Fire Safety Assessment of Sprinkler Systems for Car Parks using the J-value Methodology

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ABSTRACT

A J-value assessment was carried out to quantify the costs and benefits of sprinkler system installation in car parks, both with respect to life safety and property protection. Nine scenarios were established based on collected input data. All car park types were considered for the USA, England, Scotland, Wales and the UK nations collectively, while separate considerations were made for multi-storey car parks (MSCPs) in the UK and for MSCPs, underground and other parking types in England.

Even when assuming 100% sprinkler effectiveness, the J-values for the nine scenarios were all larger than unity (ranging from 5 to 555), thus indicating that the installation of sprinklers is not a cost-effective investment for car parks from a societal point of view. The analysis showed that different car park types must be treated separately, due to specifics of structure and fire statistics. The lowest J-values were obtained for MSCPs and underground car parks. Sprinkler installation mainly provides property protection benefits, because of property loss savings substantially outweigh those associated with life safety.

Even though sprinklers were not cost-effective for car parks in the current analysis, the scarcity of data and new emerging technologies suggests that further investigation is needed.

Keywords: cost-benefit analysis, J-value, life quality index, car parks, sprinkler systems

1. INTRODUCTION

1.1 Background

Historically, car parks have been associated with a relatively low fire risk due to limited fire load and low fire spread probability [1][2]. The frequency of fires in car parks is also lower compared to other premises. For instance, in 2006 in the United Kingdom (UK), the total number of registered fire incidents was 426 200, with less than 0.1% of that number occurring in car parks [3]. For comparison, in the same year in England, 13% of fires took place in dwellings and 14% in road vehicles [4]. The current fire safety requirements and guidance on car parks are based on those traditional beliefs, because they use fire tests of cars that were available at the time when codes were in development [5][6].

More recently, changes in the design and manufacture of vehicles have taken place, including a greater use of plastics, increased vehicle size, the use of alternative fuel types, and the concept of self-driving cars [7]. Such changes can potentially pose an increased risk to the fire safety of car parks. A comprehensive analysis of the fire hazards of modern vehicles in parking structures is presented in the work by Boehmer et al. [5][6].

Recently, a few significant fires that challenge the arguments for low fire risk in car parks have occurred, such as the Stavanger airport fire with several hundred cars burnt [8] and the Liverpool Kings Dock fire with around 1150 cars destroyed [9]. These incidents together with the changes in car designs and car parking technologies have led to an increased pressure for installing sprinklers in car parks to enhance fire safety [10]. However, there is a lack of clarity to what extent innovations have affected previous assumptions and whether sprinklers are necessary in car parks. Therefore, the installation of a sprinkler system in car parks should be assessed from a cost-benefit point of view to allocate societal resources efficiently. This paper presents a CBA for the installation of sprinkler systems in car parks to assess whether they present a societal benefit in terms of life and property safety. To carry out the CBA, the paper uses the J-value methodology, which has been detailed and applied elsewhere [11][12].

1.2 Cost-benefit analyses

In fire safety engineering the main goal and subsequent main acceptance criteria is that an adequate level of safety is achieved. However, an “adequate level of safety” is not explicitly quantified anywhere. This is normally not an issue for traditional buildings because of years of collected experience and various past examples that can guide the design by deterministic evaluations or by following prescriptive regulations. Considering the rapid development of new technologies, the prescriptive approach is less applicable since it requires past experience. Therefore, for uncommon buildings, where there is a lack of experience and knowledge, the performance-based design (PBD) approach is used. In this case “adequate level of safety” needs to be demonstrated. To have an evidence-based answer, this is done through probabilistic risk assessment (PRA) to determine compliance with ALARP principle or criterion. ALARP stands for As Low As Reasonably Practicable, meaning for the safety system to be accepted, residual risk shall be as low as possible, but investment cost shall not be disproportional to benefits. The ALARP criterion is related to society’s capacity to pay and includes some form of CBA [11] [13] [14].

In order to carry out CBA, it is necessary to express associated costs and benefits in a monetary form. The cost of providing a fire safety system typically consists of installation and maintenance, which can be directly estimated; while benefits are mainly expressed through a reduction in fatalities, injuries, property damage and potentially avoided indirect costs. Reduction in fatalities is not easy to quantify in monetary form. Previously, the value of statistical life (VSL) or the value of preventable fatality (VPF) were widely used to quantify the potential benefit of a safety system [15]. However, there are debates on how to quantify human life and whether human life can be exchanged for money [12] [16], as well as questions on the validity of VPF [15].

As an alternative to using VSL or VPF the Life Quality Index (LQI) puts the focus not on the value of human life but on risk reduction measures. LQI solves the problem without putting stress on quantifying human life, allowing a trade-off between societal wealth and risk to life. LQI is expressed through Gross Domestic Product (GDP) per capita, which is a measure of societal wealth, work-life balance, and life expectancy, which represents a reduction in risk. The main principle behind LQI is that a long lifetime and good health are the most important values for society and individuals [17]. Using LQI, it is possible to identify the maximum investment cost that society is willing to pay (SWTP) or societal capacity to commit resources (SCCR) for the risk reduction measure. This criterion is used to assess whether the new safety system is financially justified. One of the CBA methodologies, which is based on LQI and SCCR and can be applicable to fire safety engineering, is a J-value assessment [11]. The J-value methodology allows making an objective decision based on principles of maximising societal benefits. A single value is obtained from the analysis where if less than unity, the safety system is considered beneficial; if more than unity, costs outweigh benefits, and thus the system is not beneficial to society. J-value acts as an objective indicator of whether the safety system is cost-efficient or not and, therefore, is used in this work.

1.3 Car parks

For the purpose of this paper, the term 'car' is defined as a motor vehicle with at least four wheels and a maximum of nine seating positions, mainly used to transport passengers [18]. The term 'car park' is defined as a temporary vehicle storage space designed to admit and accommodate only cars, motorcycles and passenger or light goods vehicles that weigh a maximum of 2500 kg gross [19]. This definition excludes detached private garages that are designed for single or multifamily housing [20] and also does not include repair and service facilities.

