Modern Vehicle Hazards in Parking Structures and Vehicle Carriers

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ABSTRACT
Fires in vehicles are not uncommon, but the majority of these occur along the road or after a 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). There has been an increase in the fire hazard due to changes in vehicle design and the increased use of plastics and other combustible materials in vehicle construction. The increased plastic content of modern vehicles manifests as faster flame spread through the vehicle and easier ignition of and more rapid fire spread to neighboring vehicles. The spread of fire between cars, 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. Limited 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 the basis for development of codes and regulations.

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 many 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.

KEYWORDS: vehicle fires, parking structures, hazard analysis, modern vehicles

IDENTIFICATION OF THE PROBLEM
There is a concern that the materials used in modern vehicles, as well as adoption of different engine technologies and alternative fuels such as battery electric vehicles and hydrogen fuel cells, present a significant increase in energy content during a fire, both in intensity and duration, compared to older vehicles [1] [2]. Especially concerning is that many design guidelines and standards were developed based on vehicle fire tests performed many decades ago and assume there will be limited fire spread between vehicles. The possible change in the fire hazard associated with modern vehicle design has two major causes:

1. Larger vehicles with increased use of polymers and other combustible materials in construction. 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 alternatives include plug-in hybrid electric vehicles (PHEVs), fully electric vehicles (EVs), and hydrogen fuel cell vehicles.

Evaluating data for fires occurring in commercial parking garages in the USA for the period 2014-2018, Ahrens [3] found that on average there were annually 1,858 fires, causing $22.8 million in direct property damage and 20 civilian injuries. One recent event noteworthy for the severity occurred in Liverpool, England in December of 2017 in an open, 8-level concrete parking garage. The fire started in a single vehicle and spread throughout the whole parking structure, resulting in damage to over 1,400 vehicles, and structural damage so severe the building will be demolished [4]. Another fire occurred in January of 2020 in an open parking garage at the Stavanger airport in Sola, Norway [5]. The fire destroyed 200 to 300 vehicles, and part of the five-story steel structure collapsed. Even though the driver was in the vehicle when the fire started, delays in notification caused the fire department to arrive 19 minutes after ignition [6]. In accordance with local codes, neither of these garages had any form of automatic detection or suppression systems. While automobile fires themselves are the second largest cause of fatalities in the US (after residential fires) [7], 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 [3]. Since 2014 there have also been six significant fires involving automobiles 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).

MODERN VEHICLE HAZARDS

There are many developments to modern vehicles which may increase the fire hazard, including changes to materials, construction techniques, 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 within the vehicle over the past few decades. There has also been an increase in use of vehicles using different power sources, replacing traditional internal combustion engines. The fire hazards associated with modern vehicles were analyzed from both sides of the issue:

1. Impact of changes to vehicle design, material use and fuels
2. The design of fire protection systems used for parking and vehicle storage and transportation.

This established a picture of to what degree the various types of modern vehicles represent a changed fire hazard than legacy vehicles. The changes to modern vehicle construction and materials have an effect on the fire behavior in several ways, including peak heat release rate (HRR), fire duration, and heat flux to nearby objects.

There is not a substantial amount of heat release rate (HRR) data for burning automobiles (especially for newer ones) and the data that is available is not consistent in how the tests were configured and executed, including ignition sources, data collection, and other variables. This leads to scatter in the measurements, making it difficult to make any definitive conclusions from this data about changes to HRR over the past 50 years. As the total amount of plastics and polymers used in vehicles has increased over the years, the total available fire energy from a vehicle will scale with the weight of combustible material. Thus, it can be assumed that the change in available chemical energy is directly equal to the weight of plastic added, multiplied by the heat of combustion for the material.

