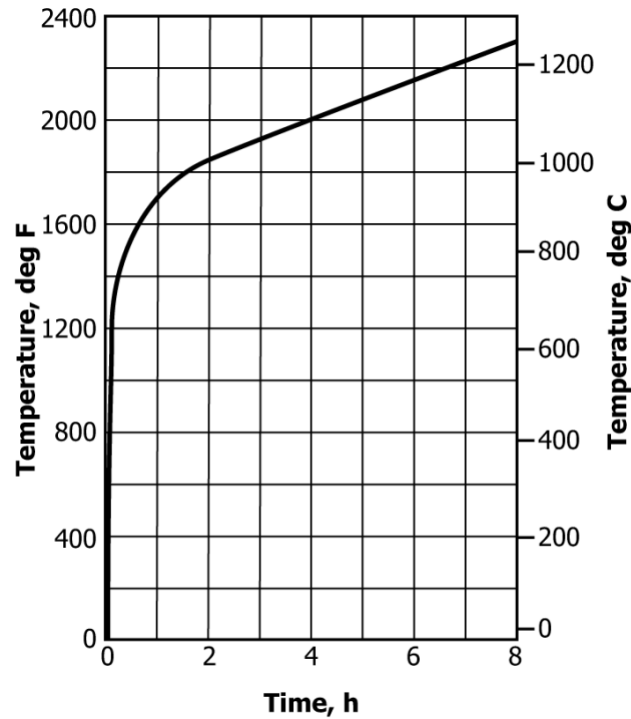
Figure 8 – ASTM E119 time-temperature curve [ASTM, 2014].

As described in NFPA 88A, open garages are required to have a fire resistance rating of 1 to 2 hours. Per the E119 curve, that means the ability to resist a max temperature exposure of just over 1,000°C at around two (2) hours. Vehicle fire tests are often conducted under oxygen consumption calorimetry hoods, or in large test halls. Thus, the temperature developed in a ceiling layer at the typical height of parking garage ceiling is not available from these tests. When hot gases are not allowed to collect above the vehicle, the results will underestimate the fire load impact on overhead structural members in a parking garage fire.

The test performed at BRE is rare as it involved a mock-up of a parking garage. However, it still had some limitations, such as being a small area, tested no more than 3 cars, and had no beam pockets to collect hot gases. Conversely, more open test configurations often show lower temperatures around the vehicle, and much slower time for temperature increase; often over an hour to reach above 1,000°C. In test series with lower ceilings, a temperature over 1,000°C can be reached in a few minutes. In the BRE testing it was found that a temperature of over 1,100°C can develop under the ceiling in even a relatively open garage with single vehicles burning after 5-10 minutes, significantly earlier than prescribed in the E119 testing. As nearby vehicles ignite, the hot gas will continue to be supplied to the ceiling layer. Ship and Spearpoint [1995] tested relatively small cars in a low (height: 7.2 ft (2.2 m)) corridor-like configuration, to simulate a fire in the France-England Channel Tunnel train shuttle wagons. Under this configuration the ceiling temperatures reached above 1,000°C at around 7 minutes, as shown in Figure 9. These results show that the typical configuration of a parking garage will have a significant effect on the resulting hazards from a vehicle fire, including fire spread. This configuration may not be fully accounted for in the fires used for building design if data from less confined tests are used.
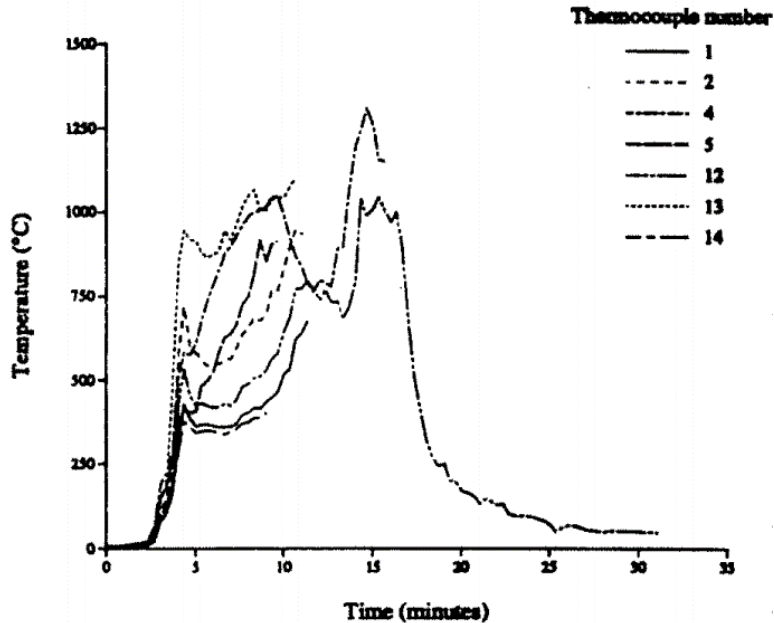
Figure 9 – Temperature above the car during full scale testing [Shipp and Spearpoint, 1995].

5.1.7. Plastic Fuel Tanks

A plastic fuel tank in passenger vehicles will introduce approximately 8 to 10 kg (18-22 lb) of HDPE (high-density polyethylene) to the vehicle [Dai, Kelly and Elgowainy, 2016]. With polyethylene (PE) having a heat of combustion of 43.6 kJ/g [Khan, Tewarson, and Chaos, 2016] in a fully involved fire this would yield at least 371 MJ of energy released. Compared to the total fire energy of a fully involved vehicle (3,500 MJ and up) this is a relatively small contribution (11.3% of total or less). The large weight of plastic, and high heat of combustion results in replacing a metal fuel tank with a plastic one will account for 16% of the increase in potential fire energy from added plastic in vehicles from 1970 today. It should be noted that the fuel tank is already included in the total vehicle plastic content calculated above.

An important concern with plastic fuel tanks is the earlier release of fuel when exposed to an external flame as compared to a metal fuel tank. There are fire resistance requirements for plastic fuel tanks, specified in ECE R34.01, Annex 5 Section 5.0 "Resistance to Fire" [United Nations Economic Commission for Europe, 2012]. This standard requires a tank to show no leak of fuel after exposure to a direct flame for 2 minutes. The flame source is from a pool fire, typically using diesel or gasoline, that is slightly larger than the footprint of the tank, and a distance away equivalent to the height above the road as the tank would be installed in the vehicle. In the case of burning gasoline underneath a car from a full fuel tank release, the fire exposure could last much longer than the two minutes required in the tests. The concern with the two-minute requirement lies in the inability for firefighting personnel to arrive in that timeframe to extinguish a fire before the tank would melt and empty its contents. Even if the structure is sprinklered, the fire would be shielded which could slow down activation time and inhibit extinguishment. Based on this requirement a worst-case assumption could be that a plastic fuel tank would leak fuel after two minutes of direct fire exposure.

Figure 10 – Failing plastic fuel tank [Digges, 2003].

