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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 modern car parks, both with respect to life safety and property protection. Nine scenarios were established based on a substantial literature review and carefully collected and analysed input data. All car park types were considered for the UK, England, Scotland, Wales and the US, while separate considerations were made for multi-storey car parks (MSCPs) in the UK, as well as for MSCPs, underground and other parking types in England. The baseline assessment was made for a car park size of 4000 m^2, but the analysis procedure can be applied to any car park size.

The J-values for the nine scenarios were all larger than unity (ranging from 5 to 555), thus showing that the installation of sprinklers is not a cost-effective investment for car parks from a societal point of view. Unsurprisingly, the lowest J-values were obtained for the scenarios and car parks with relatively higher annual fire occurrence rates. It was also found that the sprinkler installation in car parks mainly provides benefits with respect to property protection, which is due to the fact that property loss savings substantially outweigh lives saved and injuries prevented. This is primarily due to the relatively low fire fatality rate in car parks.

A sensitivity analysis showed that even when assuming 100% sprinkler effectiveness, sprinklers would still not be cost-beneficial for the car parks considered. In fact, the system installation can only become cost-effective if the car park size or installation cost are reduced by as much as a factor of 20. The optimum realistic combination to obtain a cost-effective result for one of the scenarios with the lowest J-value is 100% sprinkler effectiveness and a car park area of 500 m^2 or 1000 m^2. Even though sprinklers were not cost-effective for car parks in the current analysis, the scarcity of data and new emerging technologies in the car industry suggests that further investigation of the topic is needed to make a more absolute recommendation based on this type of analysis.

ABSTRACT in Russian (АННОТАЦИЯ)

Оценка J-значения (J-value) была проведена для анализа затрат и выгод от установки спринклерных систем на современных автостоянках, как с точки зрения безопасности жизни, так и защиты имущества. Девять сценариев были разработаны на основе обширного обзора литературы и тщательно собранных и проанализированных исходных данных. Все типы парковок рассматривались для Великобритании, Англии, Шотландии, Уэльса и США, в то время как отдельно рассматривались многоэтажные автостоянки (MSCPs) в Великобритании, а также MSCPs, подземные и другие типы парковок в Англии. Анализ была сделан для автостоянок размером 4000 м^2, но процедуру анализа можно применить к автостоянкам любого размера.

J-значения для девяти сценариев были больше единицы (от 5 до 555), что показывает, что установка спринклеров не является рентабельным вложением для автостоянок с социальной точки зрения. Неудивительно, что самые низкие J-значения были получены для сценариев и автостоянок с относительно более высокой годовой частотой возникновения пожаров. Было также установлено, что спринклерная установка на автостоянках в основном обеспечивает преимущества в отношении защиты собственности, поскольку экономия от потери имущества существенно превышает количество спасенных жизней и предотвращенных травм. В первую очередь это связано с относительно низким уровнем смертности от пожаров на автостоянках.

Анализ чувствительности показал, что даже при условии 100% эффективности спринклеров их установка все равно не будут рентабельной для рассматриваемых автостоянок. Фактически, установка системы может стать рентабельной только в том случае, если размер автостоянки или стоимость установки уменьшатся в 20 раз. Оптимальная реалистичная комбинация для получения рентабельного результата для одного из сценариев с наименьшим J-значением - 100% эффективность спринклера и площадь автостоянки 500 м^2 или 1000 м^2. Несмотря на то, что в текущем анализе спринклеры оказались нерентабельными для автостоянок, нехватка данных и новые появляющиеся технологии в автомобильной промышленности предполагают, что необходимо дальнейшее исследование этой темы.

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NOMENCLATURE

Acronyms

ADB	Approved Document B
ALARP	As Low As Reasonably Practical
BRE	Building Research Establishment
CBA	Cost-Benefit Analysis
EV	Electric Vehicle
GDP	Gross Domestic Product
HRR	Heat Release Rate
ICE	Internal Combustion Engine
LPG	Liquefied Petroleum Gas
LQI	Life Quality Index
MSCP	Multi-Storey Car Park
NFPA	National Fire Protection Association
PBD	Performance-Based Design
PRA	Probabilistic Risk Assessment
SCCR	Societal Capacity to Commit Resources
SHC	Smoke and Heat Control System
SWTP	Societal Willingness To Pay
SCCR	Societal Capacity to Commit Resources
VPF	Value of Preventable Fatality
VSL	Value of Statistical Life

Symbols

C	Total costs of safety measure (£/car park)
C_0	Upfront cost (£/car park)
C_x	Demographic constant (years)
C_γ	Total discounted costs of safety measure (£/car park)
G	GDP per capita (£/year/person)

J-value	Judgement value (-)
L	System lifetime (years)
m	Annual maintenance cost of safety measure (£/year/car park)
m_γ	Discounted maintenance cost of safety measure (£/car park)
$N\lambda_{f,0}$	Fatalities per fire before implementation (fatalities/fire)
$N\lambda_{f,1}$	Fatalities per fire after implementation (fatalities/fire)
$N\lambda_{Si,0}$	Severe injuries per fire before implementation (injuries/fire)
$N\lambda_{Si,1}$	Severe injuries per fire after implementation (injuries/fire)
$N\lambda_{si,0}$	Slight injuries per fire before implementation (injuries/fire)
$N\lambda_{si,1}$	Slight injuries per fire after implementation (injuries/fire)
q	Work-life balance parameter (-)
X	Life expectancy (years)
ΔD	Total discounted benefits over a lifetime (£/ car park)
ΔD_d	Damage reduction benefit (£/year/ car park)
ΔD_f	Life preservation benefit (£/year/car park)
ΔD_i	Injury reduction benefit (£/year/car park)
$\Delta\zeta_{d,0}$	Cost of damage before implementation (£/fire)
$\Delta\zeta_{d,1}$	Cost of damage after implementation (£/fire)
λ_{ig}	Annual fire occurrence rate (fires/year/car park)
ζ_i	Average cost per injury (£/injury)
γ	Discount rate (-)

1. INTRODUCTION

Car parks are traditionally associated with a relatively low fire risks due to rare fire occurrence compared to other premises. For instance, in 2006 in the United Kingdom (UK), the total number of registered fire incidents was 426200, with less than 0.1% of that number occurring in car parks [1]. For comparison, in the same year in England, 13% of fires took place in dwellings and 14% in road vehicles [2]. Furthermore, previous studies have claimed that there is low fire load and fire spread probability in car parks [3][4]. However, recent significant fires in car parks, such as the ones in the Stavanger airport with more than 300 cars burnt [5] and in Liverpool Kings Dock with around 1150 cars destroyed [6], have raised concerns about car park fire safety.

Current fire safety requirements and guidance on car parks are based on fire tests of cars that were available at the time when codes were in development [7] [8]. However, different car designs and parking technologies have become available in the last decades, including a greater use of plastics, increased vehicle size, alternative fuel types, the installation of a stacking system or the self-driving car concept [9]. Such changes can potentially pose additional risk to the fire safety of car parks.

These modern changes, together with significant car park fires, have led to an increased interest in putting sprinklers in car parks to enhance fire safety. However, there is a lack of clarity to what extent innovations have affected previous assumptions and whether sprinklers are actually needed in car parks. Therefore, the installation of a sprinkler system in car parks needs to be assessed from a cost-benefit point of view to allocate societal resources efficiently. There are different cost-benefit analysis (CBA) methods; one of them is a judgement value (J-value) analysis, which is discussed in this work.

1.1 Car parks and fire safety

For the purpose of this work, the term "car" is defined in the same way as in the report by Spearpoint et al. [10], which is as a motor vehicle with at least four wheels and a maximum of nine seating positions, mainly used to transport passengers [11]. 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 [12]. This definition excludes detached private garage boxes that are designed for single or multifamily housing [13]. As in the report by Spearpoint et al. [10], the chosen term “car park” does not embrace 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 residential building. Car parks can be public or private, single-level or multi-level construction, located underground or above ground [10]. Specific features of car parks compared to other facilities: relatively low ceiling and a large area in both 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 [8]. Respective norms and guidelines contain further details on ventilation criteria. Ventilation plays an important role in fire development. For open car parks it can allow exhaust gases and smoke to escape, but at the same time, sufficient ventilation can promote sustained burning. In closed parking, due to enclosed structure, smoke temperatures can be higher, but at the same time, if ventilation is further restricted, fire can die out. It is clear that fire behaviour in these types of car parks is different. Also, for closed car parks due to higher temperatures spalling of concrete can be a matter of concern [14]. In some countries additional requirements are placed only for enclosed car parks (refer to Section 1.3), possibly because in open car parks hot gases can be vented, and they are more accessible to fire and rescue service [8].

Due to the nature and purpose of car parks, people are present there only for a limited time. Therefore, the frequency of fatalities is lower when compared to continually occupied spaces. However, it does not mean that fires in these structures cannot lead to human injuries or death. These structures can pose a danger to firefighters, especially in the case of structural damage. This happened during the fire in the car park in Gretzenbach in 2004, where seven firefighters died due to structural collapse [1]. Another potential loss of lives can occur when a car park is adjacent to another building and fire spreads further to that construction. Such an incident took place in Monica Wills House in Bristol, where fire spread from car park to residential building, and as a result, one person died [1]. Consequently, it can be said that apart from property and business losses, fires in car parks can also lead to loss of human lives, but the probability of such event taking place is low.

Previous studies on car fires concluded that car parks do not pose significant fire danger due to low fire load and low fire spread probability. For example, Butcher et al. [3] in 1968 conducted experiments and found that fire spread is unlikely and "the amount of combustible material (in an average motor vehicle) presents a comparatively low fire load". Another example is an argument from Marchant [4] in 1990 that "because of the spacing of cars in normal car parks the chance of fire spread between cars is negligible". It should be noted that the tests of Butcher et al. were done on the cars that were available at that time. As was mentioned in National Fire Protection Association (NFPA) Research on car parks [7] [7], tests of old cars should not act as the grounds for current regulations and guidance.