Vehicle Fire Tests

Tohir and Spearpoint [1] gathered and summarized a large amount of data on vehicle fire tests up to about 2002 model years, including where available; model year, curb weight, mass loss, peak heat release rate, and total heat released. They attempted to establish a correlation between vehicle model year and peak HRR but found it difficult due to a 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. As the data from multiple sources presented below shows, there are light-weight vehicles with peak HRR over 8 MW, and medium- and heavy-weight vehicles with less than 3 MW HRR. Analyzing this data and looking at the mass loss (due to fire consumption) as a percentage of vehicle curb 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 below about 17% show a much lower peak HRR compared to other tests of similar size vehicles. Details of the tests are shown in Table 1. The data is from Tohir and Spearpoint (T&S) [1], Lam et.al. [8] and Building Research Establishment Group (BRE) in the UK [9]. The data has been sorted by increasing mass loss percentage as it was found to generally be associated with larger fires.

Table 1 – Select vehicle fire test results from several sources.

Source	Test	Vehicle Year	Vehicle 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 either age of vehicle or curb weight. The placement and method of ignition, as well as ventilation and other environmental factors, has a large impact on how a vehicle fire develops. If the mass loss percentage is high (20%+) both older and smaller vehicles can yield high peak HRRs and total heats 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 or greater), but it is possible that it is *more likely* to occur with modern vehicles. This data is not conclusive in this hypothesis however.

The fire sizes used as the basis for developing parking garage fire codes are not explicitly stated. There are design fire scenarios for tunnel fires where values such as peak HRR are provided. For example, Ingason [10] summarized several HRR values provided as guidelines for tunnel design. This included a car fire scenario with a 4 MW peak HRR, proposed by Ingason in 1995. Reference is also made to French regulations, where a design fire with a peak HRR of 8 MW is associated with "2-3 cars, tunnel height 2.7 m" [10]. Comparing this to the HRR data for a single car fire shown in Table 1, 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 the National Cooperative Highway Research Program (NCHRP) in 2011 [11], references a number of vehicle HRRs from different sources. Several single vehicle HRRs are again around the 5 MW range, for example a design fire from Germany, and a reference to "absolute minimum water requirements" that specifies a car fire as 5 MW. The article does reference the 2008 edition of NFPA standard 502 *"Standard for Road Tunnels, Bridges, and Other Limited Access Highways*" [12], which specifies 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.

Plastic Fire Energy

There has been a steady increase in the use of polymeric or plastic materials in the auto industry. In most cases the plastics have a higher heat of combustion than the materials they replace (often metals) [13] yielding a higher chemical energy per weight of material, and more potential energy in the same volume [14]. 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 large consumer markets, there has also been a general shift to heavier and larger personal vehicles [1]. This could lead to more severe vehicle fires, either in intensity (peak heat release rate), fire duration, or both. As an example, two of the most popular vehicles in the USA for many decades were the Toyota Corolla and Ford

F150, which from the 1970s to 2018 increased in width by 21 cm and 8 cm respectively. The curb weight increased by 430 kg and 150 kg for the Corolla and F150 respectively.

Data was found on the amount of plastics used in the average vehicle fleet over time for the US, and similar trends are expected in other Western markets, though more data should be gathered for confirmation. The Economics & Statistics Department of the American Chemistry Council released a report “Plastics and Polymer Composites in Light Vehicles” [13] 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 [15] 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 [16]. Plastic materials have in large part replaced metal in vehicle construction. From 1970 to 2004, the average steel content per vehicle dropped by 458 kg, a 32% reduction [17] (though some is replaced by other lighter-weight metals).

From 1976 to 2018 the weight of plastic materials used in the average US vehicle increased by 91%, from 83 kg to 159 kg [13][15]. Plastics are often used to reduce the weight of vehicles, primarily to improve fuel efficiency. But as customers have bought larger and heavier vehicles, the weight of the average vehicles has remained steady or gone up in the last decades, while the percentage and absolute weight of plastics has similarly gone up. The weight of the average light vehicle in 1976 was 1,618 kg, which had risen to 1,805 kg in 2018, an increase of about 12% [13][15]. Here “light vehicle” or “light-duty vehicle” denote passenger vehicles, excluding trucks, which the US Environmental Protection Agency (EPA) classify as having a “Gross Vehicle Weight Rating of less than 8,500 lbs (3,856 kg)” [18].