A series of tests performed by the Southwest Research Institute, and summarized by Digges [Machado, 2003; Digges, 2003], tested six different fuel tanks placed above fires that lasted past the two-minute requirement. The time when the tanks started to leak fuel was found to be from 10 seconds before the two-minute requirement, up to 2:36 min after the two minutes (i.e. after 1:50 to 4:36 minutes of fire exposure). It should be noted that the failure before the two minutes was performed on a new tank installed in a vehicle already damaged by fire, which could have led to increased ventilation. Per this testing, in a best-case scenario, a plastic fuel tank will leak fuel 4:36 min after exposed to an under-car fire. Only one metal tank was tested in this series. It was found to fail 4:22 min after the required time, i.e. 6:22 min after the fire started. The plastic fuel tank failed due to leaks and minimal venting whereas the metal fuel tank developed excessive pressures and vented large amounts of fuel.

5.2. Battery Electric Vehicles

The two main types of alternative fuel vehicles that are of concern are currently fully battery-electric vehicles (EVs) and hydrogen fuel cell vehicles. As noted in Section 4.4, hydrogen vehicles are not close to widespread use so these vehicles will not be evaluated here.

5.2.1. Battery Energy Release

Two pairs of similar EV and ICE vehicle models from two manufacturers were tested by Lecocq [Lecocq, 2012]. The first pair were smaller vehicles, both around 1,100 kg, while the second pair were larger at 1,400 and 1,500 kg for the ICE and EV model respectively. The vehicles were ignited by a gas burner placed in the front seat, with the window open. The peak heat release rate results were similar for the first pair at 4.2 MW and 4.8 MW, with the ICE vehicle being higher. For the second, larger pair, the EV had a peak of 4.7 MW, while the ICE vehicle had a peak HRR of 6.1 MW. The HRR plots for all four tests are shown in Figure 11. The ICE vehicles are represented by dark lines with markers, while gray lines are used for the EVs.
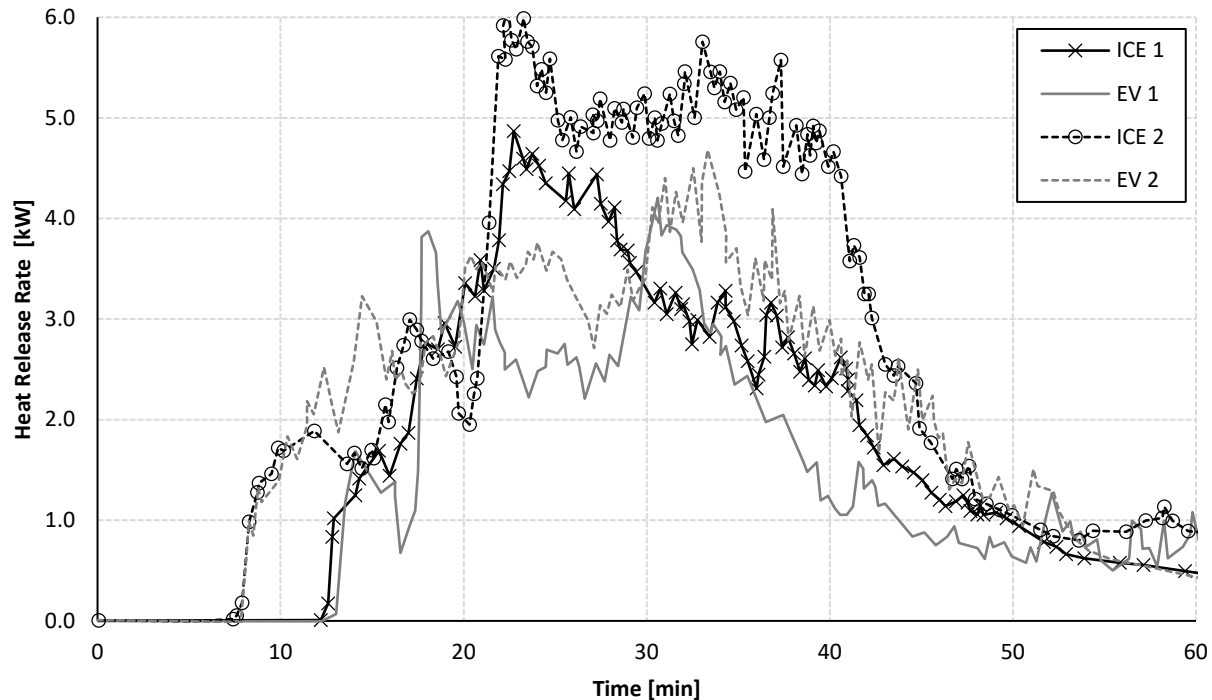
Figure 11 – Heat release rate for two pairs of similar ICE and EV vehicles for tests conducted by Lecocq, [2012].

The figure shows that the heat release rate for the first vehicle pair is very similar, both in peak HRR, and in growth rate. The second pair start with similar growth for the first 20 minutes, when the HRR for ICE 2 rapidly increased to its peak value and stays higher than the EV 2 curve until near the end.

Another paired-vehicle test series using sets of similar ICE vehicles and EVs were performed by Lam et.al. [Lam et.al., 2016] of the National Research Council Canada. All vehicles were exposed to an identical, realistic simulated pool fire; a propane burner underneath the vehicle. The HRR was measured by a hood, as well as temperature and heat flux. This test is also a good representation for the dynamics of fire spread between vehicles in a garage or carrier vessel caused by burning, leaking fuel running under the neighboring vehicles. The findings from the study concluded that:

> *Overall, the EVs did not present a greater hazard than the ICEVs. The peak HRR and heat flux levels measured in the ICEV tests were due to the burning of a full tank of gasoline and were higher than those measured in the comparison EV tests.*

The tests also found that the peak HRR from the burning gasoline occurred at the same time or earlier than that for the EV batteries. The comparison of HRR for two sets of ICE vehicles and EVs from the Lam study is shown in Figure 12. The EVs are shown with the dark lines, while light gray is used for the ICE vehicles. The tests yielded similar peak HRR for the ICE vehicles and EVs, with the former being slightly higher.
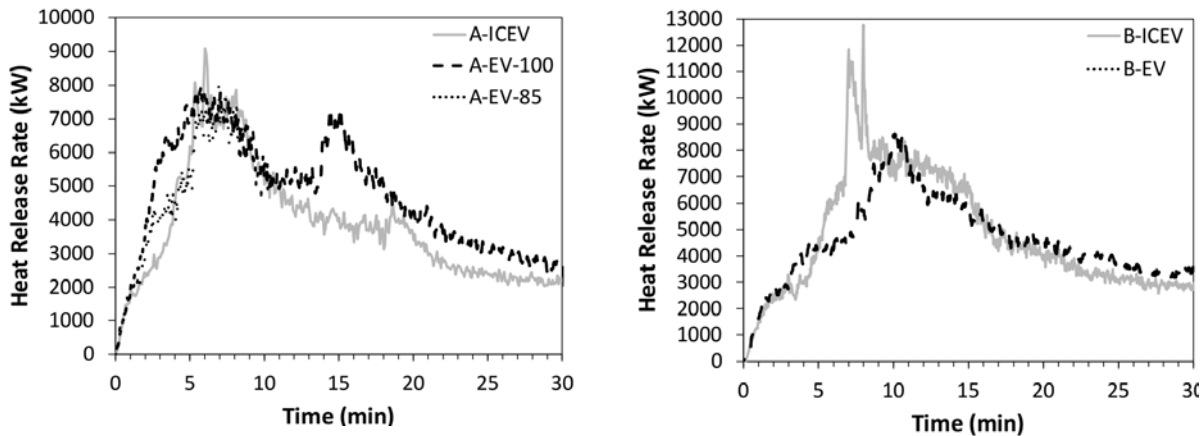
Figure 12 – Comparison of heat release rate from internal combustion and electric vehicles in Lam et.al. [2012]

As the fuel tank or batteries placed underneath the vehicle is the main distinguishing feature between ICE vehicles and EVs, with the rest of the vehicle body being largely identical (the exception being the engine). A pool fire under the vehicle is likely the fire scenario where the largest differences between the two vehicle types would manifest. The other difference could be in ignition and the response to collision damage and effects of a fuel leak versus a damaged battery. Ignition risk and collisions are outside the scope of the present study.