In terms of design, car parks can be a stand-alone construction or adjacent to another structure, for example, underground parking in a residential building. Car parks can be public or private, single-level or multi-level construction, located underground or above ground. Specific features of car parks compared to other facilities are that they have relatively low ceilings and a large area in both horizontal directions without subdivision to compartments. In terms of ventilation, car parks can be open or enclosed. Open car parks are the ones with permanent distributed openings of a certain minimum area and with walls open to the outside [6]. Respective norms and guidelines contain further details on ventilation criteria. In some jurisdictions additional requirements are placed on enclosed car parks, expecting that in open car parks hot gases can be vented, and they are more accessible to the fire and rescue services [6].

At the time of this research, only one previous CBA on installing sprinklers in car parks was identified. It was published in 2004 in New Zealand, and the analysis was made with the primary goal of property protection. Life safety aspects were not included in this work. Calculations were made using the annual usage ratio, which was defined as "annual vehicle visits divided by the number of parking spaces in a parking building". This study has found that the installation of sprinklers in car parks is not financially feasible from the building owner's perspective [21].

The CBA evaluation presented herein is made from life safety and property protection perspectives. Including both aspects provides an understanding of whether the installation of sprinklers in car parks is predominantly a question of life safety or property protection. Considered benefits in this work are the reduction in fatalities, injuries and property damage since those parameters can be found from statistical data. There are other possible benefits, such as reduction in environmental impact and business continuity [22]. Those are not included in the analysis due to associated challenges and uncertainties with their quantification. System costs included in the analysis are the upfront investments and annual maintenance of the sprinkler system. This paper examines conventional parking technology and vehicles that use internal combustion engines. Automatic parking systems, such as stackers and alternatively fuelled cars, such as electric vehicles, are not included in this work. Depending on data availability, different parking types were considered, such as MSCP, underground and others.

Given that various economic factors play a role [23] in completing a CBA, it is important to point out that assessments can be made at different levels and from different points of view, such as individuals, organizations, an industry sector or society in entirety. Based on that choice, an outcome to the same question might be different. This assessment of sprinkler system installation in car parks is carried out at a societal level.

2. INPUT DATA

Based on the availability of data, input parameters were gathered for nine scenarios presented in

Table 1. Although the assessment is made mainly in the context of the UK, a scenario for USA is included given that in the UK sprinklers are not required by the applicable regulations and guidance documents, while in the USA as per NFPA13 [24], sprinklers are required for certain car park configurations.

Table 1: Summary of scenarios

Scenario	Description	Dataset	Source
UK All	All parking types	1994-2005	BRE [3]
UK MSCP	Only MSCP	1994-2005	BRE [3]
England All	All parking types	2010-2020	The UK Home Office [25]
England MSCP	Only MSCP	2010-2020	The UK Home Office [25]
England Underground	Only underground car parks	2010-2020	The UK Home Office [25]
England Other	Other car parks, as described in Chapter 2.2	2010-2020	The UK Home Office [25]
Scotland All	All parking types	2009-2020	Scottish Fire and Rescue Service [26]
Wales All	All parking types	2009-2020	StatsWales [27]
US All	All parking types	2014-2018	NFPA Research Foundation [5]

Due to the fact that car parks vary in size and the statistical data does not reflect this, where possible, most of the input parameters have been established on a per m^2 basis. Furthermore, since no details are present in fire statistics regarding type of cars and parking technology, traditional internal combustion engine cars and conventional parking systems are assumed for all scenarios. A system lifetime has been chosen to be 50 years, as per Eurocode 0 Table 2.1 [28], assuming that the lifetime of a sprinkler system is the same as the lifetime of the structure. The same system lifetime was used in the previous sprinkler CBA for New Zealand car parks [21]. Based on Fischer [29], HM Treasury [30] and

ISO2394:2015 [31], a discount rate of 3% has been chosen and 4% for the derivation of demographic constant (ő̧).

2.1 Societal Capacity to Commit Resources

The aforementioned SCCR can be estimated through GDP, demographic constant and work-life balance parameter. GDP per capita both for the UK [32] and the USA [33] have been taken for the middle year of corresponding available fire statistical datasets. The work-life balance parameter (ή) was found to be 0.18 and 0.22 for the UK and the USA, respectively, based on previous studies [34]. The demographic constant (ő̧) has been derived from ISO 2394 [31] and it is taken to be 17.2 years for the UK and 13.1 years for the USA. As a result, for the UK dataset from 1994–2005, the SCCR is calculated to be £2,253,200, for 2010–2020 it is £2,629,784 and for the USA scenario it is £2,318,938.

2.2 Fire statistics in car parks

Fire statistics for England can be found on the official government website [4]. However, no specific information is available for car parks. Such data appeared as an ad-hoc data posted on 11th February 2021 [25], for the 2010–2020 period. Information is given for three types of car park structures: MSCP, underground and other. Since types of car parks belong specifically to 'other' was not described, it is assumed that this category holds all other parking types except MSCP and underground, inferring single-level surface car parks. There is also an additional category 'other outdoor' that has not been considered because it appeared in the fire and rescue service's Incident Reporting System (IRS) as free-filled additional information, and there is no further data on casualties and property damage for this category. Interrogation of the ad-hoc data finds that the fire frequency is 79 fires in car parks annually, with approximately half taking place in MSCPs.

As far as casualties in car park fires are concerned, there was only one fire-related fatality between 2010 and 2020 in England, and 20 non-fatal casualties, half taking place in the MSCP fires. The non-fatal casualties are subdivided into four types: severe hospital treatment, slight hospital treatment, first aid treatment and precautionary checks. However, only the proportion requiring hospital treatment is considered further in the assessment because this is the one that is likely to involve significant immediate and long-term medical treatment costs. Taking all car parks together, the proportion between severe and slight hospital treatment is one to nine.