1.2 Modern changes and car parks

One of the main concerns of modern cars is increased plastic content. NFPA Research has compiled data from previous studies on the plastic content of vehicles, mainly from United States (US), Canada and Mexico, and results can be seen in Figure 1. While comparing cars from 1976 and 2018, one can observe a dramatic increase in plastic content. The fact that plastic fuel tanks become more widespread, accounting for 85% in Europe and 75% in the US, also adds up 8-10 kg to the plastic content compared to cars with metal tanks. As a result, modern vehicles (2018) contain 91% more plastics than older vehicles (1970s). Increased plastics content also leads to increased energy content. In the same research this increase was found to be 2298 MJ. An increase in plastic content is significant (91%), but one can see that the actual percentage of plastics by vehicle curb weight in 2018 was less than 10%. However, it is also expected that in the future use of plastics in the car industry will further grow [7][8].

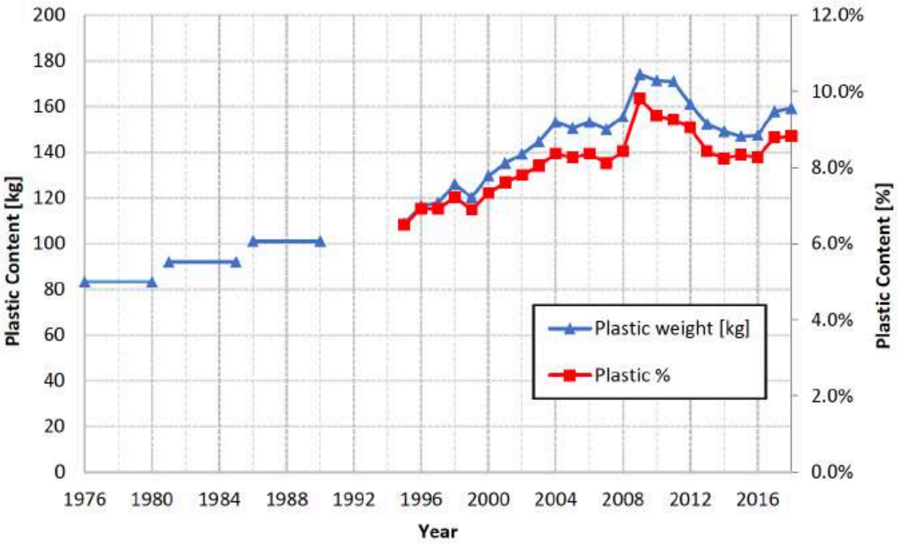


Figure 1: Amount of plastic in average US light vehicles in weight (kg), and as a percentage of vehicle curb weight [7]

It is believed that increased plastic content leads to an increased fire load. While comparing cars from the 1960s and modern ones (2000s), BRANZ reported a 10-fold increase, from 9 kg to 90 kg, in the amount of combustible materials used in car construction, which leads to greater fire load [14]. The comparison between the fire load of the 1960s and 1980s cars made by Marchmont gives a less significant 17% increase in fire load. However, if to compare the work of Butcher performed in 1968 [3] and work of Shipp and Spearpoint that was done in 1995 [15], the energy content of two cars was 4540/5910 MJ and 4000/5000 MJ, respectively [10]. This means the fire load did not change in the given period. Clause 11.1 in Approved Document B (ADB) states that for car parks "fire load is well defined" [12]. The variance in the provided data and given different time periods studied show that the question of an increase in fire load of modern vehicles requires more research.

Another concern is that modern cars are larger than older ones, and therefore represent a greater fire hazard. To demonstrate this change, NFPA Research has compared the curb weight and width of the two most popular US cars between the 1970s and 2018. From Table 1 it can be seen that an increase in car width was 8 cm and 21 cm and growth in weight was 150 kg and 430 kg, for Ford F150 and Toyota Corolla, respectively. Increased car size leads to a greater amount of potentially combustible material and a reduction in distances between parked cars. This in turn can promote rapid fire spread [7][8].

Table 1: Size of two most popular cars in the US from the 1970s and 2018 [7]

	Width Increase	Weight Increase
Toyota Corolla	21 cm	430 kg
Ford F150	8 cm	150 kg

It can be logically inferred that all of these changes have led to more severe fires in car parks. However, it was also found that the maximum heat release rate (HRR) from modern and older cars has no significant difference. In Figure 2 HRR curves from five decades from the 1970s to 2010s are presented. Data was compiled from previous tests by NFPA. It can be seen that both cars from the 2010s and 1980s can produce 8-9 MW fires. Figure 2 shows that there is no distinct correlation between HRR and car age. It was also found that there is no correlation between HRR and curb weight. However, it should be emphasized that test conditions were different; therefore, data cannot be directly compared [7] [8].

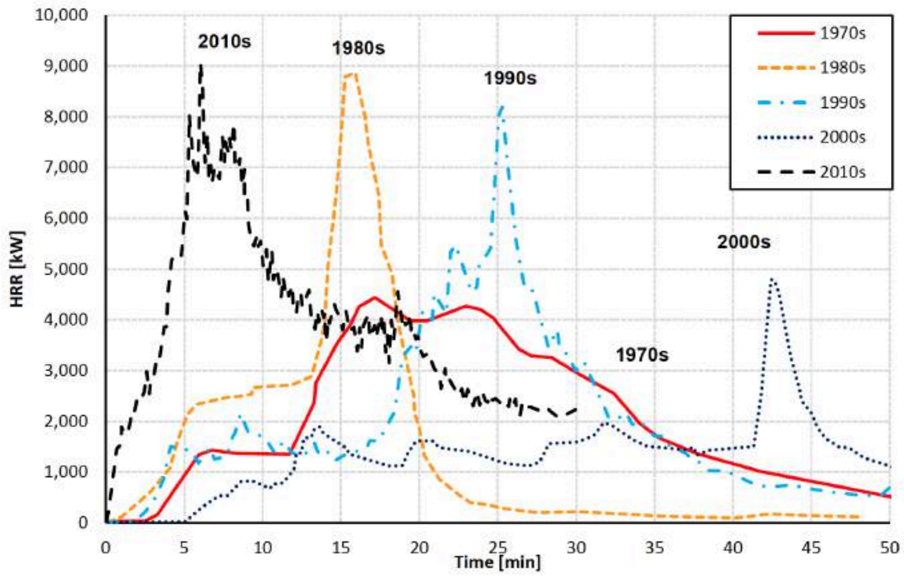


Figure 2: HRR curves for cars from each decade from the 1970s to 2010s [7]

As far as fire spread is concerned, it depends on several factors. First of all, it is heat radiation to nearby vehicles. The degree of radiation energy depends on fire size, temperatures, the distance between cars and car park enclosure configuration. Fire size and temperatures in turn depend on the degree of the vehicle's combustible content. Another factor that affects fire spread in car parks is car materials' critical flux to ignition. It is also clear that time plays an important role. To be specific, the time before actual firefighting operations are established. This depends on detection time, fire and rescue service's response time and accessibility to the structure [16].

As was mentioned earlier, previously it was assumed that fires in car parks mostly do not spread beyond the origin. However, experimental tests that were carried out between 2006 and 2009 by Building Research Establishment (BRE) have shown that in car parks without additional suppression system fire readily spreads from one vehicle to another. Fire spread occurred either through direct flame impingement or radiative heat transport [1]. Furthermore, recent major accidents in car parks can prove that fire can go beyond the initially burned car. For instance, in 2020 fire in a multi-storey car park (MSCP) in Stavanger airport led to the collapse of the building and more than 300 cars destroyed [5]. Another example is the Kings Dock fire in Liverpool in 2017, where around 1150 cars were fully burnt. It was reported that "additional vehicles became involved every 30 seconds" [6].

Apart from increased car size and plastic content, there are also other changes in modern carы, such as the alternative power options. Traditionally, cars are operated with the energy from fuel combustion, typically diesel or petrol. However, due to the current tendency to move to environmentally friendly solutions, there are various alternatives, such as liquefied petroleum gas (LPG), natural gas, electric cars and hybrid systems. It should be noted that the majority of previous fire tests and studies were done based on vehicles with an internal combustion engine (ICE). Therefore, there is a lack of knowledge on how alternatively powered vehicles will behave in fire, but some point tests are available. For example, during BRE tests it was found that "the potential explosion risks associated with gas-fuelled cars, particularly LPG but also, potentially, hydrogen, do not appear to be of concern to firefighters" [1].

As far as electric vehicles (EVs) are concerned, previous tests have shown that HRR from EVs is similar or less than of ICE vehicles. However, there is a potential danger from EVs because reignition and thermal runaway can take place. The battery pack is typically protected, and if it is not involved in the fire, fire behaviour is the same as with ICE cars. When a battery is exposed to fire and heated to thermal runaway temperature (130-200°C), uncontrolled chemical heat production is inevitable. Since battery fires have a long duration, a large amount of extinguishing medium must be applied to ensure no reignition occurs. Currently, extensive cooling is the only tactics against battery fires [17]. Overall, EVs do not pose more significant danger than ICE vehicles, as long as they are not sufficiently heated to cause thermal runaway. Inspection of Stavanger airport car park fire, where fire initiated in the EV, also concluded that fire behaviour was not different from a conventional ICE car. No data suggests that thermal runaway took place [16].

Another modern car parking technology that poses a threat to fire safety are automated parking systems using stackers. A stacking system is "a space-saving design, where one vehicle can be stacked above another in the same space typically required for a single parking stall" [18]. While saving space capacity is maximised in this design, the vertical distance between lower and upper cars is smaller than if they were parked horizontally. BRE also conducted a test with stacked cars, and results have shown that fire rapidly spreads from the lower car to the upper one [1].