5.2.2. Extinguishment

As shown in Figure 11 and Figure 12, tests performed on similar ICE vehicles and EVs find a comparable HRR for both vehicles types in peak value, and largely in growth rate and fire development as well. In addition to ignition and collisions behavior which will not be covered here, there could also be differences in fire behavior.

For ICE vehicles in a fire, the fuel tank will eventually rupture or melt, and depending on the nature and orientation of the surface beneath, free-flowing gasoline can disperse from the burning vehicle and spread the fire to neighboring items. A lithium-ion battery back on the other hand will remain in place, generally underneath the passenger compartment making up the floor of the vehicle. As the fire penetrates the layers of the battery, high-temperature jet flames can occur (see Figure 13) which can extend some distance out from the vehicle. This flame may or may not extend further than running gasoline would, as that depends on the slope where the vehicle is parked, and the nature of the battery rupture. In a narrow parking spot this flame could certainly ignite another vehicle parked immediately next to the EV.

In 2017, an EV in California crashed into a private garage and caught fire [NBC LA, 2017]. The firefighters put the fire out and pulled the car out. A video shows flames jetting out from underneath the car, shown in Figure 13. In a different incident, an EV is reported to have reignited twice after a fatal collision [Reuters, 2018].

Figure 13 – Flame jet from Tesla model X battery electric car [NBC LA, 2017].

The recommendations to firefighters to deal with EVs is to apply very large amounts of water directly to the outside of the battery pack, potentially for several hours. If necessary, also lifting one side of the vehicle [Archer, 2019]. These issues are important for firefighters to keep in mind and are a concern for extinguishment tactics, water supply and containment of the fire.

5.3.   Marine Vehicle Transport Vessels

The fire hazard that modern vehicles pose to marine transportation vessels is largely similar to that for parking garages except, as noted in Section 3, in all cases fire alarm and active protection systems will be required. With rapid fire growth and/or spread to adjacent vehicles representing some of the greatest hazards associated with modern vehicles, the presence of sprinkler or other protection systems, and early notification of a trained crew will significantly reduce the hazard associated with vehicle fires onboard.

It is possible that with the large size of modern vehicles, in combination with extensive plastic use throughout the vehicle, including underneath and in the engine compartment, a significant shielded fire could occur in a vehicle that the sprinkler system would have difficulty containing. Combined with rupturing of fuel tanks and the release of large amounts of burning fuel underneath the vehicles, a fire could overwhelm a solely water-based system. However, based on testing of sprinkler systems in similar scenarios [BRE, 2010; BRE, 2009], it is likely a simple sprinkler system will at least be able to contain the fire in most cases, preventing further spread and allowing the crew time to respond. Extensive tests of the ability of sprinkler systems to extinguish or contain particularly challenging fires are limited.

Response to a fire should occur more rapidly and in a more organized manner on a vessel with trained personnel than in parking garages on land, where the first on the scene are typically civilians or facility security personnel while waiting for firefighters to arrive. As was the case in the Liverpool Echo Arena fire, professional firefighting response could take 15 to 20 minutes or more [Merseyside Fire & Rescue Service, 2018]. In the Echo Arena case, this was due to slow notification, confusion and long travel times. It is important to remember that marine vessel crews are not professional firefighters, and at sea, assistance from professionals can be hours or days away. If the fire protection system and the crew are overwhelmed, the chance of saving the vessel

decline drastically. However, due to the significance of fire spread within and between vehicles on the development of vehicle fires, the rapid response of personnel with limited training and equipment could potentially be more beneficial than a slower response from professional firefighters. The level of training, experience and equipment can also vary significantly depending on the vessel and the resources available to the owner/operator.

A report looking into 35 fires in a ro-ro passenger vessel, and nine fires in ro-ro vehicle carriers in the period of 2005-2016 found that failures of the fixed firefighting systems were important for severity of fires, where failure of the systems, or delayed activation, resulted in extensive damage, including total loss of the vessel [DNV, 2016]. In contrast, rapid activation of the protection systems is associated with successful extinguishment of the fire and limited fire damage and losses. In all cases analyzed, when the deluge system did not apply water to the fire, the vessel was a total loss. For closed spaces were CO_2 was applied, the report concluded that incident data suggests that agent must be applied within 10 minutes of ignition to avoid severe damage.

An example of the protection systems in action occurred when a fire broke out onboard the US flagged MV Honor vehicle carrier while in the English Channel [National Transportation Safety Board, 2017]. The vessel was 190 m (623 ft) and carried 5,000 vehicles, both personal and military. The fire started at the vehicle deck and crew outfitted in firefighting gear had to retreat from the deck due to smoke and heat. The crew cooled the bulkheads with water and after clearing all personnel, activated the CO_2 system to flood the garage deck and extinguished the fire. The fire is believed to have started due to a failed starter motor solenoid in a personal vehicle. The vessel returned to port under its own power. The damage was estimated at $700,000 to the vehicle cargo and the vessel. A smaller ro-ro vessel, the MV Courage with 600 vehicles also experienced a fire which was extinguished when the crew activated the CO_2 flooding system. Approximately 100 of the vehicles on board suffered damage [Konrad, 2015].

5.4. Fire Spread

The combination of several factors discussed above has led to changes in vehicle fire hazard where a major concern has become the spread of fire between vehicles. Factors such as changes in the mix of vehicle construction materials, overall enlarging of vehicle physical dimensions, and tighter parking arrangements has increased the risk of fire spread between vehicles. It appears that fire spread from vehicle to vehicle was not considered a major risk in the early versions of the codes when applied to older vehicles and parking structure designs.

For example, the introduction to a study by Mangs [1994] of vehicles built in the 1970s notes (emphasis added) "In an open car park building, the **fire is likely to be constrained to the burning car** or at most be spread to one or two adjacent cars". As the report on the Liverpool/Kings Dock car park fire of 2017 noted (emphasis added): "in 1968, The Ministry of Technology and Fire Offices' Committee Joint Fire Research Organization researched and concluded **that fire spread from one vehicle to others would not occur** and that if it did, the Metropolitan Brigades would invariably be in attendance within 3 to 4 minutes". First published in 2001, NFPA 1710 "*Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*" [NFPA 2010] sets a benchmark goal of a total response time of the first fire engine in 5:20 min, and 9:20 for full assignment of larger resources, for 90% of incidents,. However, not all fire departments are able to achieve this. For example, a study by International Association of Fire Fighters (IAFF) noted that 34% of fire departments surveyed exceeded the travel time limits for both the first-due engine and the full response [FireRescue1, 2019]. There is also accounting for time to navigate modern large and cramped parking structures, which itself can take well

beyond 3-4 minutes. As surveillance video of the Liverpool Echo Arena fire showed the fire was not even reported to the local fire department until at least 13 min after smoke can be observed, and the fire department arrived 21 minutes after smoke is seen from the initial vehicle [Merseyside Fire & Rescue Service, 2018].