An estimate of the increase in heat release rate associated with the growth of plastic use can be calculated with assumptions made for the heat of combustion of the plastics. 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 2 [13].

Table 2 – Most common plastic types used in US vehicles [13].

Type	**%-weight**	**Heat of Combustion [19]**
Polypropylene	32%	43.4 kJ/g
Polyurethane	17%	25.3 kJ/g
PVC	16%	16.4 kJ/g

Heats of combustion were found from the literature for all but four of the remaining 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 from 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. The total increase in energy content from plastics in the average vehicle (in the USA/NAFTA) from 1976 to 2018 was 2,298 MJ, a total increase of 91%. The increase in vehicle curb weight and plastic fire energy is plotted in Figure 1.

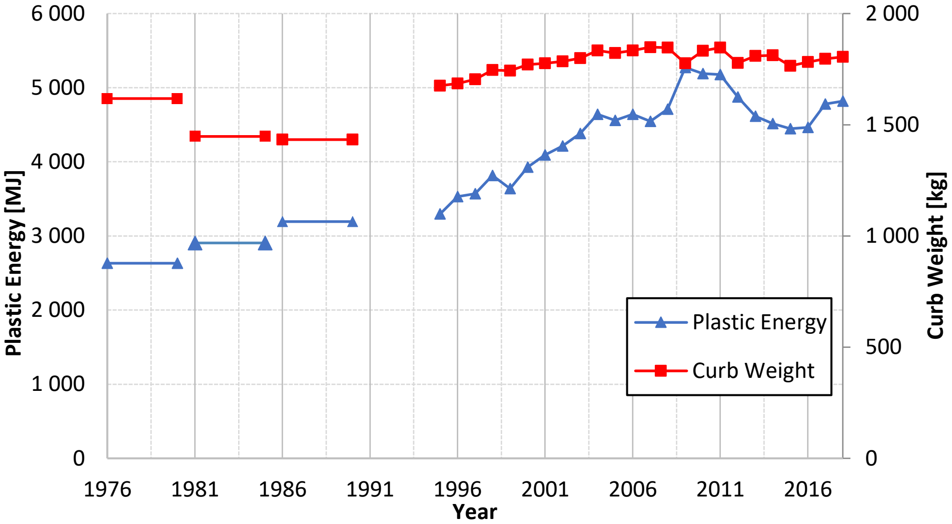

Figure 1 – Curb weight and plastic content potential fire energy from average North American vehicles from 1975 to 2018.

A full-scale fire test series performed on vehicles from the 1970s [20] 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 70% 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 the ease of ignition of plastics, and more rapid fire growth rate of vehicle fires involving significant plastic content.

Plastic Fuel Tanks

Another development is the increasing use of plastic fuel tanks, which have largely replaced metal tanks. The share of cars built in Europe with plastic fuel tanks is reported to be over 85% today [21]. It was estimated to be around 75% for US cars in 2010 [22] and has likely risen since then. This will increase the amount of plastic in the vehicle, and could result in the release of fuel from the tank when it is exposed to heat from a fire in the vehicle itself, or adjacent vehicles. As fuel leaks from a tank and ignites, the fuel could pool under several neighboring vehicles in a garage, ferry or transport vessel. If this fuel ignites, it could damage the fuel tanks of those vehicles. This could result in 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 if directly exposed to a pool fire [24]. However, with a sufficiently severe thermal exposure, both plastic and metal fuel tanks will eventually leak or rupture.