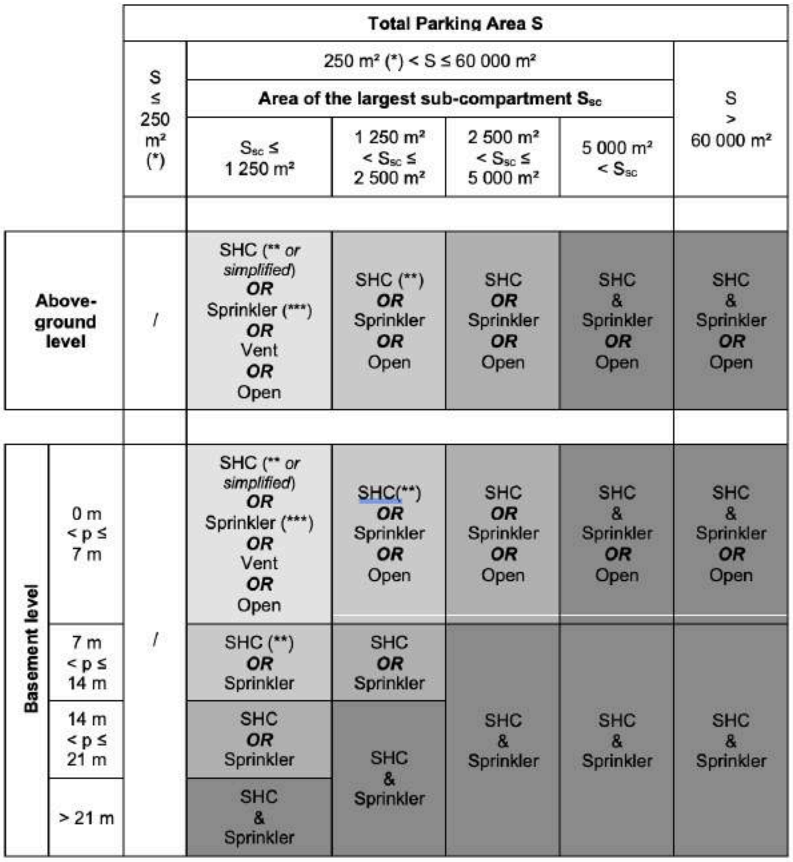
Overall, it can be seen that new developments in the car industry affect previous assumptions on fire behaviour in car parks. It is clear that to make detailed conclusions, more research in this field is required. However, from the available data, it is already clear that the fire behaviour of legacy and modern cars is not the same, at least because of car size, plastic content and fire spread. Therefore, current regulations need to be reviewed to make sure fire safety requirements reflect those changes, and if required, additional safety measures need to be installed. This work focuses on sprinkler system installation in car parks as a possible measure to tackle discussed issues. It should be noted that car stackers and alternatively fuelled cars are not included in this work due to the lack of statistical data and fire tests.

1.3 Current requirements

There is no common standard on the fire safety regulations among different countries, and car park fire safety is not an exception. In this work the focus is on the UK (England), where the installation of sprinkler systems in car parks is not a code requirement. Additionally, regulations of other countries, such as Belgium and the US, have been studied, where sprinklers are required for certain car park configurations. Further details on car park requirements, such as fire resistance or smoke and heat control system (SHC), have not been assessed since the focus is on the sprinkler system. Details on the design, installation and maintenance of sprinkler system can be found in appropriate standards such as BS EN 12845 [19] or NFPA13 [20].

Each country within the UK has its own regulatory framework. In this work only the regulations in England are presented since it is the largest country. The English Building Regulations 2010 contain functional requirements and have the force of law. Guidance on how the fire safety requirements of these regulations can be met is provided in the Approved Document B. Guidance on the fire safety of car parks is provided in Section 11 with the purpose group 7b. The guidance is given depending on ventilation conditions. It distinguishes open-sided and not open-sided car parks, either with natural or mechanical ventilation [12]. As far as a sprinkler system is concerned, from clause 8.14, sprinklers are required for purpose groups from 3 to 7a (7b is not included) if the building's height is above 30 m. In clause 18.11, it is also stated that “car parks are not normally expected to be fitted with sprinklers” [12].

In the US provisions for car parks are given in the NFPA88A “Standard for Parking Structures” (2019 edition) [20]. Same as in the UK, a distinction is made between open and enclosed car parks. As per clause 6.4.4, no provision of sprinklers is required for open car parks. As per clause 6.4.2, an automatic sprinkler system is required for portions of enclosed parking structures below grade, regardless of construction type, and enclosed parking of Type III (ordinary) or Type IV (heavy timber) construction over 15m in height. Also, automatic sprinklers system is required for automated mechanical-type parking structures (clause 9.2.4.1).



		Total Parking Area S					
		S ≤ 250 m² (*)	250 m² (*) < S ≤ 60 000 m²				S > 60 000 m²
			Area of the largest sub-compartment S_{sc}				
			S_{sc} ≤ 1 250 m²	1 250 m² < S_{sc} ≤ 2 500 m²	2 500 m² < S_{sc} ≤ 5 000 m²	5 000 m² < S_{sc}	
Above-ground level		/	SHC (** *or simplified*) **OR** Sprinkler (***) **OR** Vent **OR** Open	SHC (**) **OR** Sprinkler **OR** Open	SHC **OR** Sprinkler **OR** Open	SHC & Sprinkler **OR** Open	SHC & Sprinkler **OR** Open
Basement level	0 m < p ≤ 7 m	/	SHC (** *or simplified*) **OR** Sprinkler (***) **OR** Vent **OR** Open	SHC(**) **OR** Sprinkler **OR** Open	SHC **OR** Sprinkler **OR** Open	SHC & Sprinkler **OR** Open	SHC & Sprinkler **OR** Open
	7 m < p ≤ 14 m		SHC (**) **OR** Sprinkler	SHC **OR** Sprinkler	SHC & Sprinkler	SHC & Sprinkler	SHC & Sprinkler
	14 m < p ≤ 21 m		SHC **OR** Sprinkler	SHC & Sprinkler			
	> 21 m		SHC & Sprinkler				

Figure 3: Annex 7 of HR 1632 R3 (Belgium, English translation) [21]

In Belgium new stricter guidelines for car park fire protection are expected based on amendments in Royal Decree "Basic standard" (Normes de base) HR 1632 R3. This document was approved in May 2017 by the High Council for Fire and Explosion Security. These are "future" guidelines, but the fire and rescue service and other related people already follow them [22] [23]. Amendments provide a matrix of guidelines depending on car park configuration, particularly car park total area, sub-compartment area, level and basement depth. Details can be seen in a translated version in Figure 3 and the original Dutch version in Appendix A. HR 1632 R3 [21] provides a choice between SHC and sprinkler systems for specific car park configurations. There are four types of SHC and two sprinkler system options, depending on severity. Most of the times, standard sprinkler hazard OH2 is required. However, if the car park's sub-compartment area is less than 1250 m^2 and the structure is located either above ground or at a depth of a maximum 6 m, then a "light" sprinkler system hazard design can be adopted. This corresponds to OH1 and 30 minutes of operation instead of OH2 and 60 minutes [21]. In general, according to European Fire Sprinkler Network, in most European countries, sprinklers are required for specific car park configurations [24].

1.4 Sprinkler system and car parks

An automatic sprinkler system is a fire suppression system that discharges water when a fire is detected. Sprinklers control the fire, not allowing it to spread before the fire and rescue service arrives. Only those sprinkler heads in close proximity the fire activate. There are different types of sprinkler system; the one considered in this analysis is a wet type sprinkler system, where water is always present in the pipes [19]. Before evaluating whether a sprinkler system is worth installing in car parks or not, it is essential to address aspects of sprinkler effectiveness in car parks. Due to the lack of data on car parks, studies on residential and industrial sprinklers are considered. However, it should be noted that if the operation principle of a sprinkler system is the same for different structures, fire behaviour in car parks is different due to specific features of such type of construction.

Definitions of “reliability”, “efficacy”, and “effectiveness” have been considered the same as presented by Frank et al. [25] in their sprinkler effectiveness study. Criteria for accessing sprinkler performance are occupant fatalities, injuries, damage to property, fire containment, fire and rescue service intervention and number of sprinklers activated. It also should be noted that performance of the sprinkler system depends on various factors, such as building design, modifications, maintenance, age, system characteristics and other. From the past fires in sprinkled buildings, it was found that sprinkler effectiveness lies between 70.1% and 99.5%. This variation is due to different approaches and practices used in different studies and legislations [25].

Another important aspect to consider is the reliability of the system. In the research conducted by NFPA on home fires between 2010 and 2014, it was found that sprinklers operated in 92% of the home fires, where sprinklers were present. Out of this 92%, they were effective in controlling the fire in 96% of fire incidents [26]. The study by Frank et al. made a review on sprinkler effectiveness based on previous studies, and the mean reliability was found to be 94.7%. This work also highlights system shut-off as the most common reason for a sprinkler to fail to operate, accounting for 73%. There are also cases, where sprinklers were activated, but were not effective in controlling the fire. The main causes are water not reaching the fire, inappropriate system or insufficient water released [25].

In order to see the effect of sprinklers on fatalities, injuries and property damage, one can refer to the BRE study carried out for the Welsh government on residential sprinklers. This study has found that in sprinkled buildings, reduction in the number of deaths is in the range of 55% - 85%, injures are 15% - 45% less, and property damage is reduced to 35% - 65%. During conducted 18 fire tests, it was also concluded that sprinklers are not effective for slowly growing fires [27]. Another study by BRE for the Welsh government gives the effectiveness of sprinklers per different accommodation type: houses of single or multiple occupancies, flats and care homes. Values for fatality, injury and property reduction are given in the ranges 43% - 100%, 50% - 80%, 84% - 95% respectively [28]. NFPA did another research project that provides data on reduction in fatalities and property damage on the US experience with automatic extinguishing systems based on fire statistics in the period 2003-2007. Estimated reduction in fatalities and property damage are given for several building types, but there is no category for car parks. It is assumed that the category “all public assembly” with a 100% reduction in civilian death and 56% in property is the most appropriate one [29].

There was also a study carried out in New Zealand, which evaluated sprinkler effectiveness from fire incident reports between 2001 and 2010. From statistics, it was found that sprinkler system operated in 69% of total reported fires in sprinkled buildings, out of this number was effective in 76%. This study also highlights various sources of uncertainty in fire investigation reports, which influences data interpretation. Therefore, this study suggests that the usefulness of such incident reports for analysing sprinkler effectiveness is limited [30].