A series of tests evaluating the fire spread between vehicles in different parking configurations (side by side, front to front) were performed in the UK [BRE, 2010] using vehicles constructed in the late 90s to early 2000s. The tests found that fires starting inside the cabin spread to adjacent vehicles after 10 min in one test, and after 20 minutes in two others. In one test, ignition of a third vehicle two spots over occurred less than 5 minutes later. After spreading to the second vehicle the fire quickly grew beyond 10 MW. If the fire department is not on the scene before the fire spreads to the second vehicle, there is a high probability they will be unable to extinguish it, or even contain the spread, as has been the case in several recent parking garage fires.

5.4.1. Spill Fire as Method of Fire Spread

One possible scenario in which multiple vehicles can become involved in a parking structure fire would involve the leaked contents of a fuel tank igniting and spreading the fire to surrounding vehicles. As shown in this report, most modern vehicles utilize a plastic fuel tank, which are mandated to remain intact for two minutes when exposed to direct flame impingement. Testing has shown that most tanks remain intact for 4 minutes, before starting to leak their contents to the ground below [Machado, 2003]. The behavior of the fuel upon tank rupture is critical to determine the conditions under which the spread of the fire to adjacent vehicles is possible.

A number of researchers have studied the spread of liquid fuels in spills and the effect of this burning configuration on fire dynamics. Notably, Putorti [2001] and Mealy and co-workers [2011, 2014] have studied fuels spills for a wide range of fuels, including gasoline and diesel. These studies have also looked at the effect of the substrate on the fire characteristics, including concrete which would be a typical flooring material in parking structures (asphalt typically only allowed on the lowest level, for example in the IBC [ICC, 2018]). Important parameters for a burning fuel spill include the spill dynamics (i.e. size of the spill, thickness of the fuel layer etc.), flame dynamics (heat release rate and burning rate of the spilled fuel, etc.) and time of ignition relative to start of the spill. Measurements on flat, level surfaces have found that spills, especially of limited volumes of fuel, will have lower heat release rates than of pan fires with the same fuel. This is due to the thinness of the fuel layer of the expanding spill and heat transfer to the surface substrate. This impedes the heat feedback mechanism that allows for liquid fuel vaporization and reducing the fuel burning rate and heat release [Klassen et al. 1992]. The heat release rates can be substantially less than found for confined pool fires in metal pans [Mealy et al., 2014]. Eventually the fuel layer become so thin that the heat loss to the substrate become greater than the heat feedback from the flame, preventing further fuel vaporization and the fire is not able to be sustained.

The heat release rate of the fire is greatly impacted by the time of ignition relative to the start of the spill. Early ignition once the fuel is spilled can lead to larger heat release as the fuel layer thickness is deeper since the fuel has not spread and thinned out. Ignition later after the spill begins, especially for a finite fuel volume, allows the fuel to spread and the layer to become thin. It is unclear how effective an ignited fuel spill would be for spreading fire from a burning vehicle to adjacent vehicle. This is due to the muting effects on fire characteristics for a thin-layer of fuel spilled on a surface such as concrete. If the adjacent vehicles are quite close and ignition of the fuel occurs before the spill area becomes large and the fuel layer becomes too thin, a burning pool spreading to adjacent vehicles may be possible. A sloped ramp will allow the fuel to reach

the neighboring vehicle but will also more quickly reduce the thickness of the pool. The interaction between these competing effects must be studied further. Tests have been performed to determine the time required until the fuel tank leaks, but these did not evaluate what occurs once the fuel is released. This scenario needs additional study to assess the true hazard and determine if safeguards are warranted.

5.5. Thermal Effects of Modern Vehicle Fires

As described in Section 5.1.6, the ceiling layer temperature that develops above a burning modern vehicle inside a parking garage can, in as little as 10 minutes, reach the value associated with the 2-hour mark in the ASTM E119 testing (and the similar ISO fire curve). A fire in a single vehicle will start to burn out and will not sustain this temperature as long as the E119 curve, but with more vehicles parked close by catching on fire, the structural elements will very quickly be exposed to a significant fire load, potentially more severe than what is experienced in the standard tests used for design purposes.

5.5.1. Spalling of Concrete

Concrete spalling is reliant on high temperatures over a long period of time, potentially several hours, and is a complex phenomenon that is difficult to predict [Hertz, 2003]. But generally, internal concrete temperatures are required to reach at least 374°C, the critical point of steam. Any constant exposure above this level can eventually lead to spalling, and the higher the concrete temperature the quicker it occurs. Significant spalling was observed in both the Liverpool, England 2017 fire (see Figure 14) and the Stavanger, Norway 2020 parking garage fire (Figure 15). The spalling created large penetrations between the different garage levels and undoubtedly contributed to vertical fire spread. It is important to note that spalling typically occurs several hours into the fire once it had grown to a substantial size [Hertz, 2003]. The spalling phenomenon is highly unlikely to have any effect on the early phases of the fire. It is not unique to vehicle fires and has the potential to occur in any building with uncontrolled fire spread through a large fuel load.

Figure 14 – Concrete spalling in Liverpool, England 2017 fire.

Figure 15 – Concrete spalling in Stavanger, Norway 2020 fire.

5.5.2.   Failure of Structural Steel

The critical temperature for steel is usually taken as 538°C (1,000°F) [Kodur and Harmathy, 2016], where the modulus of elasticity of construction steel has been reduced by half, and deformations become permanent. The critical temperature refers to the internal steel temperature, but with the high heat transfer coefficient of uninsulated steel this can occur rapidly once the air temperature reaches similar levels. Vehicle fire tests with a lower ceiling height have found that these temperatures are measured within a few minutes after ignition of the vehicle. With a single burning vehicle, it is not certain a high enough ceiling temperature can be sustained for long enough to pose a threat to overhead load-bearing steel members, especially in a well-ventilated open garage configuration. But with fire spread to multiple vehicles, it is likely that modern vehicle fires have the potential to rapidly threaten the integrity of steel structures. The most dramatic example of this is the collapse of large parts of the steel parking garage at the Stavanger Airport after the fire in January 2020. One news article reports that the steel structure started to collapse after "nearly two hours" [Klingenberg and Ramsdal, 2020b] though the specific timeline has not been confirmed. Columns and beams in the garage that collapsed were constructed of unprotected steel, with pre-cast concrete floors elements. The building had been granted a deviation from the local code-required 15-minute fire resistance, needing only a 10 minute fire resistance [Klingenberg and Ramsdal, 2020c].

For high rise building construction, there is extensive research on fire protection of load bearing steel members. A multitude of techniques exist to increase the fire resistance to a range of levels, depending on the application and code requirements, from intumescent paint to full coverage in insulated batting. The different systems will have varying cost of installation and maintenance, as well as architectural impact.

5.6. Design of Parking Garages

5.6.1. Vehicle Stackers

A single test of a sprinklered two-car stacker configuration was performed by BRE in September of 2009 [BRE, 2009]. This test showed that sprinklers placed overhead contained the fire to the lower vehicle, allowed some spread to the above vehicle, but prevented it from becoming fully involved. This was a replication of a test performed with no sprinkler protection in January 2009 [BRE, 2010] where both vehicles became fully involved and consumed by the fire.