Unlike England, fire statistics in Scotland and Wales, available from the Scottish Fire and Rescue Service and StatsWales, have a separate subdivision for car parks. Between 2009 and 2020, there were 94 car park fires reported overall in Scotland, which gives a frequency of 8.55 fires per year. There were no fatalities and one injury reported [26]. In Wales there were 25 fires reported from 2009 to 2020 in car parks, which gives 2.27 fires annually. Casualty information is available only for the last two fiscal years (i.e. 7 fires in 2019 and 2020) in which there were no fatalities and one injured person [27]. Considering the general trend of a small number of injuries in car parks, the same as for Scotland, one injured person in 11 years has been assumed. Since there is no information on the degree of injury, given only one injury both in Scotland and Wales, it has been assumed that it was a slight injury in both cases.

In the previous research done by BRE, statistical data for the UK was collected for the period between 1994 to 2005. During these 12 years, there were 3096 car park fires with an average frequency of 258 per year, 2 fatalities and 87 injuries. Within this information, separate data is also available for purpose-built MSCPs. From 1994 to 2005, there were 2138 MSCP fires with an annual frequency of 178 fires per year, 2 fatalities and 39 injuries [3]. The severity level of injuries was not indicated in this work. Based on the 2010/2020 ad-hoc data from England, it has been assumed that there is the same proportion between slight and severe injuries, accounting for 90% and 10% overall, and 100% and 0% for MSCPs, respectively.

It should be highlighted that the fire statistics only contain information regarding those incidents that fire and rescue services attended. Moreover, accuracy and completeness cannot be guaranteed since information is filled by a human, and this is not the main focus of the fire and rescue services [35].

Gathered statistical data could not be directly used in the analysis because to apply the J-value methodology, all inputs need to be expressed with the specific units as detailed in previous studies [11][12]. For that purpose, information on the overall number of car parks and number of different car park types in a given region is needed. Since no credible publicly available information was found to get this data, the British Parking Association (BPA) was contacted. As per their estimations, overall, there are between 23 000 to 26 000 public car parks in the UK [36]. The average of 24 500 is used for further calculations in this study. It is assumed that this average value applies for both the period between 1994–2005 and 2010–2020, given the lack of more specific information.

To use the collected UK fire statistical data for the J-value calculation, information on the proportion between different car parks and between different countries within the UK is required. There is no organized database on all cark parks, but some details are available for those that hold the 'Park Mark' award. The 'Park Mark' Safer Parking Scheme is "a national standard for UK car parks that have low crime and measures in place to ensure the safety of people and vehicles", where details can be found on the official website [37]. The BPA shared the latest (2020) information on 'Park Mark' car parks (total 4723) [36]. This data required further processing to correspond to the published fire statistics namely the country location of listed car parks needed to be found, as well as grouping of car parks according to type i.e., MSCP, underground and other. The 'Park Mark' data was extrapolated to all other UK car parks assuming that the number of car parks correlates with the number of people living in the country.

As far as the US fire statistics are concerned, due to limited information about car parks from the US Fire Administration [38], the statistical data mentioned in the aforementioned NFPA research [5] has been used. Boehmer et al. report that as per Ahrens, during the period from 2014 to 2018, there were 1858 fires with no fatalities and 20 injuries in commercial parking garages. It is unclear what parking types 'commercial parking garages' involve, but given no other alternatives, was assumed to be the same as the earlier mentioned definitions. Boehmer et al. provided no details on injury types, thus the ratio of slight and severe injuries has been assumed to be the same as for England dataset. Since the number of car parks in the USA has not been found, this value has been estimated based on the population ratio between the UK and the USA, and therefore, based on the number of car parks in the UK (24500), a USA value of 122500 has been assumed.

By combining statistics on fires and the number of car parks, final input values on fire occurrence, fatalities and injuries before sprinkler system implementation for all nine scenarios are shown in Table 2. The UK fire statistics are derived from incidents attended by the fire and rescue services, and the car park statistics from BPA were gathered independently. This means it is highly likely that different definitions and interpretations have been used, and data may not perfectly match. Furthermore, since installing a sprinkler system in car parks is not mandatory in the UK, and no details have been found, it is assumed that all car parks are not equipped with sprinklers. In the BPA 'Park Mark' list [36], information on whether sprinklers are fitted or not is also not given. A comparison of the annual fire occurrence and fire fatality rates are presented in Figure 1 and Figure 2, respectively. Those figures are analysed further in the sensitivity analysis in the next sections.

Table 2: Fire occurrence, fatalities and injuries before sprinkler system implementation based on the collected fire statistics

	Annual fire occurrence rate	Fatalities per fire	Severe injuries per fire	Slight injuries per fire
Scenario	fires/year/car park	fatalities/fire	injuries/fire	injuries/fire
UK All 1994/2005	258/24500= 0.0105	0.0006	0.0029	0.0252
UK MSCP 1994/2005	178/3675= 0.0484	0.0009	N/A	0.0183
England All 2010/2020	79/22050= 0.0036	0.0013	0.0013	0.0114
England MSCP 2010/2020	40.6/3185= 0.0128	0.0025	N/A	0.0074
England Underground 2010/2020	21.2/601= 0.0353	0	N/A	0.0189
England Other 2010/2020	17.2/18263= 0.0009	0	0.0058	0.0116
Scotland All 2009/2020	8.55/1715= 0.0050	0	N/A	0.0106
Wales All 2009/2020	2.27/490= 0.0046	0	N/A	0.0401
US All 2014/2018	1858/122500= 0.0152	0	0.0005	0.0102