There are limited examples in the literature on fire tests that were specifically performed to assess sprinkler effectiveness in car parks. In the aforementioned BRE study on car parks, some experimental tests also included sprinklers. Tests showed that, where sprinklers were present, the fire did not spread beyond the initially ignited vehicle [1]. BRE tests with the staking system showed that fire from the lower car reached the bottom of the upper car before sprinklers were activated. Once activated, the sprinkler system contained the fire within this involved region [31]. Another experimental work on examining sprinklers' performance in a car park was done by collaboration between Belgian companies Fire Engineering Solutions Ghent, Cegelec Fire Solutions and Ghent University. This study was carried out in 2018 in response to new stricter guidelines from Belgian authorities (refer to Section 1.3), and in total 60 large scale tests were carried out. This research is confidential, and therefore, only some overall results were published. It has been experimentally shown that sprinklers are effective in controlling the fire, particularly for small car parks connected to the water main. For large car parks combination of sprinklers and limited SHC gives the best performance. Besides, it was demonstrated that reduced sprinkler water discharge density is also sufficient, but no details were provided on the exact reduction configuration [32] [33].

There are several concerns about installing a sprinkler system in car parks. First of all, it should be pointed out that “sprinklers are effective in controlling fire development, but not for extinguishing the fire within a vehicle” [14]. This means that the fire still develops inside, but does not spread to the outside, given discharge rate is sufficient. There is also a concern that spilt petrol may flow over sprinkler water and thus enhance fire spread by creating a pool of burning fuel. For that reason, the design of the car park should accommodate drains for sprinkler water, or the car park floor should have a slope. Another point to address is that when sprinkler water is released into a hot burning environment, it turns into steam, and this fogging effect may impede visibility for firefighters. One suggestion can be to use mechanical ventilation to remove steam [14]. However, previously mentioned large scale tests from Belgian companies have shown that visibility remained intact via handheld thermal imaging cameras, even after sprinkler activation [32]. Furthermore, not only for car parks, , in but in general, maintenance of sprinklers must not be neglected [19] [20]. To have an effective suppression system, it is important to address all these points of concern in the car park design.

As far as potential water damage from the sprinkler system is concerned, from residential sprinkler studies, it is claimed that the probability of accidental sprinkler activation because of manufacturing defect is 1 in 16 million [34]. London Fire Brigade also states that the same scope of work by sprinkler system requires 15 times less water than the one from firefighting hoses [35]. Due to the low likelihood of accidental activation and relatively smaller water usage compared to the fire and rescue service, the aspect of water damage was not further studied.

From tests identified in the literature it can be concluded that there is a potential benefit from an automatic sprinkler system installed in car parks. It is also believed that installation of the sprinkler system in closed car parks may be more reasonable, as mentioned before, due to higher temperatures, larger risks of incapacitation and potential danger from concrete spalling in such type of construction [14]. It should be emphasized that all presented experimental tests and studies were done in test conditions with a particular set up. This set up may not be the same in a real fire scenario. For example, one of the complications can be if a vehicle or another item in a car park, where a fire is initiated, are located near the wall or corner. In this case, fire development will have another pattern with greater temperatures due to lower air entrainment. Moreover, some tests were done more than ten years ago, meaning the fire behaviour of recent car models is not captured.

Overall, it can be seen that the sprinkler system is not 100% reliable and effective; and evaluation of system effectiveness is associated with various uncertainties. However, based on previous research there is a reduction in the number of fatalities, injuries and property damage in sprinkled buildings. This means that this system can positively affect life safety and property protection aspects, but the whole fire protection strategy should not solely rely on it, and all other required measures should be in place. Available tests on sprinkler performance in car parks have revealed that sprinklers can effectively control fire and prevent fire spread. It is also crucial to remember that the available data and car park tests cannot fully represent real-case scenarios, especially modern car industry changes.

1.5 Cost-Benefit Analysis (CBA) and J-value

In fire safety engineering the main goal and subsequent main acceptance criteria is that an adequate level of safety is achieved. However, what is meant by an "adequate level of safety" is not explicitly quantified. It does not pose an issue for traditional buildings because of years of collected experience and various past examples. Therefore, they rely on deterministic evaluations and follow prescriptive regulations. Considering the rapid development of new technologies, the prescriptive approach is not valid 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. ALARP criterion is related to society's capacity to pay and includes some form of CBA [36] [37] [38]. Such an evidence-based approach is used in this work to assess the cost-effectiveness of the sprinkler system installation in car parks.

CBA is a type of analysis that shows the relationship between investment costs for a new safety system implementation and benefits that this system can potentially provide. It is evident that if the costs of the new system outweigh its benefits, overall, such a system is not beneficial for society. Given limited resources, in this case it is better to allocate money somewhere else. In order to carry out CBA, it is necessary to know associated costs and benefits in monetary form. The cost of the system comprises typically installation and maintenance, which can be directly estimated; while benefits are mainly expressed through a reduction in fatalities, injuries and property damage. Reduction in fatalities is not easy to quantify in monetary form. Previously, the value of statistical life (VSL) or value of preventable fatality (VPF) was widely used to quantify the potential benefit of a safety system [39]. However, there are debates about how to quantify human life and whether human life can be exchanged for money [40] [41], as well as questions on the validity of VPF [39].

There is another method, which puts the focus not on the value of human life but on risk reduction measures. It is Life Quality Index (LQI). LQI solves the problem without putting pressure 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. Using LQI, it is possible to identify the maximum investment cost that society is willing to pay (SWTP) for the risk reduction measure. This criterion is then the one to assess whether the new safety system is financially justified. One of the CBA methodologies, which is based on LQI and SWTP and can be applicable to fire safety engineering, is a J-value assessment [36]. The J-value methodology allows making an objective decision based on principles of maximising societal benefits. At the end single value is obtained. 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 [36]. Calculation details of the J-value are presented in Chapter 2, based on the recent work by Hopkin et al. [36][40].

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 [42].

1.6 Problem statement, aims and objectives

Given recent major car park fires and modern changes in the car and car park industry, it is important to consider possible fire safety measures to overcome new potential risks. As discussed above, one of the solutions discussed in this thesis is the installation of automatic sprinkler systems in car parks. However, the installation of any additional measure is associated with costs. To make an objective decision, a quantitative evidence-based approach is required. Quantification in fire safety engineering is a challenge [43], and from the literature review only one CBA for installing sprinklers in car parks was identified, namely the one carried out in 2004 in New Zealand. Another concern is with the monetary expression of human fatalities in such type of analysis. Therefore, in this work, the feasibility of installing sprinklers in car parks is assessed using the J-value methodology, which is based on LQI and SWTP principles. This work primarily can benefit people associated with policy making and development of guidance documents. Potentially, engineering consultancies, car park owners and other interested bodies can take an advantage of this work during their decision-making stage.

In this research, assessment is made only for sprinkler system; other fire protection systems are not considered. The evaluation 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 [44]. 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 research examines conventional parking technology and vehicles that use ICE. 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.

This research aims to conduct the J-value analysis to evaluate whether the installation of a sprinkler system is a cost-effective solution for car parks. Given the lack of data for car parks and lack of quantification in the field of fire safety engineering, a secondary aim is to build a background for future calculations and indicate gaps and limitations, where more research is needed.

To accomplish these aims, the following objectives are established as necessary:

- Review existing literature on the fire safety of car parks to understand current knowledge and assumptions, modern changes in this field and to what extent they affect traditional believes
- Review car park fire safety regulations and guidance for some selected countries and discuss their relevance for the current work
- Review the J-value methodology and identify input parameters that need to be gathered for the current study
- Collect input data for the selected analysis parameters
- Conduct the J-value assessment based on gathered data and determine whether the sprinkler installation is economically beneficial for car parks
- Evaluate the obtained results and identify areas where more research is needed

This thesis consists of five chapters. Chapter 1 gives background information on previous car park tests, modern changes in cars and car parks, general information on the sprinkler system, sprinkler effectiveness, and a justification of the chosen CBA methodology. More detailed information about the J-value methodology with corresponding calculation procedure is provided in Chapter 2. Then, Chapter 3 presents the significant amount of input data that was gathered as part of the study. The data was gathered from various sources and based on collected information, scenarios for analysis were identified. Results of J-value analysis for all selected scenarios are presented in Chapter 4, which also contains a discussion of results, sensitivity analysis and outlines limitations of conducted research. Chapter 5 presents conclusions and recommendations for the future work.

2. METHODOLOGY

2.1 Life Quality Index (LQI)

LQI is a tool to evaluate whether decisions concerning life safety and health are effective and reasonable. The main principle behind LQI is that long lifetime and good health is the most important value for society and individuals [45]. LQI is expressed as

$$Q = G^q X \tag{1}$$

where G is GDP per capita (£/year/person), q is a measure for work-life balance, and X is life expectancy (years). From previous studies, it was found that the work-life balance parameter (q) is 0.15 for France, 0.17 for Germany, 0.19 for Canada, 0.22 for the US and 0.18 for the UK [46].

From Eq.1 it can be seen that investment costs are exchanged for the risk reduction, which is expressed through life expectancy. However, it is essential to remember that goods and services, including risk reduction measures, available for society today are more valuable than those you cannot use right away and instead have to wait [47]. To account for this preference in present benefit over future one, discounting needs to be taken into consideration. In health-related aspects, like life expectancy, it is typical to have a discount rate in the range of 1-4% [45].

2.2 Societal Capacity to Commit Resources (SCCR)

When the potential effect of the safety system has been considered, it is assumed that after implementation new value of LQI (Q') will be obtained:

$$Q' = Q + \Delta Q = (G + \Delta G)^q (X + \Delta X) \tag{2}$$

This expression can also be written as:

$$Q + \Delta Q = G^q (1 + \frac{\Delta G}{G})^q (X_d + \Delta X_d) \tag{3}$$

When changes in GDP and life expectancy are small, Eq.3 can be reduced to [47]:

$$\frac{\Delta Q}{Q} = q\frac{\Delta G}{G} + \frac{\Delta X}{X} \tag{4}$$

For the safety system to be justified, a change in LQI ($\Delta Q/Q$) must be equal or greater than zero. This is known as “LQI net benefit criterion”. To find out what is the maximum investment cost that society is ready to pay for the proposed safety system, ΔQ is equated to zero:

$$q\frac{\Delta G}{G} + \frac{\Delta X}{X} = 0 \;\rightarrow\; -\Delta G = \frac{1}{q}G\frac{\Delta X}{X} = -\delta D_f \tag{5}$$

where $-\delta D_f$ is the maximum per capita investment, which leads to societal benefit [36].