The sprinklers were installed in accordance with protection requirements for an Ordinary Hazard 2 item, as the European standard for sprinkler systems; BS EN 12845, does not explicitly cover car stackers. This includes four quick response sprinklers above both cars, including sprinklers in the stacker system, shown in Figure 16 taken from the BRE report. Location of sprinklers marked with green X.
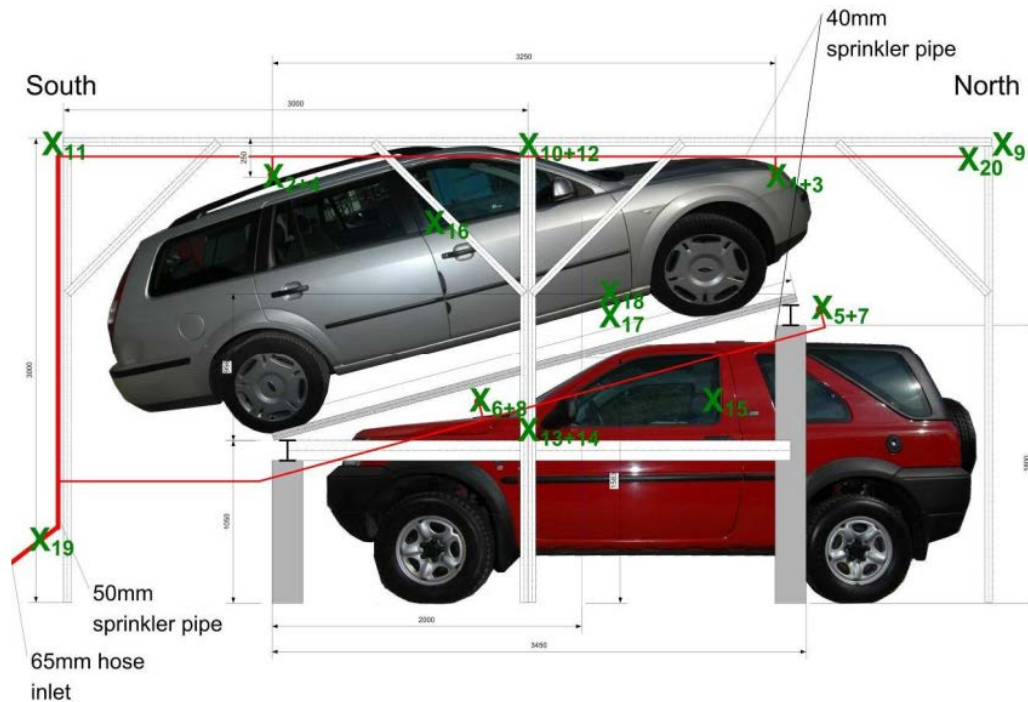
Figure 16 – Vehicle and sprinkler arrangement for the BRE stacker test [BRE, 2009].

The fire was ignited on the seat of the lower vehicle. After 13 minutes the first roof sprinkler activated, followed by a second at 23 min, and were left on for one hour before being shut off. The fire continued to burn after this. After the test it was found that the lower vehicle was almost entirely consumed by the fire, while the upper vehicle suffered significant exterior and engine compartment damage, but fire never spread to the interior. The test showed that two activated overhead sprinklers control and limit the spread of the fire in the stacker system, but does not extinguish the fire, nor prevent total consumption of the lower vehicle. As a comparison of the fire development, the non-sprinklered test at 10 min is shown in Figure 17, while the sprinklered test at 1 hour 23 min is shown in Figure 18.

Figure 17 – Non-sprinklered test at 10 min [BRE, 2010].

Figure 18 - Sprinklered test at 1 hour, 23 min [BRE, 2009].

5.7.   Modern Vehicle Fire Hazard Summary of Findings

An analysis of the available data on the fire hazard of legacy and modern vehicles, and the codes, regulations and design trends of parking structures and vehicle carrier vessels has found the following:

Nature of the problem and current codes
- As a percentage of total number of fires, those fires involving parking garages are relatively rare events. Data has indicated that until recently it was rare for a fire to spread to multiple vehicles. Recent fire experience has however raised concerns regarding vehicle to vehicle spread, and indicated that when this occurs, those events can have catastrophic outcomes.
- Human injuries are very rare in parking garage fires. This is likely due to few occupants, all persons awake, and relatively simple wayfinding with multiple easily accessible exits.
- The NFPA codes distinguish open and closed parking structures. In open garages, constructed of non-flammable materials, automatic sprinkler and fire alarm systems are not required.

Modern versus legacy vehicles
- Modern vehicles were found to not show reliably higher peak heat release rates in vehicle fire tests compared to legacy vehicles. The peak HRR over 7 MW was found in tests of vehicles from every decade, and is highly dependent on test conditions such as:
  - Type and placement of ignition source
  - Ventilation configuration (vehicle and surroundings)
  - Vehicle size
- The average US vehicle in 2018 contains 91% more plastic by weight than the average vehicle in 1970, yielding an equivalent increase in potential chemical energy in a fire.
- Plastics can lead to easier ignition and faster flame spread, within and between vehicles (especially with exterior plastics).
- Plastic fuel tank tests found the start of a fuel leak after 2-5 min of pool fire exposure
- Tests of older vehicles should not be used as basis for development of codes and regulations. At the time of writing, vehicles older than 15-20 years show a significant difference in average curb weight and plastic content. Even if the HRR is found to be similar, these construction changes have numerous other effects on the fire ignition, spread and development.

Alternative fuel vehicles
- Hydrogen fuel cell (electric) vehicles are at this time in the research stage with limited distribution. These show very different fire characteristics from ICE vehicles and if the use expands, a thorough analysis of the impact on fire protection should be performed.
- Battery electric vehicles have not been shown in tests to yield larger fires than internal combustion vehicles of similar size and design. Battery fires have different burn characteristics and may present challenges for firefighters. Very large amounts of water are required to cool the battery unit for a long time.

Marine carriers
- Marine vehicle carrier vessels have strict international regulations for fire protection, and few large fire incidents are reported when these are followed and executed properly.

Parking garage design
- There is limited hard data on trends in modern parking garages, but developers and designers predict more dense parking, larger garages, and increasing integration into other occupancies such as retail and residential.

6. Existing Design Criteria and Modern Vehicle Fires

The current design of parking garages is dictated by the fire safety codes and regulations, as detailed in Section 3. The fire hazard presented by modern vehicles has been evaluated in Sections 4 and 5. While catastrophic vehicle fire incidents remain relatively rare, the impact when the fire spreads out of control can be extreme. Consider that the annual property damage caused by all vehicle fires in the USA averaged $22.8 million (2014-2018) [Ahrens, 2020]. The Echo arena fire in Liverpool, England will by some estimates cost almost $25 million [Hamilton, 2018]. The direct property loss associated with the Stavanger, Norway fire is estimated as high as $47 million, which is not including flight disruptions at the airport [Jupskaas, 2020].

Whether the current protection requirements are appropriate for the hazards will be discussed below for the three main locations: marine carriers, enclosed parking garages, and open parking garages.