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 [23]. With polyethylene (PE) having a heat of combustion of 43.6 kJ/g [19] in a fully involved fire this would yield at least 371 MJ of energy released, a relatively small contribution. The fuel tank is also already included in the total vehicle plastic content calculated above. There are fire resistance requirements for plastic fuel tanks, specified in the United Nations document ECE R34.01, Annex 5 Section 5.0 “Resistance to Fire” [25]. This standard requires a tank to show no leak of fuel after exposure to a direct flame pool fire for two minutes. 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. With a two minute requirement, firefighting personnel are unlikely to arrive before the tank starts to leak contents. Even if the structure is sprinklered, the fire would be shielded which could slow down sprinkler activation time and inhibit extinguishment. A series of tests performed by the Southwest Research Institute, and summarized by Digges [26][27], 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. 1:50 to 4:36 minutes). Thus, 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 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 vapors.

Fire Spread

The combination of several factors has led to an increase in the fire hazard from modern vehicle, where a major concern has become the spread of fire between vehicles. Factors such as changes in the mix of vehicle construction materials, large vehicle dimensions, and tighter parking arrangements has increased the risk of a fire spreading rapidly beyond the vehicle where the fire originate. 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 and Keski-Rahkonen [20] 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". As surveillance video of the Liverpool Echo Arena fire showed, the fire was not reported to the local fire department until at least 13 minutes after smoke can be observed, and the fire department arrived at 21 minutes after this point [21].

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 [9] using vehicles constructed in the late 1990s 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, separated by an empty parking spot, 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 likelihood they will be unable to extinguish it with the first on-scene equipment, or even contain the spread, as has been the case in several recent parking garage fires.

Tohir [28] provides a summary of multi-vehicle full-car fires that have been performed with adequate details to make a reasonable analysis on fire spread. Tohir cites three studies as the most detailed and reliable; Joyeux [29], Steinert [30], and BRE [9]. These studies had vehicles spaced between 0.4 to 0.8 m apart. 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. Most of the cars used in the testing were older (pre 2000s), indicating the need for updated testing with more current vehicles.

Testing by the BRE [9] on flammable exterior materials for vehicles found a critical heat flux range of 11.0-18.5 kW/m^2, with most plastic components at the upper end of the range; bumpers at 17.5 kW/m^2, fuel tanks at 16.5 kW/m^2, and the tires lowest at 11.0 kW/m^2 [9]. An upper layer temperature of 500-600°C is typically associated with the 20-25 kW/m^2 criteria where most ordinary flammable materials in residential settings will ignite [31], thus the layer temperature criteria could be lower for these vehicle components. Modern parking garages often have relatively low 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 in parking structures.

A full-scale test series by BRE [9] involved several multi-vehicle, car fires in a parking garage mockup. The tests found that with the second vehicle involved the ceiling temperatures reached 1100°C, quickly heating and igniting the adjacent vehicles. 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 of openings, including a fully open wall. The openings on the walls were low to the ground, supplying air to the fire, but not venting hot gases as might be the case with a fully open configuration. Large beam pockets are common in parking garages, but the beams were relatively shallow in the BRE garage mockup. In NFPA 88A, open parking 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 2 hours [32]. 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.

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. 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 fuel spills and the effect of this burning configuration on fire dynamics. Notably, Putorti [33] and Mealy and co-workers [34][35] studied 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 is the common flooring material in parking structures (asphalt is typically only allowed on the lowest level [36]). 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 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 [37]. The heat release rates on concrete can be substantially less than found for confined pool fires in metal pans [35]. Eventually the fuel layer becomes so thin that the heat loss to the substrate becomes greater than the heat feedback from the flame, preventing further fuel vaporization and the fire is not sustained. The heat release rate of the fire is greatly impacted by the time of ignition relative to the start of the spill. Ignition immediately after the fuel is spilled can lead to larger heat release as the fuel layer thickness is deeper as the fuel has not spread substantially and the pool has not thinned out. If ignition does not occur until later after the spill begins, especially for a finite fuel volume, the fuel may spread and form a thin layer. It is uncertain how effective an ignited fuel spill would be for spreading fire from a burning vehicle to adjacent vehicle. If the adjacent vehicles are quite close and ignition occurs before the spill area becomes large and the fuel layer becomes quite thin, spread to adjacent vehicles may be possible.