In Eq.5 parameters G and q can be estimated for a particular safety scheme, whereas a change in life expectancy ($\Delta X/X$) is challenging to estimate. Therefore $\Delta X/X$ has been considered to be proportional to the change of mortality rate d_m and the proportionality constant C_x specific for a given demographic profile:

$$\frac{\Delta X}{X} \approx -C_x d_m = -C_x\frac{\Delta f}{N} \tag{6}$$

where Δf is the change in the annual expected number of fatalities due to the proposed safety scheme, N is population size. This expression for $\Delta X/X$ from Eq.6, can be substituted to Eq.5 and result in:

$$-\delta D_f \approx -\frac{G}{q}\frac{C_x\Delta f}{N} \tag{7}$$

This can be further simplified by taking G as a total GDP by multiplying to N, then N cancels out, and Δf can be taken as -1 assuming one fatality. As a result, SWTP or Societal Capacity to Commit Resources (SCCR) can be obtained:

$$SCCR \approx \frac{GC_x}{q} \tag{8}$$

As noted by Hopkin et al. [40], the term "SCCR" is used since it refers to societal limited resources instead of "willingness", that can be treated subjectively. SCCR represents the limit when the safety investment is societally effective [40].

2.3 Judgement Value (J-value)

As mentioned earlier, cost-benefit analysis is a ratio between investment cost and potential benefits of the proposed scheme. Using LQI benefits are represented through risk reduction. Therefore, J-value can be expressed as:

$$J = \frac{C}{\Delta D} \tag{9}$$

where C corresponds to total investment costs (£/year) for a particular safety system and ΔD for monetary valuation of risk reduction. ΔD can be written as ΔD_f as it was used for deriving SCCR, then by using previously derived SCCR based on LQI Eq.9 can be rewritten as:

$$J = \frac{C}{\Delta D_f} = \frac{q\,C}{G\,C_x \Delta f} = \frac{C}{SCCR\ \cdot \Delta f} = \frac{C}{SCCR\ \cdot \lambda_{ig} \cdot N \cdot (\lambda_{f,0} - \lambda_{f,1})} \tag{10}$$

Here reduction in annual expected fatalities (Δf) is expressed through λ_{ig}- annual fire occurrence rate (1/year), N - number of exposed people, $\lambda_{f,0}$ and $\lambda_{f,1}$- probability of fatality per person as a result of fire before and after implementation [40].

2.4 Other safety benefits

All the previous calculations were based on the risk reduction in a fire-induced fatality. However, the implementation of a new safety system may also result in a reduction in injury and property damage. To account for that, the previously denoted ΔD will not consist only from ΔD_f (change in fatality), but also from ΔD_i (change in injury rate) and ΔD_d (change in material damage):

$$\Delta D = \Delta D_f + \Delta D_i + \Delta D_d \tag{11}$$

Precise estimation of injury is challenging since the exact nature of the injury is not known. Therefore, the average cost per injury is taken as for a typical injury, resulting in:

$$\Delta D_i = N\Delta_i\zeta_i = N\lambda_{ig}(\lambda_{i,0} - \lambda_{i,1})\zeta_i \qquad (12)$$

where Δ_i is a reduction in injury rate due to fire (1/person/year), ζ_i is the average cost per injury for typical injury (£/injury), $\lambda_{i,0}$ and $\lambda_{i,1}$ are the probability of a person having injury before and after implementation of safety system (1/fire). It should be mentioned that Eq.12 focuses on the effect on the rate of injury, irrespective of what kind of injury.

Using the same approach, an expression for the change in material damage per fire can be derived:

$$\Delta D_d = \lambda_{ig}\left(\Delta\zeta_{d,0} - \Delta\zeta_{d,1}\right) \qquad (13)$$

where $\Delta\zeta_{d,0}$ and $\Delta\zeta_{d,1}$ are expected material damage before and after the introduction of the new system (£/fire) [36].

Taking into account change in injury rate and material damage, J-value will transform to:

$$J_{fi,T} = \frac{C}{\Delta D_f + \Delta D_i + \Delta D_d} = \\ = \frac{C}{SCCR \cdot \lambda_{ig} \cdot N \cdot (\lambda_{f,0} - \lambda_{f,1}) + N\lambda_{ig}(\lambda_{i,0} - \lambda_{i,1})\zeta_i + \lambda_{ig}\left(\Delta\zeta_{d,0} - \Delta\zeta_{d,1}\right)} \qquad (14)$$

2.5 Discounting

As discussed earlier, when future costs and benefits are considered, preference for the present values needs to be addressed. Discounting is also required to have one common reference point, especially when different parameters are expressed with different time scale. One way is to use annualised values with a continuous discount rate (γ) [36]. For the benefits, discounted value is expressed as:

$$\Delta D_{\gamma} = \frac{\Delta D}{\gamma}(1 - e^{-\gamma L}) = \frac{\Delta D_f + \Delta D_i + \Delta D_d}{\gamma}(1 - e^{-\gamma L}) \tag{15}$$

2.6 Costs

The implementation cost of sprinkler system consists from upfront investment costs (C_0), such as cost of the whole installation, and further ongoing annual costs over a lifetime (m), such as maintenance, with a discount rate. Therefore, the total cost can be expressed as:

$$C_{\gamma} = C_0 + m_{\gamma} \tag{16}$$

$$m_{\gamma} = \sum_{t=1}^{L} \frac{m}{(1+\gamma)^t} \tag{17}$$

where L is the lifetime and γ is the discount rate.

The final formula of the J-value with discounted costs and benefits then transforms to:

$$J_{fi,T} = \frac{C}{\Delta D} = \frac{C_0 + m_{\gamma}}{\Delta D_{\gamma}} = \frac{(C_0 + \sum_{t=1}^{L} \frac{m}{(1+\gamma)^t}) \cdot \gamma}{\left(\Delta D_f + \Delta D_i + \Delta D_d\right) \cdot (1 - e^{-\gamma L})} =$$

$$= \frac{(C_0 + \sum_{t=1}^{L} \frac{m}{(1+\gamma)^t}) \cdot \gamma}{(1 - e^{-\gamma L}) \cdot (SCCR \cdot \lambda_{ig} \cdot N \cdot (\lambda_{f,0} - \lambda_{f,1}) + N \cdot \lambda_{ig} \cdot (\lambda_{i,0} - \lambda_{i,1}) \cdot \zeta_i + \lambda_{ig} \cdot \left(\Delta\zeta_{d,0} - \Delta\zeta_{d,1}\right))} \tag{18}$$

3. INPUT DATA

For the J-value assessment of sprinkler system in car parks based on the methodology described in Chapter 2, input parameters need to be established, as detailed in Table 2:

Table 2: List of input parameters required for the J-value assessment

Input parameter	Symbol	Unit
GDP per capita	G	£/person/year
Demographic constant	C_x	years
Work-life balance parameter	q	-
Discount rate	γ	-
Fatalities per fire before implementation	$N\lambda_{f,0}$	fatalities/fire
Fatalities per fire after implementation	$N\lambda_{f,1}$	fatalities/fire
Average cost per severe injury	ζS_i	£/injury
Average cost per slight injury	ζs_i	£/injury
Severe injuries per fire before implementation	$N\lambda_{Si,0}$	injuries/fire
Severe injuries per fire after implementation	$N\lambda_{Si,1}$	injuries/fire
Slight injuries per fire before implementation	$N\lambda_{si,0}$	injuries/fire
Slight injuries per fire after implementation	$N\lambda_{si,1}$	injuries/fire
Annual fire occurrence rate	λ_{ig}	fires/year/car park
Cost of damage before implementation	$\Delta\zeta_{d,0}$	£/fire
Cost of damage after implementation	$\Delta\zeta_{d,1}$	£/fire
Upfront cost per m^2	c_0	£/m^2
Annual maintenance cost	m	£/year
System lifetime	L	years

Overall, input parameters were gathered for nine scenarios presented in Table 3. Due to the fact that car parks vary in size and statistical data does not reflect it, where possible, most of the input parameters were established per m^2. Therefore, the choice of the actual size of a car park for the base scenario is not critical. Average size was chosen, based on an average number of parking slots in “Park Mark" accredited car parks (357) [48] and the UK standard space for one slot (2.4m by 4.8 m for a car) [49], that give a value of a bit more than 4000 m^2. Furthermore, since no details are present in fire statistics regarding type of cars and parking technology, traditional ICE cars and conventional parking systems are assumed for all scenarios. Where necessary, all values were converted to GBP based on OECD currency exchange [50] and an account for inflation was also made [51].

Table 3: Description of the scenarios considered in the current study

Scenario	Description	Dataset	Source
"UK All"	All parking types	1994-2005	BRE [1]
"UK MSCP"	Only MSCP	1994-2005	BRE [1]
"England All"	All parking types	2010-2020	The UK Home Office [52]
"England MSCP"	Only MSCP	2010-2020	The UK Home Office [52]
"England Underground"	Only underground car parks	2010-2020	The UK Home Office [52]
"England Other"	Other car parks, as described in Chapter 3.3	2010-2020	The UK Home Office [52]
"Scotland All"	All parking types	2009-2020	Scottish Fire and Rescue Service [53]
"Wales All"	All parking types	2009-2020	StatsWales [54]
"US All"	All parking types	2014-2018	NFPA Research Foundation [14]

It is important to remember that assessment can be made on different levels and from different points of view, such as individual, organization, industry or the entire society. Based on that choice, an outcome to the same question might be different. Various economic factors also play a role [52]. This assessment of sprinkler system installation in car parks is carried out on a societal level.