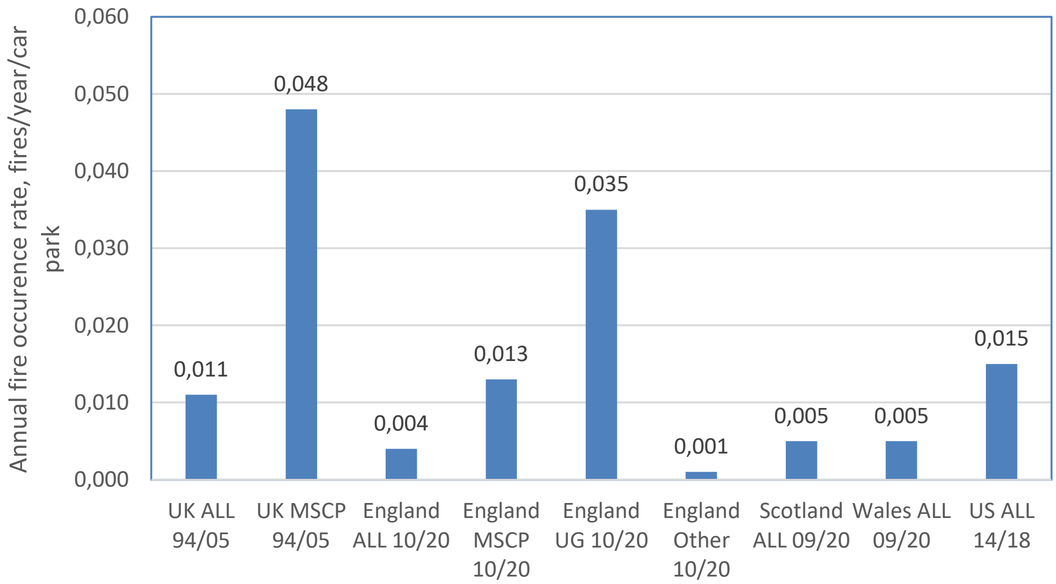

Figure 1: Annual fire occurrence rate for different types of car parks

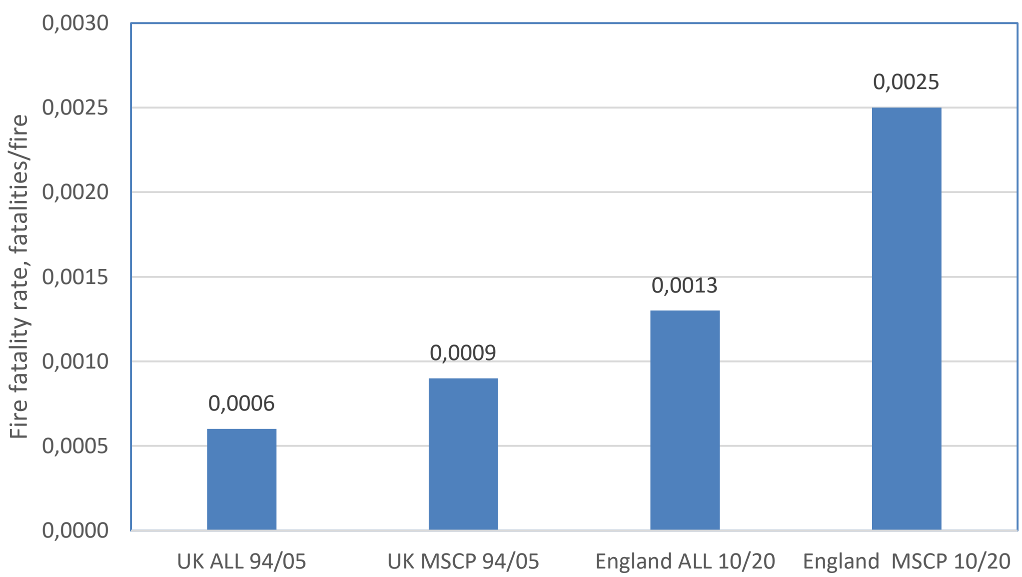

Figure 2: Fire fatality rate for each of the scenarios considered where there is a history of fatalities.

2.3 Cost per injury

There can be various types of injuries after a fire incident, from minor, that can be treated on the spot to major, that involves several months in hospital. Quantification of the burn injury involves health effects and other aspects such as loss of work or psychological trauma [39]. The value for the cost of injury has been taken from the UK Department of Transport (DoT) that publishes data for road accidents [40]. Data from the DoT is used as a standard by regulatory bodies and industry to identify the cost for protection systems directed to reduce harm to people. It should be noted that those values are based on VPF, which raises several concerns while assessing safety measures [15]. However, the cost of injury does not raise the same degree of ethical problems as the cost of human life does [16]. Due to lack of information for fire incidents, the cost of injury was taken from DoT 2019 as £17579 for slight and £228029 for serious non-fatal casualties. Based on inflation for the older dataset 1994–2005, £10366 and £134460 have been used, respectively.

2.4 Cost of property damage

Estimation of direct property damage for the UK scenarios has been carried out based on the average fire damage area. Information on the average extent of fire damage in the UK car parks was obtained by contacting the UK Home Office Fire Statistics Department [41]. Data was provided for the years 2010–2020 for England, the same period as the ad-hoc fire occurrence data. Only average values for given years were obtained, and there is no description of how the damaged area was classified, and the damage could range from a complete structural collapse to a minor impact from smoke. Therefore, such data does not give a complete picture of property damage. However, the data was used, as this is the only information that was available. In addition, the value of damaged cars is not reflected.

The average damage area fluctuated from about 4 m^2 to 1260 m^2. According to the Home Office's comment, the average damage area can be significantly impacted by a small number of extensive fires due to a relatively small number of car parks fires [42]. Indeed, it was noticed that a higher number of fires in a given year does not always correspond to a more significant fire damage area and vice versa. Based on this data, the average fire damage area per year and car park type is provided in Table 3. Accounting for the impact of large damage values on the overall average values, alternative results, excluding such events are also calculated. Therefore, certain years are excluded: for MSCP this is year 2017/18, for underground – 2014/15, and for other car park types – 2010/2011. From Table 3, it can be seen that difference between the cases, when all events considered and when a specific year is excluded, is significant, accounting for average values of 90.6 m^2 and 27.3 m^2, respectively.