6.1. Marine Vehicle Carrier Vessels

The IMO SOLAS regulation that governs the vast majority of international shipping vessels, clearly requires much more extensive fire protection systems, training, and preparations than is the case for land-based parking garages, especially those garages classified as "open" design. The latest major revision of SOLAS in 2002 significantly increased the requirement for fire protection systems for new vessels, those undergoing significant refit, and for certain categories of existing ships.

As the DNV report [DNV, 2016] and examples mentioned in Section 5.3 show; when these requirements are followed, systems are functional, and procedures are correctly implemented at the time of the fire, the ship's crew are likely to be able to successfully extinguish the fire with minimal damage to the ship, and low risk of injuries. Damage to the cargo is still likely to be significant due to the open nature of the cargo hold of many ro-ro vessels. The cases where significant vessel damage or loss occurred are usually the cases were systems failed [DNV, 2016]. There is no indication that the systems mandated for vehicle carrier vessels are unable to control or extinguish modern vehicle fires when functional and employed in their intended manner.

This analysis has found that ensuring proper protection of marine vehicle carrier vessels from the fire hazards associated with modern vehicles is primarily an implementation and enforcement issue, not a code requirement issue.

6.2. Enclosed Parking Garages

Enclosed parking garages (including those attached to or within other occupancies) which require automatic detection and notification systems, as well as sprinkler or smoke extraction, appear to be well-protected against modern vehicle fires. But considering the limited number of tests of full vehicle fires performed with overhead sprinklers in a typical garage configuration, and the most recent using 1992-2001 model year vehicles, further research with modern vehicles is recommended. The tests that have been performed have indicated that sprinklers are able to extinguish the fire in the scenarios and configurations tested. In the case of fire within a vehicle stacker, where the lower vehicle is burning, the sprinklers may only be able to control the fire and prevent further fire spread. Testing at BRE showed that the fire flared back up when the sprinklers were turned off. But with sufficient water supply, this should allow firefighting personnel to arrive and extinguish the fire. Note that this testing was only done on a two-level stacker system with sprinklers over both cars. It is unclear how the sprinklers would perform on larger systems, or a stacker with only ceiling level sprinklers.

While the sprinkler requirements for enclosed parking structures may be likely to prevent large, out of control fires in these structures if systems are correctly designed, maintained, and operational, further research on sprinkler protection with modern vehicles would be appropriate. Some questions remain regarding the interaction between a spreading fire and sprinklers, and the ability to properly protect larger stacker systems (3+ vehicles high).

6.3.   Open Parking Garages

Regarding civilian injuries, the current codes for open parking garages could be considered highly successful. There is an annual average of fewer than 20 people injured in over 1,800 parking garage fires, some of whom are also intimate with the initial fire, i.e. present in the vehicle. There are several factors which lead to the low injury rate. People spend little time in parking garages, are awake, and are usually spread out. The egress paths are clear, numerous, and easy to reach. Structural integrity requirements are mainly for the benefit of fire fighters and property protection.

But when considering property loss, three main findings indicate that modern vehicle fires present an unacceptable hazard in open parking structures under the current code requirements in NFPA 88A (as well as similar code requirements elsewhere). The potential for very large losses is significant, and there is a small safety margin as many factors can push a small fire to become a major one. Trends in vehicle and parking garage design indicate that this margin will continue to shrink in the future. Important factors that impact fire spread include:

- Potential for very rapid spread of fire between vehicles, in as little as 10 minutes from ignition, due to:
  - The increased use of plastics in vehicle construction
  - The shrinking distance between parked vehicles
  - The low ceilings in many garages that enhance heat transfer from hot gases
- No requirement for automatic fire detection, notification or extinguishment.
- Large, tightly packed garages where it takes fire department a long time to respond and makes extinguishment difficult.

With no detection or notification system, preventing a single car fire from spreading and potentially causing a conflagration throughout the whole parking structure is therefore solely reliant on the rapid response of the local fire department. In both the fires incidents at Liverpool (England) and Stavanger airport (Norway), the design was based on an expectation that the fire department would be on the scene in 5-10 minutes after ignition. This is approximately the time when fire can start to spread to other vehicles according to some tests [BRE, 2010]. However, in both cases it took 20 minutes or more for fire department arrival, and as a result the fire was already involving multiple vehicles. There is little indication that these two structures are unique in any way that would lead to slower response time than can be expected for many other parking garages around the world, including in the United States.

Environmental elements, such as wind conditions at the time of the fire, also can potentially affect fire growth rates and spread. In open parking garages, the effect of wind through the parking garage venting the hot gases from a vehicle fire has not been thoroughly evaluated, but given the low-ceiling height, and rapid fire growth and spread (often via direct radiative heating from the burning vehicle, which would not be significantly mitigated by ventilation) it is likely this would not significantly slow the fire spread in many scenarios. In fact, wind will provide more oxygen to the fire and can increase the fire spread. As was seen in the fire incidents discussed previously, when late notification and/or response is combined with a rapid fire spread between vehicles the result

can be fire that is out of control by the time the fire department arrives. These considerations may require further evaluation of the how 'open' parking structures are defined and classified.

7. Addressing Hazards from Modern Vehicles

While catastrophic vehicle fire incidents remain relatively rare, the impact when the fire spreads rapidly can be extreme, which can mean spread to just one or two neighboring vehicles. Preventing these fires that are infrequent, but with outsized property damage impact, is economically challenging, and is likely to depend on a combination of pressure from building codes and insurers. The two possible approaches to reduce the risk of large catastrophic fires in open parking structures is (1) improved detection; to allow fire department to respond more rapidly, and/or (2) automatic suppression of the early fire. To provide options for the developer and allowing flexibility in the codes, these could be codified as equal or equivalent options, provided further testing shows detection gives a significant benefit (see below). If automatic sprinkler systems were mandated in open garages, a performance-based option could, for example, instead allow only automatic detection if it can be shown that the fire department can respond within a certain time. If necessary, other requirements could also be made in that case, such as increased structural integrity or barriers. This would likely have to include fire engine accessibility considerations within the garage as well. There would also be a risk that changes occurring over the life of the building could invalidate the original design calculations.

7.1. Detection and Notification

There are significant challenges to installing detection and notification systems in any parking garage open to the environment. Smoke alarms that rely on optical obscuration will be susceptible to false alarms due to the large amount of dust, exhaust fumes, tire rubber abrasion or other sources. Heat alarms and sprinklers can be slow to activate in cases were wind flowing through the garage blows the hot gases away before enough heat can accumulate under the ceiling. There are potential solutions to the fire detection problem in modern detection systems. These include infrared flame detectors and other visual systems, linear heat detectors, or smart detectors where multiple signals are interpreted by computer algorithms to distinguish false alarms from actual fires. These are marketed towards enclosed garages but could conceivably be used in open ones as well.

These would still impose a cost on the developer for installation during construction, as these systems are more expensive than simple smoke alarms for indoor spaces, and there will be significant ongoing maintenance costs to keep alarms functioning properly in these harsh environments. Manufacturer must also be consulted to ensure the alarms are appropriate for the building and they are installed properly. In residential settings, most fatal fires are associated with lack of working smoke detection [Ahrens, 2018; Ahrens, 2019]. As there are very few people injured in parking garage fires (due to low number of occupants, who are awake and can easily exit), the main effect of detector coverage would be improved fire department response time. It is expected that this would translate into a reduction in property damage, but it is not obvious how significant it would be. If the earlier notification enables the fire department to arrive when the fire is contained to a single vehicle, they are likely to extinguish it and stop a potentially devastating fire. However, if the fire has already spread to more vehicles when the firefighters arrive, even with automatic detection, there is a chance there would not be any difference in the resulting property damage.