3.1 Discount rate and system lifetime

When establishing an assessment, like the installation of sprinkler in car parks, it is necessary to agree on a system lifetime. In the Eurocode 0 (Basis of structural design) in Table 2.1, design working life for buildings and other common structures is given as 50 years. It is assumed that the lifetime of a sprinkler system is the same as the lifetime of the structure. The same assumption was used in the previous sprinkler CBA for New Zealand car parks [42]. Therefore, 50 years is further used as a system lifetime.

The importance of discounting when evaluating future benefits and costs of risk reduction measures were discussed in Chapter 2. Fisher [53] describes that there are societal (γ_S) and market (γ_M) discount rates. A societal discount rate is used for both future cost and future life-saving benefits since acceptance criteria come from societal interests and need of future generations is taken into account. HM Treasury suggests this value for risk reduction measures with a lifetime between 31-75 years to be 3% [54]. The societal discount rate is used for all parameters except demographic constant (C_x). For C_x a market discount rate is used because "future life years are discounted as a proxy for future individual consumption" [53]. C_x can be derived from ISO2394:2015, that provides values for 2%, 3% and 4% discount rates [55]. Taking into account that and $\gamma_M > \gamma_S$ [53], the market discount rate was taken as 4%.

3.2 Societal Capacity to Commit Resources (SCCR)

The aforementioned SCCR can be estimated through GDP, demographic constant and work-life balance parameter. GDP per capita both for the UK [56] and the US [57] were taken for the middle year of corresponding available fire statistical datasets. The work-life balance parameter (q) for the UK was found to be 0.18 and 0.22 for the US from previous studies [46]. Demographic constant (C_x) was derived from ISO 2394 standard. ISO 2394 provides SWTP values for selected countries based on their GDP in 2008. It should be noted that there are two mortality regimes: π and Δ regimes. In the former, mortality change is proportional to the age distribution, while in the latter, change in mortality uniformly distributed over all ages [58]. The Δ regime is mostly applicable since risk reduction measures, including sprinklers, typically affect everyone irrespective of age. Therefore, by taking q=0.18 and SWTP Δ regime with a 4% discount rate from Table G.2 [55], the demographic constant was derived to be 17.2 years for the UK and 13.1 years for the US. The summary of inputs and final SCCR values are presented in Table 4. Note that the same SCCR value was used for all three UK countries.

Table 4: Inputs and final SCCR values for different datasets

Dataset period	GDP per capita G, £/person/year	Work-life balance parameter q	Demographic constant C_x, years	$SCCR$, £
1994-2005 (UK)	23580 (2000)	0.18	17.2	2253200
2009/2010-2020 (UK)	27521 (2015)	0.18	17.2	2629784
2014-2018 (US)	38944 (2016)	0.22	13.1	2318938

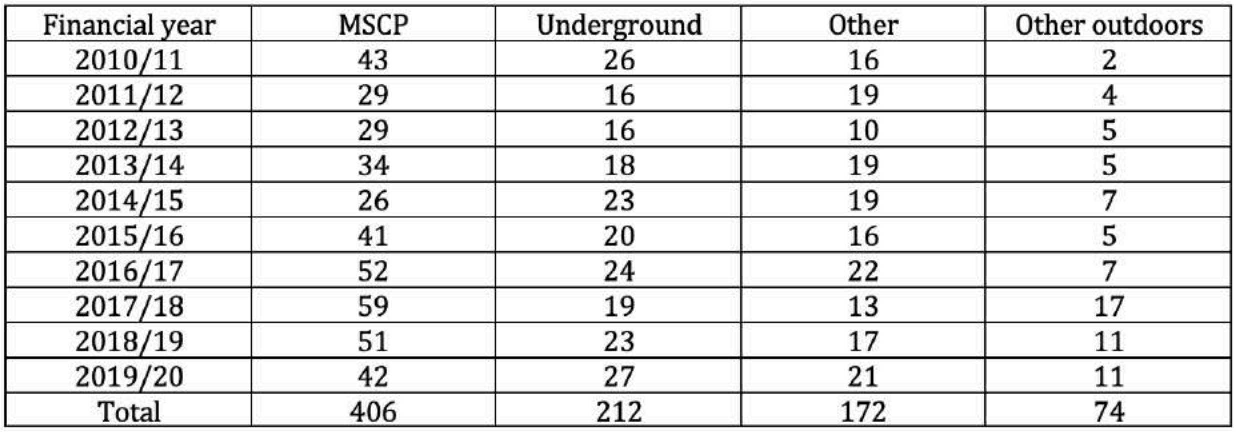
3.3 Fire statistics in car parks (before system implementation)

Fire statistics for England can be found on the official government website [2]. In the category non-dwelling fires, there are several building types presented. However, no specific information is available for car parks. It might be in the sub-category “unspecified”, or “other public buildings”, or “private non-residential buildings”, but there are no further details [2]. Unlike England, fire statistics for Scotland have a separate subdivision for car parks. Between 2009 and 2020, there were overall 94 fires reported in car parks, which gives the frequency of 8.55 fires per year. There were no fatalities and one injury reported [59]. Fire statistics for Wales also contains details for car parks fires, but the information is incomplete. 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 (7 fires): no fatalities and one injured person [60]. Considering the general trend of a small number of injuries in car parks, the same as for Scotland, one injured person in 11 years was assumed. Since there is no information on the degree of injury, given only one injury both in Scotland and Wales, it was 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 MSCP. From 1994 to 2005, there were 2138 MSCP fires with an annual frequency of 178 fires per year, 2 fatalities and 39 injuries [1]. The severity level of injuries was not indicated in this work. Based on England 2010/2020 ad-hoc data presented in Table 6, it was assumed that there is the same proportion between slight and severe injuries, accounting for 90% and 10% overall and 100% and 0% for MSCP, respectively.

As was mentioned earlier, statistics for England does not contain separate information on car park fires. The UK Home Office Fire Statistics Department was contacted to get this data. They shared information on ad-hoc data posted on 11th February 2021 [61], which contains information on car park fire statistics for England between 2010 and 2020. Details on the number of car park fires in different parking types and casualties can be seen in Table 5 and Table 6, respectively. There were overall 790 fires in car parks during these ten years, and if to include the category "other outdoors" - 864 fires. It should be pointed out that data in the category "other outdoor" means that the term "car park" appeared in the Incident Reporting System as free-filled additional information. Therefore, out of these 74 fires, some might not have taken place in a car park, and at the same time, some outdoor car parks fires probably were not captured [61]. Due to the fact that further information on casualties and property damage was not provided for this category, those 74 fires will not be further considered in the analysis. Fire frequency is therefore 79 fires in car parks annually, with approximately half taking place in MSCP. It should also be noted that data is given for three types of car park structures: MSCP, underground and other. Since what belongs 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.

Table 5: Number of fires in car parks attended by fire and rescue services per car park type, England 2010-2020 [61]



Financial year	MSCP	Underground	Other	Other outdoors
2010/11	43	26	16	2
2011/12	29	16	19	4
2012/13	29	16	10	5
2013/14	34	18	19	5
2014/15	26	23	19	7
2015/16	41	20	16	5
2016/17	52	24	22	7
2017/18	59	19	13	17
2018/19	51	23	17	11
2019/20	42	27	21	11
Total	406	212	172	74

As far as casualties are concerned, there was only one fire-related fatality between 2010 and 2020, and 20 non-fatal casualties, half taking place in the MSCP fire, as detailed in Table 6. Note that no data is available for the earlier mentioned category "other outdoor". These non-fatal casualties can be subdivided into four types: precautionary checks, first aid treatment, severe and slight hospital treatments. Here first aid is meant at the scene, and precautionary check is a recommendation by anyone to attend hospital or doctor [61]. Only hospital treatment is considered further in the assessment because this is the one that is likely to involve significant costs. It can be seen that overall there were ten casualties that required hospital treatment, one severe and nine slight.

Table 6: Total number of non-fatal and fatal casualties in car park fires attended by fire and rescue services, England 2010-2020 [61]

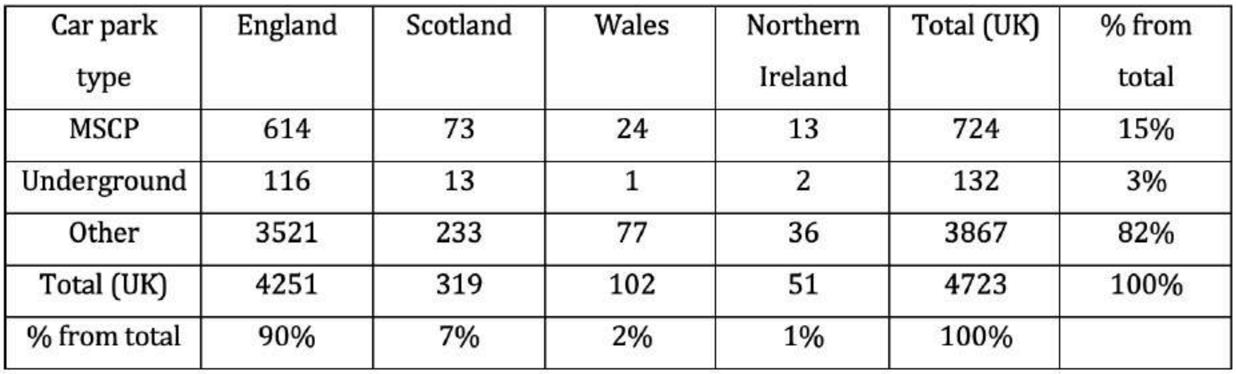
	MSCP	Underground	Other	Total
Hospital treatment - severe	0	0	1	1
Hospital treatment - slight	3	4	2	9
First aid treatment	3	0	0	3
Precautionary checks	4	3	0	7
Total non-fatal casualties	10	7	3	20
Fire-related fatalities	1	0	0	1

It should be remembered that fire statistics contain information only about incidents that fire and rescue service attended. Moreover, accuracy and completeness cannot be guaranteed since information is filled by a human, and it is not the main task of the fire and rescue service [62].