Table 3: Average damage area from car park fire per year per different car park type

	MSCP	Underground car park	Other type of car park	Average
All events included	65.5 m^2	63.8 m^2	142.3 m^2	90.6 m^2
Excluding one year with large fire damage	31.6 m^2	31.9 m^2	18.3 m^2	27.3 m^2

In order to derive the cost of the property damage knowing fire damage area, construction costs for car parks have been considered. Statista.com provides figures for the average cost per m^2 for building a MSCP in the per UK country for 2016 and 2018 [43]. Costs differ depending on whether it is above or below ground construction. It has also been assumed that the given numbers are applicable for other car park types. The final result of the total average cost of direct property damage in car parks can be seen in Table 4, which is based on combining the average damage area and construction costs. This method is only an approximation since there can be different types of damage, and construction costs are likely overestimated for minor ones. As discussed, and seen in Table 3, years with large damage areas have a significant influence on the average value. Therefore, the second row in Table 4, which excludes specific years with large fire damage area, is used in the base scenarios in the analysis presented in the next section. All fire events (the first row of Table 4) are considered in the sensitivity study that is presented later.

Table 4: Property damage per car park based on average fire damage area and average construction cost (for 1994-2005 dataset)*

	MSCP	Underground car park	Other type of car park	Average
All events included	£49322 £29829*	£57229 £34612*	£86661 £52412*	£68222 £41260*
Excluding one year with large fire damage	£23795 £14391*	£28614 £17305*	£11145 £6740*	£20557 £12433*

For the US dataset, direct property damage for the period 2014-2018 was estimated by Boehmer et al. [5] to be $22.8 million. During this time 1858 car park fires were reported. Therefore, the property damage per fire is $12271 or £9093.

In this assessment, the costs associated with the loss of any vehicles, potential property damage to neighbouring buildings, losses due to environmental impact, cost of emergency response and other possible factors are not taken into account due to lack of data and challenges with quantification. It should also be noted that since the analysis is from the societal view, who pays the cost does not play a role. The focus is that the cost has been paid, irrespectively whether it is paid by insurance, the car park owner or anyone else. Due to these reasons, insurance savings are also not discussed in this work. As stated by Hasofer et al. [16], insurance is a transfer of money from one societal group to another, and since CBA is a societal indicator, insurance does not affect CBA.

2.5 Effects of sprinkler systems

No previous research has been found which quantifies the effectiveness of sprinklers in car parks. Therefore, it is assumed that the category "all public assembly" from the US experience with sprinklers [44] is the most applicable one. For this category sprinkler effectiveness was found to be 100% for the reduction in civilian deaths and 56% in property damage [44]. In the previous sprinkler CBA for New Zealand car parks, a value of 85% was assumed for the property damage reduction [21]. The fact that sprinklers do not always operate also needs to be taken into account. Information on reliability was taken from Frank et al. [45] which gives a mean value that accounts for 94.7%. Information on reduction of injuries was not found, neither specifically for car parks nor for commercial buildings. Therefore, 100% reduction, the same as for fatalities, was considered for the base scenarios.

2.6 Cost of sprinkler system

In general, various factors can affect the cost of the sprinkler system. Based on the US home sprinkler study, those are: system requirements, extent of coverage, piping, source of water, permit, inspection and additional fees, system design type, foundation type and the existence of state-wide requirements [46]. It was not possible to carry out such an extensive cost break-down due to lack of data. Instead, the guidance from PD7974-7 on ALARP criterion has been followed, where the cost of safety measure is related to installation and maintenance costs [14].

The total cost of sprinkler system installation can be estimated from existing design projects. OFR Consultants obtained permission to share the sprinkler installation cost for a large new MSCP in the UK. By translating this information into a square metre equivalent, a value of £24.3/m^2 was obtained as the upfront installation cost (ő̧ي) [47]. The annual maintenance cost was taken from the New Zealand CBA [21] that consisted from fixed and marginal cost per m^2. The value for annual fixed and marginal maintenance costs were taken as 750 NZ$/year and 0.025 NZ$/year/m^2, respectively, and converted into GBP.

Table 5 provides the summary of all input parameters and derived quantities for the J-value calculation for the 'England All' scenario, as an example.

Table 5: Input parameters and derived values for the 'England All' scenario

Symbol	Unit	Description	Value
̈O	£/person/year	GDP per capita	27521
őذ	years	Demographic constant	17.2
ή	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2629784
ٱ	-	Discount rate	0.03
ΰ	years	System lifetime	50
ΰ̋ ـثـĝ	fatalities/fire	Fatalities per fire before implementation	0.0013
ΰ̋ ـثـĥ	fatalities/fire	Fatalities per fire after implementation	0
– ̈Y	£/injury	Average cost per severe injury	228029
– ỉ	£/injury	Average cost per slight injury	17579
ΰ̋ ـئ ĝ	injuries/fire	Severe injuries per fire before implementation	0.0013
ΰ̋ ـئ ĥ	injuries/fire	Severe injuries per fire after implementation	0
ΰ̋ ـخ ĝ	injuries/fire	Slight injuries per fire before implementation	0.0114
ΰ̋ ـخ ĥ	injuries/fire	Slight injuries per fire after implementation	0
ـث ث	fires/year/car park	Annual fire occurrence rate	0.0036
Ў–ژ ĝ	£/fire	Cost of damage before implementation	20557
Ў–ژ ĥ	£/fire	Cost of damage after implementation	8634
A	m^2	Car park area	4000
ῷ	£/ m^2	Upfront cost per m^2	24.3
ά	£/year	Annual maintenance cost	423
őي	£	Upfront cost	97200
ά ع	£	Discounted maintenance cost over lifetime	10884
ЎOـث	£/year	Life preservation benefit	11.9
ЎOئ	£/year	Injury reduction benefit	1.8
ЎOژ	£/year	Damage reduction benefit	42.7
ЎOع	£	Total discounted benefits	1459
őع	£	Total discounted costs	108084

3. RESULTS AND DISCUSSION

3.1 Base case scenario

The collected input data has allowed results to be obtained for nine base scenarios, as shown in

Table 1. Since several input parameters use values based on estimations, a sensitivity analysis and 'what-if' analysis have also been carried out. The choice of the actual size of a car park for the base scenarios is not critical. An average size has been chosen, based on an average number of parking bays in 'Park Mark' accredited car parks (357) [36] and the UK standard space for one bay (2.4m by 4.8 m for a car) [48], that give a value slightly in excess of 4000 m^2.