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. It is important to note that even though hydrogen fuel cells and large battery packs represent high-density fuel sources, they replace the gasoline stored in ICE vehicles (an exception being hybrid vehicles). Lithium-ion batteries used in modern EVs present a different fire hazard than traditional ICE vehicles [38]. Fires in lithium-ion batteries are more difficult to extinguish than gasoline or diesel fires, requiring large amounts of water to fully contain 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 [39]. Hydrogen fuel cell vehicles are still in a very limited test release phase, estimated at about 6,000 vehicles in the USA, and 12,000 total worldwide (2018) [40], operating in small test areas with a few refueling stations. Issues with hydrogen fueled vehicles were not evaluated further at this time, but will certainly be a concern in the future and should be further studied as the fleet size and use area increases.

The main type of alternative fuel vehicle in widespread, and increasing, use is fully battery-electric vehicles. Two pairs of similar EV and ICE vehicle models from two manufacturers were tested by Lecocq [41]. 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 2. The ICE vehicles are represented by solid lines, while dotted lines are used for the EVs.

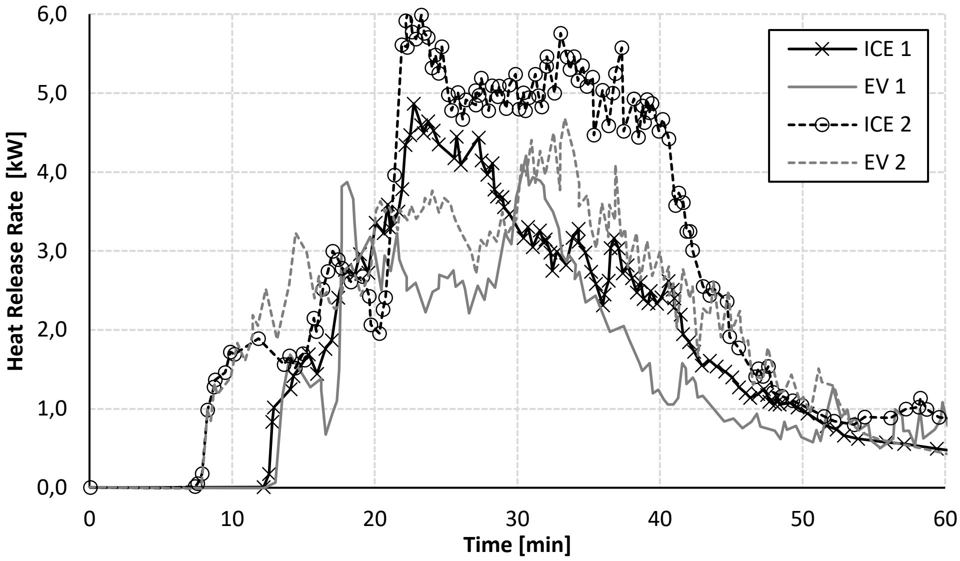

Figure 2 – Heat release rate for two pairs of similar ICE and EV vehicles for tests conducted by Lecocq [41]

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. [8] of the National Research Council Canada. All vehicles were exposed to an identical, realistic simulated pool fire; a propane burner placed 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 pooling under the neighboring vehicles. The findings from the study [8] 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. As the fuel tank or batteries placed underneath the vehicle is the main distinguishing feature between ICE vehicles and EVs, a pool fire placed 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.

EXISTING CODES AND DESIGN CRITERIA

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 US$22.8 million (2014-2018) [3]. The Echo arena fire in Liverpool, England will by some estimates cost almost US$25 million [42]. The direct property loss associated with the Stavanger, Norway fire is estimated as high as US$47 million, which is not including flight disruptions at the airport [43].