7.2. Automatic Sprinkler Systems

The effects of below-freezing temperatures can be addressed with dry-pipe sprinklers where water does not enter the pipes until the sprinkler heads are activated. This typically only adds a

delay of a few tens of seconds and should have no significant impact on the effectiveness of the sprinklers.

As is the case for smoke detectors, an automatic sprinkler system using spot-type temperature activation could have reduced effectiveness when the wind blows the hot gases away from the sprinkler head at the ceiling, potentially causing significant delays in activation above the burning vehicle. After the devastating fire at the Stavanger airport in Norway in 2020, there were questions by the media and fire experts about the lack of sprinklers. However, there was a wind of up to 15 m/s blowing that day. It is uncertain what the delay in activation would have been with a strong wind affecting the formation of a hot layer near the sprinkler heads. Hot gases being pushed downwind could activate sprinklers remote from the seat of the fire. This has the potential to reduce fire spread driven by wind, which is a concern in outside firefighting. However, if the sprinklers directly above the initiating vehicle does not activate, or does so much later, there would be less cooling effect on neighboring vehicles to limit the spread via direct radiative heating or burning pool fire spread. It is important that the effects of wind on sprinkler activation and water dispersion is assessed and considered for these applications.

Unlike smoke detectors, there are fewer options to alleviate the effects of environmental factors such as wind on sprinklers. In order to use an activation method not reliant on temperature of sprinkler heads at a single location (usually at the ceiling), a more complex system must be designed where sprinklers are tied to other fire detection methods. Deluge systems where all sprinklers are activated whenever a fire is sensed at any detector would have serious false alarm concerns. Tying the systems to smaller zones could alleviate this somewhat, and false activation in a parking garage, designed for outdoor exposure, is certainly less damaging to the building and the contents than is the case inside commercial or residential settings.

So called smart systems or "electronic sprinklers", where individual, or groups of, sprinklers are connected to detectors and will be activated for limited areas where a fire is detected (or for example a 9-sprinkler grid around the fire, cooling the surrounding vehicles) could be a possible approach. These are an emerging trend for storage applications [Sprinkler Age, 2018], but have not been tested for outdoor application or parking garages. These systems also require a very high level of complexity in design, installation and especially in maintenance, to ensure that the system operates properly in a harsh environment. Even if they were tested and found to be appropriate for the garage setting, for the foreseeable future this is likely to only be worthwhile for certain high-risk, high-value, and/or specialized building configurations.

8. Knowledge Gaps

This analysis has thoroughly evaluated the hazard modern vehicle fires pose to their surroundings. Some test data has been analyzed, and the mitigation efforts explored above reveal numerous questions regarding the optimal way of protecting against this hazard. The fire statistics reveal that this is almost exclusively a property protection concern (including; direct losses, business interruption, adverse environmental impact). The nature of car parks, and people's interaction with them, make personal injuries very rare. The requirements must therefore necessarily weigh the cost of large losses against the costs of implementation.

8.1. Effect of Earlier Fire Detection and Notification

Mandating automatic fire detection systems in open parking garages is reliant on showing an improvement in fire department response that would significantly reduce the risk of a catastrophic out of control fire. The most useful proxy for this is likely the time to achieve fire spread to neighboring vehicles. By evaluating multi-vehicle fire tests, a critical time from ignition can be

established. It is paramount that the first responding fire department units must be able to arrive early enough to be able to control the fire and prevent further spread. For example, the BRE testing [BRE, 2010] found that spread to an adjacent vehicle occurred in the range of 10-20 minutes, which in a garage could mean three (or more) vehicles on fire as it spreads to both sides, and possibly to front/back. But this is only a single test series, and there is a lack of corroborating research using modern cars to substantiate this time.

Some estimate of the real-world impact can also be made by analyzing large, devastating fires and calculating when a detector would have triggered and evaluate whether this would have made a significant difference to fire department response, possibly based on a numerical modeling of the fire. And if the data is available; how large would the fire have been at that point? Would any improved response time have made a difference to the fire department's ability to control or extinguish that particular fire?

The effects of earlier notification on response time will vary depending on the location of the individual parking garages, resources of the local fire department, population density etc. As NFPA 1710 sets requirements for maximum response time, this can be used as an ideal value. But surveys of average, actual response time of fire departments (i.e. the 34% who don't meet the benchmark [FireRescue1, 2019]) can be analyzed to find the range of detection times that would cover a larger share of fire departments.

8.2.   Effectiveness of Automated Sprinkler Systems

The limited testing (two BRE tests involving 1992-2001 model year vehicles) done with wet-pipe sprinklers at the code-required spacing applied to vehicles in a parking garage mock-up indicated that they were successful in controlling the fire in a single vehicle and a two-vehicle stacker system. In almost all configurations it may be the case that no more than one vehicle is burning when the sprinklers activate. But if activation occurs after the fire has spread to a second vehicle, it is unclear whether the sprinklers would be capable of controlling the fire. As modern vehicle fires can rapidly develop to an HRR of 7-8 MW or more over just a few minutes, and with large amounts of fuel being shielded from overhead sprinkler water spray, there could also be other situations where sprinklers are unable to control the fire. For example, one or a combination of these:

- Cars parked at unusual angles or in corners
- Cars at the edge of the sprinkler spray area
- Fires starting, and spreading, inside or under vehicles
- Strong wind through garages blowing away hot gases, delaying activation.
- Electric vehicle battery fires with jet near floor (see Figure 13)
- Stacker systems with more than two levels
- Lower water application density in stacker systems

All these issues should be considered to some degree, through calculations, statistical analysis, CFD modeling and/or full-scale testing. The effects of the sprinkler spray itself can be difficult to predict theoretically, so full-scale testing may be required to evaluate non-ideal sprinkler configurations and stacker systems. Findings from warehouse and rack storage testing of sprinklers (both overhead and in-rack) can be used where appropriate similarities exist. On the other hand, the effects of wind or other environmental conditions (such as extreme cold) on hot gases and the interaction with the sprinkler bulb or link can effectively be analyzed for a large number of configurations using CFD models. A few well-instrumented tests are likely still needed for validation and verification of the model results.

As the effects on sprinkler activation and water spray are analyzed, an effort should also be focused on determining what is an acceptable delay in sprinkler activation. At what point are sprinklers no longer able to control a vehicle fire? This may require full-scale tests where the sprinklers are manually activated at different times in the test.

8.3. Fire Spread

More work should be done to fully understand the different methods of fire spread in a parking garage. The details of ignition of adjacent vehicles should be further tested, as this is one of the most important factors determining the rate of fire development and the size of the fire when the fire department arrives. Incident data shows that there can a dramatic difference between fire department arriving to a single burning vehicle or three. Better understanding of the vehicle to vehicle spread dynamic will provide a timeframe for the critical times and will be useful for numerical modeling of these fires. Full-scale tests should be performed of multiple vehicle fires with varying parking configurations (e.g. side by side, front to front, diagonal), distances between cars, vehicle types, and ignition conditions.