The calculated J-value results are presented in Figure 3, which shows that the installation of a sprinkler system in car parks for all nine base scenarios is found not to be cost-beneficial since all J-values exceed unity. The installation of a sprinkler system is found to be most beneficial for underground and MSCPs. This can be explained by their relatively higher annual fire occurrence rate (refer to Figure 1). For underground car parks, the more significant cost of damage (refer to Table 4), which was derived from construction costs, also influences the result.

Furthermore, Figure 3 shows that the largest J-value of 555 is calculated for the 'England Other' car park type. As mentioned earlier, this category contains all car park types except underground and MSCPs, inferring single-level surface car parks. This seems to be a reasonable finding since most single-level surface car parks are associated with open structures, which, as mentioned earlier, pose relatively fewer fire risks than enclosed ones. From Figure 1 it can be seen that the 'England Other' scenario also has the lowest annual fire occurrence rate.

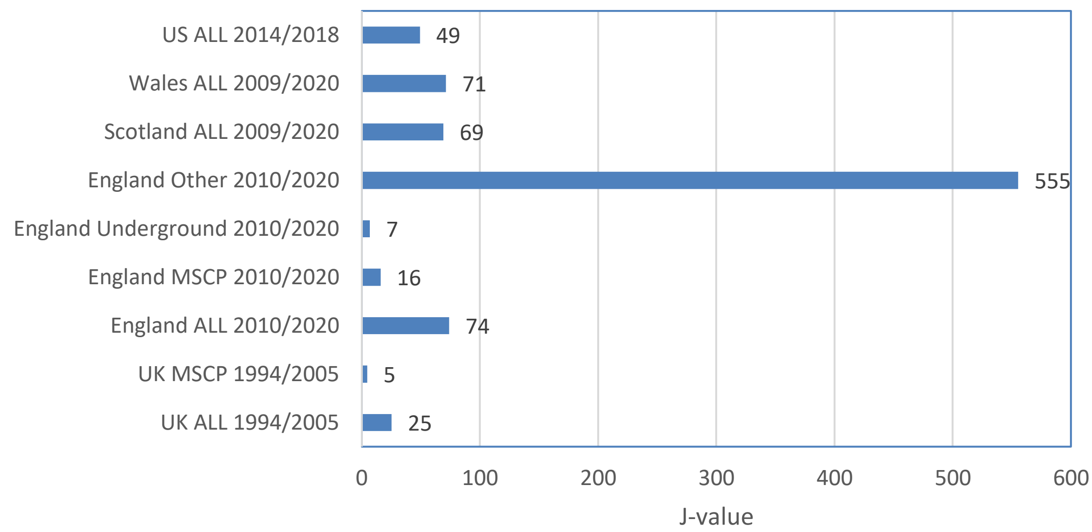

Figure 3: J-value results for all nine scenarios. A J-value of less than 1 is required in order for the fire safety investment to be cost-beneficial.

Another observation is that in the analysis, where assessment is done on all car park types, the J-value is significantly larger than unity, ranging from 25 to 74. Therefore, it can be inferred that installing a sprinkler system in car parks needs to be assessed for different car park types separately. The fact that each car park type has different fire statistics and different construction costs also supports this conclusion. The sprinkler installation may be feasible only for certain parking types, potentially underground and MSCPs. As mentioned, the regulations in USA only require sprinkler systems for a particular car park configuration. However, the basis for the code requirements are quite likely not based on a CBA. The basis for the code requirements were not studied in this work.

The breakdown of benefits and costs is similar for all nine base scenarios, and since the J-value is above unity, the costs constitute the largest proportion. The cost composition varies from 83% to almost 100%. In other words, benefits constitute from almost 0% to a maximum of 17%, with the maximum, logically, representing the scenario with the lowest J-value result and vice versa. The percentage here refers to the proportion of monetary value of benefits or cost, respectively, to the sum of benefits and costs together. As far as sprinkler system cost composition is concerned, the installation cost accounts for the largest part, 89% – 90% of the total sprinkler system costs, whereas maintenance costs contribute 10% – 11%.

As far as benefits are concerned, the J-value assessment has been performed both from life safety and property protection perspectives. The assessed benefits are averting a reduction in life expectancy, injuries prevented and property loss savings. For example, for the 'England All' scenario the breakdown is 21%, 3% and 76%, respectively. However, the general trend is the same: the benefit in property damage reduction significantly outweighs benefits in life expectancy and injury reductions for all nine scenarios. The proportion of property loss savings ranges from 67% to 98% and therefore, it can be concluded that the installation of a sprinkler system in car parks is predominantly a property protection benefit. This is mainly due to relatively low fire casualty rate in such type of structures. It is also can be seen that depending on casualty statistics (refer to Figure 2) in the 'US All', 'Wales All', 'Scotland All', 'England Underground' and 'England Other' scenarios, there were no fatalities in car parks and subsequently zero benefits regarding life expectancy reduction. The greatest value associated with a life expectancy benefit is found to be for the 'England MSCP' scenario, accounting for 32%. This scenario has the highest fire fatality rate, as indicated in Figure 2. Injury reduction benefit ranges from 2% to 19%, where 19% is for the 'England Other' scenario, which has the highest severe injury rate (refer to Table 2).

It is necessary to point out that the 'US All' scenario contains some shortcomings: an approximation of the number of car parks, the adoption of the same injury costs and sprinklers costs as for the UK scenarios. Even though this case contains several assumptions, the assessment has been made to obtain an approximate measure of the J-value for the country, where sprinklers are actually required for specific car park structures. It is found that the J-value for the presented USA scenario is 49. Since in NFPA88A [24] an automatic sprinkler system is required only for particular car park configurations and the J-value has been calculated for all car parks in the USA, this result cannot give enough information to make solid conclusions. It would be more informative to make an assessment only for those car park types where sprinklers are required.