Enclosed parking structures and marine vehicle carriers are required to be equipped with numerous layers of fire protection systems per the codes in most jurisdictions. 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. Marine vessels crossing borders must adhere to strict requirements set forth by the International Maritime Organization (IMO); International Convention for the Safety of Life at Sea (SOLAS) Chapter II-2 [44], which is enforced by nearly every nation, making it effectively a global code. The requirements include automatic detection and sprinkler systems, inert gas systems in enclosed spaces, and crew firefighting training. It was found that few large fire incidents have occurred when these regulations are followed.

Regarding civilian injuries, the current codes for open parking garages could be considered very successful. In the US, 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 fire, e.g. inside the initiating vehicle. Considering property loss, the findings indicate that modern vehicle fires present an unacceptable hazard in open parking structures under the current code requirements in NFPA 88A and similar codes elsewhere. Important factors that impact fire hazard in open parking garages include:

- Potential for very rapid spread of fire between vehicles due to:
    - The increased use of plastics in vehicle construction
    - The shrinking distance between parked vehicles
    - The low ceilings in many garages increasing heat transfer from hot fire gases
- Many codes have no requirement for automatic fire detection, notification or extinguishment.
- Large, tightly packed garages, long fire department response times and difficult extinguishment

The potential for very large losses is significant, and there is a small safety margin as many factors can allow 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. With no detection or notification system, preventing a single car fire from spreading is therefore solely reliant on the fire being discovered by occupants or staff, who rapidly notify the local fire department, and that they are able to arrive in a relatively short amount of time. In both the fire 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. However, in both cases it took 20 minutes or more for fire department to arrive, and as a result the fire was already involving multiple vehicles and unable to be contained.

In open parking garages, the effect of wind through the building 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. Multiple codes are implementing or proposing sprinklers in open parking structures, for example the 2021 edition of the IBC [45]. The effects of wind on sprinkler activation and water dispersal should thus also be evaluated.

When late notification and/or response is combined with a rapid fire spread between vehicles, the result can be a fire that is beyond control by the time the fire department arrives. These considerations may require further evaluation of the how ‘open’ parking structur es are defined and classified in the codes. 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 updated building/fire codes and insurers.

CONCLUSIONS

An analysis was performed of the current understanding of the fire hazard modern vehicles represent to parking garages. Fires in vehicles are not uncommon, but large fires in parking structures are infrequent, and loss of life in these incidents is rare. Fires in parking structures can lead to large economic losses, as evidenced by recent fires in the open parking garages at Liverpool's Echo Arena and the Stavanger Airport in Norway.

From the 1970s to 2018 data shows a large increase in the use of plastic materials in vehicle construction in western markets, 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 conclusively 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 manifests as faster flame spread throughout 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. 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. 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.

The lack of any requirements in many 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 is likely to 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 the fire spread mechanisms and rates in these configurations. 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. Available tests of vehicle fires involving sprinklers indicate good performance in controlling a single vehicle fire. But the number of tests is limited, and the most recent tests 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, environmental effects, 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 sprinklers and further evaluation of these effects is warranted.

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REFERENCES

1. Tohir MZM, Spearpoint MJ (2013) Distribution analysis of the fire severity characteristics of single passenger road vehicles using heat release rate data. Fire Science Reviews **vol 2**, issue 5. http://dx.doi.org/10.1186/2193-0414-2-5
2. Oliver, G., (2014) "Plastics and composites are reshaping car design, IHS report shows", American Chemistry Matters, https://blog.americanchemistry.com/2014/11/plastics-and-composites-are-reshaping-car-design-ihs-report-shows/ Accessed 11/12, 2019.
3. Ahrens M (2020) Sprinklers in Commercial Garage Fires, National Fire Protection Association. February
4. BBC (2018) Ferocious fire ripped through Liverpool Echo Arena car park, https://www.bbc.com/news/uk-england-merseyside-42533830, Accessed 09-22-19
5. The Local (2020) Flights at Norwegian airport delayed as 'hundreds' of cars burn in fire. https://www.thelocal.no/20200108/norway-airport-flights-held-as-hundreds-of-cars-burn-in-fire, Accessed 1-03-20