Gathered statistical data could not be directly used for analysis because to apply the J-value methodology, all inputs need to be expressed with the specific units described in Chapter 2. For that purpose, information on the number of 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) has been contacted for the UK context. As per their estimations, overall, there are between 23 000 to 26 000 public car parks in the UK [48]. The average of 24 500 is used for further calculations in this study. Note that this information is valid only for public car parks, and it is only an estimate. As Kelvin Reynolds, BPA Director of Corporate and Public Affairs, has mentioned, “no one knows (number of car parks) for certain as it has never been researched” [48]. It is also assumed that this average value applies for both the period between 1994 - 2005 and 2010-2020, given the lack of more specific information.

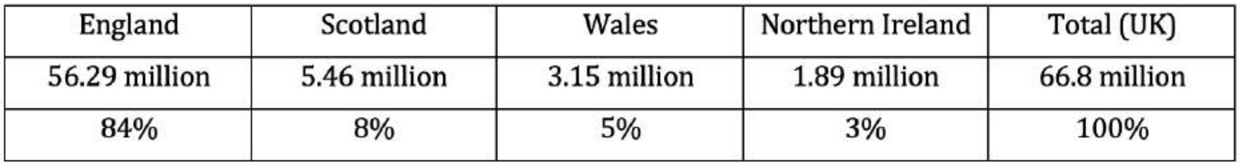
To use collected UK fire statistical data for J-value calculation, information on the proportion between different car parks and between different countries within the UK is required. There is no organized database on all cark parks, but some details are available for the accredited ones that hold the “Park Mark” Award. “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”, details can be found on the official website [63]. BPA shared the latest (2020) information on “Park Mark” car parks (total 4723) [48], but this data required further manual processing to correspond to earlier mentioned fire statistics. For example, information about “Park Mark" car parks is not provided per UK country; instead, city or county is mentioned. Therefore, using this information, and sometimes an internet search where no information about the location was given, the country location of each car park was found. This allows to make J-value analysis separately for England, Scotland and Wales. Furthermore, in the file provided by BPA the physical type of almost all “Park Mark” car parks is shown. Those are MSCP, lift operated, rooftop, surface, surface rural, surface urban and underground. Since the fire statistics in England have only three categories: MSCP, underground and other, information was filtered in the same way, and all types except MSCP and underground were placed together as category “other”. In this way, J-value analysis can be done for different car park types in England. Considering these manipulations with data that were required for J-value calculations, the summary of “Park Mark” car parks can be seen in Table 7. It is noticeable that most car parks are located in England and the car park category “other” dominate in the UK.

Table 7: Statistics on "Park Mark" accredited car parks in the UK per country and per car park type in 2020 based on BPA data [48]



Car park type	England	Scotland	Wales	Northern Ireland	Total (UK)	% from total
MSCP	614	73	24	13	724	15%
Underground	116	13	1	2	132	3%
Other	3521	233	77	36	3867	82%
Total (UK)	4251	319	102	51	4723	100%
% from total	90%	7%	2%	1%	100%	

Table 8: Population of the UK countries and their percentage from the total in 2019 [64]

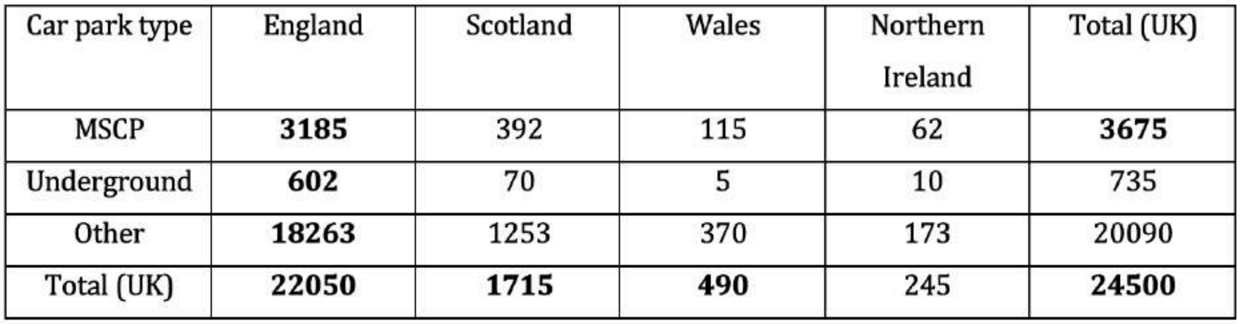


England	Scotland	Wales	Northern Ireland	Total (UK)
56.29 million	5.46 million	3.15 million	1.89 million	66.8 million
84%	8%	5%	3%	100%

Based on the information on "Park Mark" car parks, it is assumed that the data can be extrapolated to all other UK car parks; therefore percentages are presented in Table 7. In terms of the proportion of car parks between the UK countries, such assumption is reasonable since the ratio in the population is similar. From Table 8, one can see that distribution of the UK population between England, Scotland, Wales and Northern Ireland is 84%, 8%, 5% and 3%, respectively, that correspond to the accredited car parks distribution: 90%, 7%, 2% and 1%. In one of the BPA reports, it was stated that there are over 4 000 MSCP in the UK [65], which out of the assumed average 24 500 car parks, constitutes 16%. This value also corresponds to the 15% of "Park Mark" car parks in Table 7. Therefore, considering "Park Mark" accredited car parks data and observed tendency, the same proportions are applied for all other car parks. Final values used in the analysis on the number of car parks per type and per UK country are shown in

Table 9. In bold are values that are actually used in the analysis; no corresponding fire statistics were found for other values.

Table 9: Number of car parks in the UK per type and per country



Car park type	England	Scotland	Wales	Northern Ireland	Total (UK)
MSCP	**3185**	392	115	62	**3675**
Underground	**602**	70	5	10	735
Other	**18263**	1253	370	173	20090
Total (UK)	**22050**	**1715**	**490**	245	**24500**

As far as the US fire statistics are concerned, on the website of the US Fire Administration, information is present on fire statistics per different fire location [66]. However, car parks are not presented as a separate property type; instead, car parks are mentioned inside other categories. In the "Non-residential building fire" report, they are present inside the "storage" category (commercial parking for buses and tracks) and inside "detached garages" (private garages) [13]. In the "Outdoor fires" report, parking areas are mentioned with other outdoor places in the "outside or special property" category [67]. Given such statistical representation, it was challenging to figure out data that belongs to car park fires particularly. Although some statistical data was mentioned in the NFPA research, this data was further used. In the NFPA report it is stated 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 [7]. It is unclear what parking types "commercial parking garages" involve, but given no other alternatives, was assumed to be the same car park definition as given in Chapter 0. Provided no details on injury types, the ratio of slight and severe injuries was assumed to be the same as for England dataset. Since the number of car parks in the US was not found, this value was estimated based on the population ratio between the UK and the US, assuming that the number of car parks correlates with the number of people living in the country. From Table 8, the UK population was taken as 66.8 million, and for the same year 2019 in the US this value was 328.3 million [68]. The proportion of the population between these two countries is almost five, therefore based on the number of car parks in the UK (24500), the US value of 122500 has been assumed.

Regarding the Belgian context, by contacting the Belgian statistical department [69] it was found that there is a lack of systematically collected fire statistical data for car parks. Only a few figures were established based on personal communication with Prof. Jan de Saedeleer (Director Fire Prevention at the Ministry of Internal Affairs), namely the annual fire occurrence rates in underground car parks, which on average were 17.2 fires per year between 2016 and 2019 [70]. However, with this data alone and no details on casualties and property damage, further J-value assessment cannot be done for the Belgian context.

Table 10: Fire occurrence, fatalities and injuries before sprinkler system implementation based on collected fire statistics

	Annual fire occurrence rate	Fatalities per fire	Severe injuries per fire	Slight injuries per fire
Scenario	$\lambda_{i,g}$, fires/year/car park	$N\lambda_{f,0}$, fatalities/fire	$N\lambda_{Si,0}$ injuries/fire	$N\lambda_{si,0}$ 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

By combining statistics on fires and the number of car parks, final input values on fire occurrence, fatalities and injuries before sprinkler system implementation are shown in Table 10. It is important to remember that the UK fire statistics are from the Incident

Reporting System, 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 were found, it is assumed that all car parks are not equipped with sprinklers. In the BPA “Park Mark" list [48], information on whether sprinklers are fitted or not is also not given. However, such case might be present. In addition, previously mentioned limitations of the US data need to be considered. Overall, data was obtained for nine scenarios: “UK All”, “UK MSCP”, “England All”, “England MSCP”, “England Underground” and “England Other”, “Scotland All”, “Wales All” and “US All”. This data cannot be directly compared due to country specifics, different time intervals, population size and other possible factors. Further analysis on some inputs that are directly linked with results is presented in Chapter 4.

3.4 Cost per injury

There can be various types of fire injuries after a fire accident, from minor, that can be treated on the spot to major, that involves several months in hospital. Also, quantification of the burn injury involves health effects and other aspects such as loss of work or psychological trauma [71]. Thus, it was challenging to evaluate an individual injury, and an average was therefore used instead.

The value for the cost of injury was taken from the UK Department of Transport (DoT) that publishes data for road accidents [72]. 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 accessing safety measures [39]. However, the cost of injury does not raise ethical problems, unlike the cost of human life [41]. 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 were used, respectively. For the datasets, where the proportion between slight and severe injuries is not given, the same relation as for England 2010-2020 ad-hoc data was assumed. This value is 90% slight and 10% severe hospital treatment for all car parks and 100% and

0% for MSCP, respectively. It was assumed that the same values are applicable for the US scenario due to lack of data.