3.2 Sensitivity analysis for estimated parameters

It is clear that the results from the J-value assessment on the sprinkler system installation in car parks highly depend on the availability and accuracy of input data. Similar to previous fire safety J-value studies [49], a sensitivity analysis is carried out for the parameters, where estimations and assumptions have been made. These parameters are summarised in Table 6. Given that the same methodology has been applied for all nine base scenarios, the sensitivity analysis is carried out for only one scenario, 'England All', to observe an overall trend in the output result. In this scenario the calculated base scenario J-value is 74.

Table 6: Variables for sensitivity analysis ('England All' scenario)

	Lower-bound	Base	Upper-bound
Sprinkler effectiveness in fatality reduction	43%	100%	100%
Sprinkler effectiveness in injury reduction	15%	100%	100%
Sprinkler effectiveness in property damage reduction	35%	56%	100%
Cost of property damage	not considered	£20557	£68222
Sprinkler installation costs	£19/m^2	£24.3/m^2	£29/m^2
Discount rate	2%	3%	4%
Annual fire occurrence rate	0.0018 fires/year/car park	0.0036 fires/year/car park	0.0072 fires/year/car park
Fire fatality rate	0.00065 fatalities/fire	0.0013 fatalities/fire	0.0026 fatalities/fire

The main finding, as can be seen from Figure 4, is that even if sprinklers are considered to be 100% effective with respect to fatality, injury and properly damage reduction, with other input parameters being the same as in the base scenario, their installation is still not cost-effective. The same applies to the cost of property damage, even if one were to include events with extensive fire damage. As illustrated in Table 7, the J-value is reduced by 64%, but it is still greater than unity. The lower-bound for cost of property damage parameter has not been considered since with the base value the result is already greater than unity.

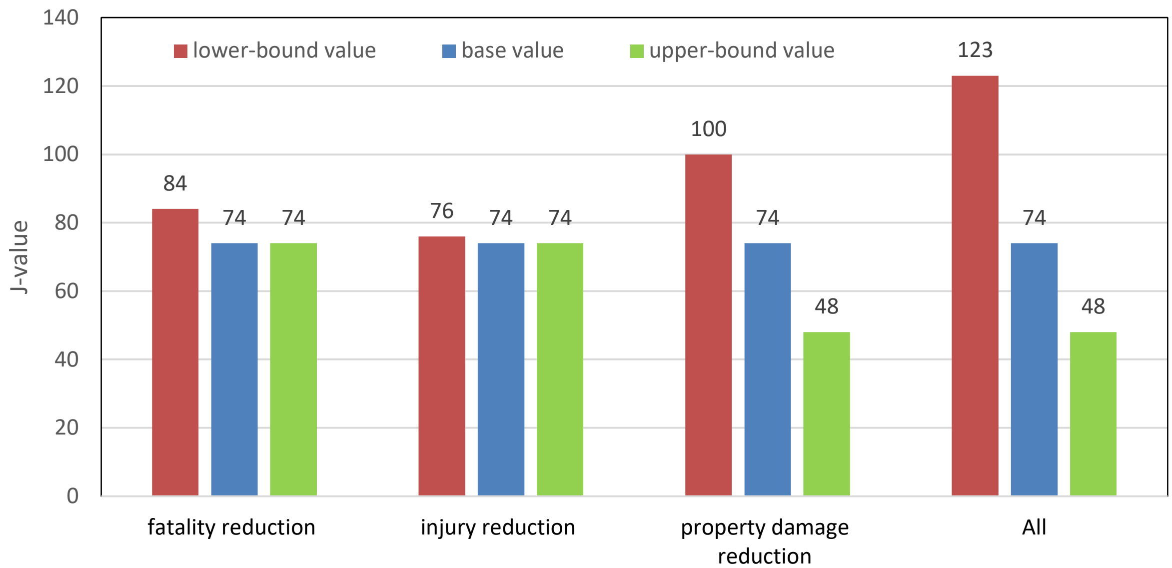

Figure 4: J-value sensitivity (fatality, injury and property damage) for varying sprinkler effectiveness. The lower- and upper-bound values are specified in Table 6.

Table 7: Sensitivity analysis results for varying cost of property damage

Cost of property damage	Base scenario (excluding large fire damage events)	Upper-bound (including large fire damage events)
J-value	74	27

Due to the lack of information on the range of sprinkler system installation cost in car parks, lower and upper-bound values were assumed to be +/- 20 % from the base scenario. This gives the change in the J-value of around 20 %, as presented in Table 8.

Table 8: Sensitivity analysis results for varying sprinkler installation cost

Installation cost	£19/m^2	£24.3/m^2	£29/m^2
J-value	64	74	84

In the given J-value assessment, a discount rate of 3% has been assumed based on guidance from HM Treasury [30]. However, in ISO2394 [31] SCCR is presented for 2%, 3% and 4% discount rates. Therefore, a sensitivity analysis has been made for these possible values of discount rate. From Table 9 it can be observed that, as might be expected, a higher discount rate gives a higher J-value and vice versa. The impact is between 18 to 20%.

Table 9: Sensitivity analysis results for varying discount rate

Discount rate	2%	3% (base scenario)	4%
J-value	61	74	89

Both for an annual fire occurrence rate and fire fatality rate, the lower and upper-bound values were assumed to be, respectively, twice as low and twice as high. As can be seen from Table 10, the relationship between the annual fire occurrence rate and a J-value are inversely proportional. That is, a twice as high fire occurrence rate results in a twice as low J-value. From Table 11 it can be observed that the impact of fire fatality rate on a J-value is less, and it is in a range of approximately 10-20%.

Table 10: Sensitivity analysis results for different annual fire occurrence rates

Annual fire occurrence rate	0.0018 fires/year/ car park	0.0036 fires/year/car park (base scenario)	0.0072 fires/year/car park
J-value	147	74	37

Table 11: Sensitivity analysis results for different fire fatality rates

Fire fatality rate	0.00065 fatalities/fire	0.0013 fatalities/fire (base scenario)	0.0026 fatalities/fire
J-value	83	74	61

The analyses presented herein uses statistical inputs derived from incidents spread over several years. However, this approach does not easily address the question of whether there should be a change to the societal provision of fire protection measures to account for rare, high consequence events. One challenge with such events when doing an analysis that relies on statistical data is whether such events should be omitted from the data, as in the analysis of the cost of property damage in Section 2.4 which removed specific years with large fire damage area. Alternatively, what is an appropriate reference period over which the data is assessed. Using a short reference period means the rare, high consequence events have a major influence but using a long reference period to alleviate this influence means the data may no longer represent the current socio-economic conditions, for example, the change in vehicle characteristics of those used on the road network over an extended period. The paper by Arnott et al. [49] briefly explores this issue in the case of the J-value of installing sprinklers in residential high-rise buildings in the light of the Grenfell Tower fire. This previous paper does not solve the question but does propose that a probability of occurrence weighting be applied to address for rare events.