6. Klingenberg M, Ramsdal R (2020) Brannvesenet: Det tok 20 minutter fra bilbrannen startet til første brannmann ankom. tu.no (norwegian). https://www.tu.no/artikler/brannvesenet-det-tok-20-minutter-fra-bilbrannen-startet-til-forste-brannmann-ankom-br/484013?key=jviLk7I5, Accessed 3-26-20
7. Diggs KH, Gann RG, Grayson SJ, Hirschler MM, Lyon RE, Purser DA, Quintiere JG, Stephenson RR, Tewarson A (2008) Human survivability in motor vehicle fires, Fire and Materials, Volume **32**, Issue 4
8. Lam C, MacNeil D, Kroeker R, Lougheed G, and Lalime G (2016) Full-Scale Fire Testing of Electric and Internal Combustion Engine Vehicles, Fourth International Conference on Fire in Vehicles, Baltimore, USA
9. BRE (2010) Fire spread in car parks. BD2552, Department for Communities and Local Government, London, UK
10. Ingason H (2009) Design fire curves for tunnels, Fire Safety Journal, **V 44,** Issue 2
11. National Academies of Sciences, Engineering, and Medicine (2011) Design Fires in Road Tunnels, Washington, DC: The National Academies Press.
12. NFPA (2008) NFPA 502-2008 Standard for Road Tunnels, Bridges, and Other Limited Access Highways, National Fire Protection Association, Quincy, MA
13. American Chemistry Council (2019) Plastics and Polymer Composites in Light Vehicles, Economics & Statistics Department
14. Spearpoint MJ, Tohir MZM, Abi AK, Xie P (2015) Fire load energy densities for risk-based design of car parking buildings, Case studies in fire safety
15. Dai Q, Kelly J, and Elgowainy A (2016) Vehicle Materials: Material Composition of U.S. Light-duty Vehicles, Systems Assessment Group, Energy Systems Division, Argonne National Laboratory
16. Brunsdale AE, Lodwick SG, Rohr DB, and Newquist DE (1991) Steel Industry Annual Report. USITC Pub 2436, United States International Trade Commission, Washington DC
17. Buckingham DA (2006) Steel stocks in use in automobiles in the United States, Fact sheet 2005-3144, U.S. Geological Survey, Denver, CO
18. EPA (2020) Vehicle Weight Classifications for the Emission Standards Reference Guide, https://www.epa.gov/emission-standards-reference-guide/vehicle-weight-classifications-emission-standards-reference-guide
19. Khan MM, Tewarson A, and Chaos M (2016) Combustion Characteristics of Materials and Generation of Fire Products, SFPE handbook of fire protection engineering, 5th ed., Society of Fire Protection Engineering, Bethesda, MD
20. Mangs J, Keski-Rahkonen O (1994) Characterization of the fire behaviour of a burning passenger car. Part I: Car fire experiments, Fire Safety Journal, V 23
21. Merseyside Fire & Rescue Service (2018) Kings Dock Car Park Fire, Protection Report
22. Vanderwerp D (2010) High-Tech Fuel Tanks, https://www.caranddriver.com/features/a15127584/high-tech-fuel-tanks/, Accessed 6/14/20
23. Rowand R (1995) Plastics gain in gas tanks: growth fueled by air-quality improvements, Plastic News, Detroit, MI, USA
24. Alvarado PJ (1996) Steel vs. Plastics: The Competition for Light-Vehicle Fuel Tanks, JOM: The Magazine, Vol **48**, issue 7
25. United Nations Economic Commission for Europe (2012) Resistance to Fire, ECE R34.01, Annex 5 Section 5.0, December
26. Machado CM (2003) Automotive Fuel Tank Evaluation, Prepared for Motor Vehicle Fire Research Institute, by Southwest Research Institute, Report on Project 01.06081.01.001
27. Digges KH (2003) Fire Exposure, Impact Tests, and Finite Element Modeling of Plastic Fuel Tanks, MVFRI research summary.
28. Tohir M (2015) Multiple Vehicle Design Fire Scenarios in Car Parking Buildings, Ph.D. Dissertation, University of Canterbury, New Zealand
29. Joyeux D (1997) Natural Fires in Closed Car Parks – Car Fire Tests. CTICM, Metz, France, INC 96/294d DJ/NB