8.3.1. Fuel spill

There are concerns regarding burning fuel running under vehicles, including reports from fire fighters in the Liverpool, England fire. Further study should be performed of vehicle fuel tank failure due to fire and analysis of the spill dynamics (patterns, rate of leakage, fuel layer thickness) and fire dynamics (heat release rate, flame heights, etc.). Methods of ignition of the fuel spill should also be investigated (hot surface, radiative, etc.). This testing should be performed on typical parking structure construction materials (concrete) and for both level and sloped (ramps) surfaces.

8.3.2. Concrete Spalling

In a number of the larger incidents involving vehicle fires in parking structures, damage to the concrete structure was extensive. Spalling of concrete is reported to have resulted in holes in floor slabs, and allowed vertical fire spread between levels of the parking structure. Heating of the water in concrete which causes explosive spalling can take some time to occur, as quick as 20 minutes for normal strength concrete, and potentially hours for denser concrete (though the denser concrete shows greater amount of spalling once sufficiently heated) [Kodur and Harmathy, 2016; Hertz, 2003]. It is therefore not certain how significant this would be for the overall prevention efforts. The concrete floor/ceiling could simply exhibit spalling after the fire has already spread to above levels. As a start, further study of any relevant fire incidents should attempt to establish at what point in the fire the spalling occurred and whether it was early enough to contribute significantly to fire spread. Coupling vehicle fire tests, concrete spalling test data, and numerical modeling can also establish timelines for how quickly a vehicle fire can lead to significant spalling of concrete above and below.

8.4. Open Garage Definition

The distinction between an enclosed and open parking garage in NFPA 88A is simply the percentage of wall area open to the outside. As mentioned in section 5.1.5 on BRE vehicle tests, openings placed low or high on the wall can both satisfy the requirement, but have very different impact on the development of the fire and hot gas layer. Certain opening placements could result in fire conditions similar to those in a fully enclosed garage, without the stricter protection requirements.

With modern vehicle fires in dense parking structures leading to more rapid fire spread, and thus greater smoke and heat production, the code distinction between open and enclosed garage currently set at 20% open area should be examined. The requirement was changed in the 2019 edition of the code. In previous edition the opening requirement was 0.4 m^2 per linear meter of exterior (1.4 ft^2 per linear foot). Depending on the height of each level this could lead to less than 20% of the wall area being open. To evaluate these issues, testing and modeling should be performed of vehicle fires in enclosures with various opening configurations, placements, and open percentages (within the 'open' definition).

9. Conclusions

This report details an analysis of the current understanding of the fire hazard modern vehicles represent to parking garages and marine vessels. The changes in vehicle and garage design have been documented, and the factors that most impact the fire development has been identified. Areas where current codes may be inadequate are presented and knowledge gaps and potential areas of research required to address the hazard are discussed.

Though fires in vehicles are not uncommon, large fires in parking structures are fairly rare and loss of life in these incidents is very rare. However, fires in parking structures can lead to very large economic losses, as evidenced by recent fires at Liverpool's Echo Arena and at Stavanger Airport (Norway). These incidents involved hundreds of automobiles and ultimately resulted in structural collapse of the parking structure and tens of millions of dollars in losses. Additionally, since 2014 there have also been six significant fires on marine vessels. It is therefore important to understand the factors that lead to large fires involving modern vehicles, especially in parking structures and vehicle carriers.

A large increase in the use of plastic materials has occurred in vehicle construction from the 1970s to 2018 (in western markets). Even with a general increase in average vehicle curb weight over the same period, there was an increase both in absolute weight of plastic and as percentage of vehicle weight, adding to the total fuel load of the average vehicle. Full-scale fire tests of vehicles are highly sensitive to the test conditions and setup, and despite the increase in potential fuel, published literature does not show that modern vehicles burn with a significantly higher heat release rate or for a longer time than those from 40 years ago. The increased plastic content may instead manifest as faster flame spread within the vehicle, easier ignition and more rapid fire spread to neighboring vehicles. There is limited test data available on this spread between multiple vehicles, especially on newer models. Some tests of multiple modern vehicles have shown very rapid fire spread between vehicles in a parking garage configuration, on the order of 10-20 minutes. Similar spread rates have also been reported in some of the larger losses involving parking structure fires. Based on the findings it is clear that test data from older vehicles (>15-20 years at the time of writing) should not be used as basis for development of codes and regulations.

Battery electric vehicles represent a large and growing share of the vehicle fleet in many western countries. These vehicles have not been shown in testing to yield larger fires than vehicles with internal combustion engines of similar size and design. Lithium-ion battery fires have different burn characteristics and present different challenges for firefighters as large amounts of water are required to cool the battery unit for an extended time to prevent reignition. Hydrogen fuel cell electric vehicles are currently very limited in distribution and use. Due to the dramatically different burning behavior of the hydrogen fuel, future development should be closely monitored by the fire protection community.

Marine vehicle carrier vessels have strict international regulations and code enforcement for fire protection, and few large fire incidents have occurred when these regulations are followed. Several noteworthy incidents on these carriers involved rapidly growing fires that were successfully extinguished by the deployment of a combination of a trained crew in firefighting, water application to the fire and surrounding bulkheads, and CO_2 flooding systems in the fire compartment.

Evaluating modern vehicle fire hazards and current code requirements it was found that for enclosed parking garages, the requirement for sprinkler protection appears adequate to control a vehicle fire until fire-fighting personnel arrive. Open parking structures emerge as the main area of concern regarding fires involving modern vehicles. The lack of any requirements in fire codes for active protection systems in open parking structures, and trends of larger vehicle widths and tighter parking spaces in garages suggest that large, devastating fires in these structures could become increasingly common. Though the risk of civilian injuries will remain low, these fires could cause extremely large property losses, business disruption, and adverse environmental impact. There is currently insufficient testing of the fire dynamics of multiple vehicles in a parking structure to understand fire spread mechanisms and rates in these configurations. This highlights the current knowledge gaps, which focus on three areas; earlier detection and notification, viable sprinkler protection, and fire spread between vehicles.

If fire department response is to remain the sole means of fire control and extinguishment in these garages, a method to ensure rapid fire detection and fire department notification should be evaluated and possibly mandated. Further testing is also necessary to determine the minimum response times required to control a vehicle fire, and whether automatic detection can provide the required benefit of the current system of manual notification of fires (i.e. guest or staff noticing and alerting). Available tests of vehicle fires involving sprinklers indicate good performance in controlling a single vehicle fire. But the number of tests are limited, and the most recent used 1992-2001 model year vehicles in a mock-up garage setting. Further testing should be conducted to evaluate more challenging scenarios with newer vehicles, such as delayed activation of the sprinklers, vehicle stacker configurations, and multiple-vehicle fires. For open garages, environmental effects such as cold weather and wind, can cause significant delays on the activation of bulb or fusible link sprinklers and further evaluation of these effects is warranted.

The spread of fire between cars in a garage, especially from the initial to the second and third vehicles, is shown to be critical in determining the extent of the fire and the ability of the fire department to successfully control and extinguish. Full-scale testing with a range of configurations should be performed to evaluate the spread dynamics and critical parameters. This data can be used as basis to evaluate additional scenarios with computational modeling.

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