3.3 'What - if' analysis to obtain a cost-effective result

As discussed, there are some challenges with the quantification of the inputs to the analysis given the lack of organized data related to this study. In order to cover these gaps, a 'what-if' analysis has been carried out which also provides a closer investigation of some of the variables that can be of societal interest. These variables are the ones that society has control over and can affect, namely the car park area and sprinkler installation cost. Only the installation cost has been considered, since as was discussed before, maintenance costs have less impact on total system costs. These parameters have been manipulated to determine what values are necessary for a sprinkler system to become cost-effective for car parks. Since the lowest J-value was found for 'England Underground' 2010/2020 scenario, the analysis is only applied to this scenario.

By changing the car park area with all other inputs remaining unchanged, the J-value becomes unity for an area of 190 m^2. Sprinkler installation becomes cost-effective for smaller car parks because system installation cost is given per m^2 and subsequently linearly decreases as the area decreases. However, care must be exercised in interpreting this finding as the cost of property damage does not change when the car park area is decreased, because it has been calculated based on average fire damage area statistics (Table 3) which is assumed to be a fixed value. If the statistics included the percentage of fire damage area compared with the total car park area, then more solid conclusions could be drawn.

Society potentially can have control over the sprinkler installation cost and therefore this parameter has been assessed herein. It has been found that, if all base parameters remain the same, the sprinkler installation cost would need to be around £1.1 per m^2 to make installation cost-effective. This value is 20 times less than the value used previously and it is clear that such cost is difficult to imagine. Repeating the same analysis but assuming 100 % sprinkler effectiveness both in reducing life safety consequences and property damage results in a value of £3.9/m^2 to make installation cost-effective.

The above adjustments to the sprinkler system cost have been applied to the base car park area of 4000 m^2. The same analysis for a range of smaller car park areas, namely 500 m^2, 1000 m^2, 1500 m^2, 2000 m^2, 3000 m^2, has been carried out to investigate the variation in the sprinkler installation cost. The evaluations have been made for two cases; 1) base values and 2) assuming 100% sprinkler effectiveness. The results can be seen in Table 12 and it can be concluded that with sprinklers being 100% effective, for car parks of 500 m^2 and 1000 m^2, the maximum necessary system installation cost to obtain cost-effective results becomes more realistic values of £31.0/m^2 and £15.5/m^2, respectively.

Table 12: Maximum sprinkler system installation costs for base values and 100% sprinkler effectiveness in relation to car park area for a J-value of unity ('England Underground' scenario)

	500 m^2	1000 m^2	1500 m^2	2000 m^2	3000 m^2	4000 m^2
Base condition	£9.0/m^2	£4.6/m^2	£3.0/m^2	£2.3/m^2	£1.5/m^2	£1.15/m^2
100% effectiveness	£31.0/m^2	£15.5/m^2	£10.3/m^2	£7.8/m^2	£5.2/m^2	£3.9/m^2

4. SUMMARY AND CONCLUSIONS

A J-value analysis was carried out to evaluate the cost-effectiveness of sprinkler system installation in car parks. Relevant input data for nine scenarios was collected from various sources, such as the UK Home Office, Scottish Fire and Rescue Service, StatsWales, BRE, NFPA, and the BPA. The assessment was made both from life safety and property protection perspectives for a car park area of 4000 m^2, corresponding to the average size of 'Park Mark' accredited car parks. Reductions in fatalities, injuries and property damage have been considered as potential benefits after installing sprinklers.

The J-values for the nine scenarios were all found to be above unity, ranging from 5 to 555. This means that installing a sprinkler system in car parks is not cost-beneficial from a societal point of view. This result is true even if sprinklers are assumed to be 100% effective in the reduction of fire fatalities, injuries and property damage. The lowest J-value was obtained for the 'UK MSCP' and 'England Underground' scenarios, which can be explained by the fact that they have the highest annual fire occurrence rate of the car parks included in the current study. The large construction cost for underground car parks, on which the property damage cost was derived, also affected the J-value for the 'England Underground' scenario. The highest J-value was obtained for the 'England Other' scenario, with a J-value of 555. Since 'Other' parking types infer single-level surface car parks, it is expected that sprinklers are anyway not a feasible option. It has also been found that sprinkler installation in car parks is mainly a property protection benefit because property loss savings constitute between 67% and 98% of the total benefits, depending on the scenario. The proportional life safety benefits are subsequently smaller, mainly due to the relatively low fire casualty rate in car parks. For five out of nine scenarios, this value is reported as zero. Another finding is that the assessment needs to treat different car park types separately due to specifics of each parking type, such as the variation in the associated fire statistics and construction costs.

Research carried out as part of this paper has identified that there is no specific data on sprinkler effectiveness in car parks and very little information also on installation and maintenance costs. Furthermore, the fact that the statistics do not contain details such as statistical distributions for the extent and cost of fire damage, the car fuel type and parking arrangement, has necessitated the use of several assumptions in the analysis presented herein. It is likely that more research is required to assess the impact of modern technologies on the fire safety of car parks. As such, there are also aspects that were not included in this work due to lack of data, such as the impacts of alternatively fuelled cars, modern parking methods, fire spread from a car park to adjacent buildings, and other potential benefits from the installation of a sprinkler system. Future analyses could include the costs accompanying the loss of vehicles, although estimating this can be difficult as the information is often held by a multitude of insurance companies associated with each individual vehicle owner.

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