30. Steinert C (2000) Experimental investigation of burning and fire jumping behavior of automobiles, (in German). Vereinigung zur Förderung des Deutschen Brandschutzes e. V. (VFDB), vol. 49, pp. 163 – 172
31. Karlson B, Quintiere JG (2000) Enclosure fire dynamics", CRC Press
32. ASTM (2014) ASTM E119-14, Standard Test Methods for Fire Tests of Building Construction and Materials, ASTM International, West Conshohocken, PA
33. Putorti A (2011) Flammable and Combustible Liquid Spill/Burn Patterns, National Institute of Justice Report 604-00, NCJ 186634
34. Mealy C, Benfer M, Gottuk D (2011) A Study of the Parameters Influencing Liquid Fuel Burning Rates, Fire Safety Science – Proceedings of the Tenth International Symposium, pp. 945-958
35. Mealy C, Benfer M, Gottuk D (2014) Liquid Fuel Spill Dynamics, Fire Technology 50, pp. 419-436
36. International Code Council. "International Building Code, 2018 edition", May 2018
37. Klassen M., J. P. Gore, A. Hamins, T. Kashiwagi, "Radiative Heat Feedback in a Toluene Pool Fire", 24th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1713- 1719, 1992
38. Mikolajczak C, Kahn M, White K, Long RT (2011) Lithium-Ion Batteries Hazard and Use Assessment, Fire Protection Research Foundation report
39. Livescience (2018) Why the Fire that Incinerated a Tesla Was Such a Nightmare to Put Out, retrieved from: https://www.livescience.com/62179-tesla-fire-cleanup-danger.html, on 8/26/19
40. Antoni L, Garland N, Han J, Rex M, and Samsun RC (2019) AFC TCP 2019 Survey on the Number of Fuel Cell Vehicles, Hydrogen Refueling Stations and Targets, IEA Technology Collaboration Programme
41. Lecocq A, Bertana M, Truchot B, Marlair G (2012) Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle, 2nd. International Conference on Fires In Vehicles - FIVE 2012, Chicago, United States
42. Hamilton S (2018) ECHO Arena car park blaze could cost £20m in claims, https://www.liverpoolecho.co.uk/news/liverpool-news/echo-arena-car-park-blaze-14108934, Accessed 4/2., 2020
43. Jupskaas SH (2020) Storbrannen på Stavanger lufthavn kan komme til å koste en halv milliard kroner (Norwegian), Aftenposten, https://www.aftenposten.no/norge/i/lAWow3/storbrannen-paa-stavanger-lufthavn-kan-komme-til-aa-koste-en-halv-milliard-kroner, Accessed 4/2., 2020
44. International Maritime Organization (IMO), "International Convention for the Safety of Life At Sea. Chapter II-2 A, Fire protection, fire detection and fire extinction", 1 May 2007
45. National Fire Sprinkler Association, "Vote on 2021 IFC and 2021 IBC — ICC Group A". Retrieved from https://nfsa.org/2018/11/08/2021-ifc-ibc-codes-icc-group-a/ on June 18, 2020. Posted November 8, 2018
46. Boehmer, H., Klassen, M.S., and Olenick, S.M., "Modern Vehicle Hazards in Parking Garages and Vehicle Carriers", NFPA Fire Protection Research Foundation report. July 2020.