3.5 Cost of property damage

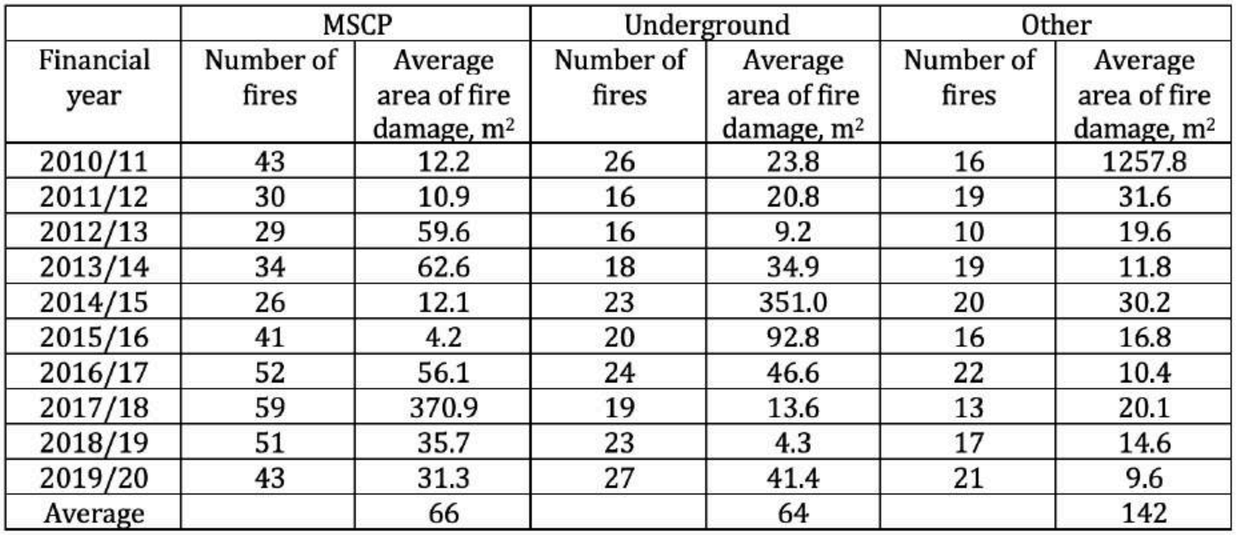
In general, property damage can be either direct or indirect. Direct property loss is due to physical contact with fire, while indirect is a consequential loss, usually associated with a business interruption. The latter usually is less than 25% of direct losses. As per a study carried out by NFPA, this proportion varies from 0 to 65%, depending on the property type. Car parks were not explicitly mentioned there, but it can be assumed to be also 10% as was indicated for residential, storage and special structure properties. If, as a result of a fire, business is closed, then the impact of indirect losses is higher. However, quantification of indirect property damage is a complex issue since various economic factors play a role. Research by the UK Home Office has found that, except for specific industries, fires do not cause indirect losses in terms of national economy perspective. If to look from the private sector perspective, then indirect losses can be calculated using the formula:

$$IL = c\,(DL)^b \tag{19}$$

where DL is direct losses, c and b are constants that can be found in Table 79.3 in SFPE Handbook Chapter 79 [52]. Since the given assessment is carried out from a societal perspective, indirect damage losses are not considered in the model.

Estimation of direct property damage in the UK is 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 [73]. Data was provided for the years 2010-2020 for England, the same period as fire occurrence ad-hoc data. Note that those values are average for given years, and there is no description of how the damaged area was classified. It can be a complete structural collapse or a minor impact from smoke. Therefore, such data does not give a complete picture of property damage, but this is the only information that was available.

Table 11: Average extent of damage (m^2) in car park fires attended by fire and rescue services, England 2010-2020 [73]



	MSCP		Underground		Other	
Financial year	Number of fires	Average area of fire damage, m^2	Number of fires	Average area of fire damage, m^2	Number of fires	Average area of fire damage, m^2
2010/11	43	12.2	26	23.8	16	1257.8
2011/12	30	10.9	16	20.8	19	31.6
2012/13	29	59.6	16	9.2	10	19.6
2013/14	34	62.6	18	34.9	19	11.8
2014/15	26	12.1	23	351.0	20	30.2
2015/16	41	4.2	20	92.8	16	16.8
2016/17	52	56.1	24	46.6	22	10.4
2017/18	59	370.9	19	13.6	13	20.1
2018/19	51	35.7	23	4.3	17	14.6
2019/20	43	31.3	27	41.4	21	9.6
Average		66		64		142

As seen in Estimation of direct property damage in the UK is 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 [73]. Data was provided for the years 2010-2020 for England, the same period as fire occurrence ad-hoc data. Note that those values are average for given years, and there is no description of how the damaged area was classified. It can be a complete structural collapse or a minor impact from smoke. Therefore, such data does not give a complete picture of property damage, but this is the only information that was available.

Table 11, 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 [73]. Indeed, it can be 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 12. Accounting for the impact of large damage values on overall average values, alternative result, excluding such events was also calculated. Therefore, certain years are excluded for MSCP (2017/18), underground (2014/15), and other car park types (2010/2011). From Table 12, it can be seen that difference between the cases, when all events considered and specific year excluded, is significant, accounting for 90.6 m^2 and 27.3 m^2, respectively.

Table 12: 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 were considered. Statista.com provides figures for the average cost per m^2 for building MSCP in the UK per region for 2016 and 2018 [74]. Provided numbers differ depending on either it is above or below ground construction. The average cost across all regions for underground MSCP is £897 per m^2 and £609 per m^2 for surface MSCP. Since the statistical data for damaged area does not mention whether MSCP is above or below the ground, the average of £753 per m^2 has been used for the calculations. It has also been assumed that given numbers are applicable for other car park types. The values are summarised in Table 13.

The final result of the total average cost of direct property damage in car parks can be seen in Table 14, which is based on average damage area and construction costs. This method is only an approximate estimation since there can be different types of damage, and construction costs can be overestimated for minor ones. Due to the significant influence of certain years with large damage area, as a base scenario further in the analysis results with exclusion are used.

Table 13: Average building cost for a car park in the UK based on data for MSCP for 2016 and 2018 [74]

	MSCP	Underground car park	Other type of car park	Average
Building costs per m^2	£753	£897	£609	£753

Table 14: 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*

Because fire destroys not only the building itself, but also the contents (in this case - cars), the cost for property damage should take into account the damaged cars. Information on destroyed cars was found only for the 1994-2005 UK MSCP dataset, and the value is 1298 cars [1]. The cost of damage per car was roughly estimated from the Kings Dock fire since information about car insurance payments was reported in the news as £20 million [75] [76]. Due to a lack of data about such financial information, this value was assumed to be credible. The total amount of destroyed cars was 1150 [6], therefore per car is around £17391. For the 1994-2005 dataset, the average cost is then 1298/2138*17391 = £10558 per fire, assuming the same number of cars damaged for the 2010-2020 dataset this value is £16030 per fire. This value is not included in the base scenario but in the sensitivity analysis.

For the US dataset, in the same NFPA research, direct property damage for the period 2014-2018 was estimated to be $22.8 million. During this time 1858 car park fires were reported. Therefore, the property damage per fire is $12271 or £9093 [7].

In this assessment, 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 also should be noted that since analysis is done from the societal view, who pays the cost, in this case, 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. [41], insurance is a transfer of money from one societal group to another, and since CBA is a societal indicator, insurance does not affect CBA.

3.6 Sprinkler effect (after system implementation)

As was previously mentioned, a sprinkler system can improve the overall fire safety of the building. This needs to be quantified to carry out the J-value assessment. Since benefits are expressed through reduced fatalities, injuries and property damage in this research, sprinkler efficiency needs to be expressed through the same parameters. As was mentioned in Section 1.4, no previous tests were found that would have quantified the effectiveness of sprinklers, particularly in car parks. However, there is available data on residential and commercial sprinklers. It is clear that commercial studies are more relevant to car park building type rather than residential. Therefore, as a baseline, results from US experience with sprinklers were considered, assuming that category “all public assembly” with 100% reduction in civilian death and 56% in property damage [29]. In the previous sprinkler CBA for New Zealand car parks, the value of 85% was assumed for the property damage reduction [42]. The fact that sprinklers do not always operate also needs to be taken into account. Information on reliability was taken from Frank et al. because it gives a mean value that accounts for 94.7% [25]. Therefore, fatalities per fire ($N\lambda_{f,1}$) and the cost of damage ($\Delta\zeta_{d,1}$) after implementation were calculated as follows:

$$N\lambda_{f,1} = 0 * 0.947 = 0 \tag{20}$$

$$\Delta\zeta_{d,1} = (1 - 0.56) * 0.947 * \Delta\zeta_{d,0} = 0.42 * \Delta\zeta_{d,0} \tag{21}$$

Information on reduction of injuries was not found, neither specifically for car parks nor for commercial buildings. Therefore, 100% reduction, same as for fatalities, was considered for the base scenario. This assumption also allows for an assessment of the J-value when all injures are prevented. This value is studied further in the sensitivity analysis.

3.7 Cost of sprinkler system

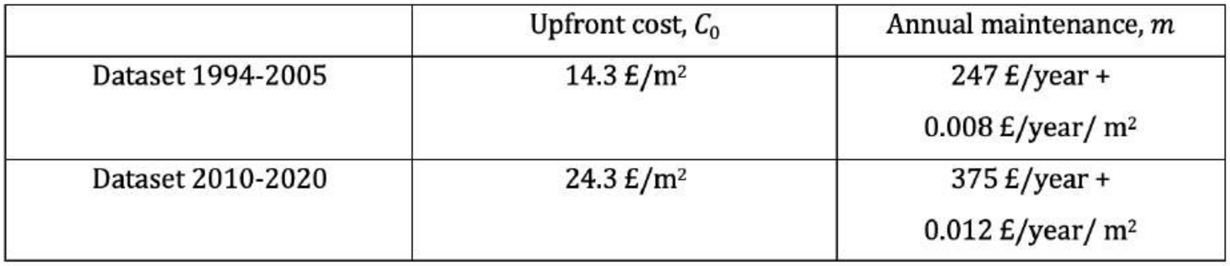
In general, various factors can affect the cost of the sprinkler system. Based on the US home sprinkler study, those are system requirements, extent of coverage, piping, source of water, permit, inspection and additional fees, system design type, foundation type and the existence of state-wide requirements [77]. 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 [38].

To get the approximate practical cost of a sprinkler system in car parks that includes upfront investment (C_0) and annual maintenance cost (m), visiting professor at Ghent University for Active Fire Protection I: Detection and Suppression Christian Gryspeert was consulted. Prof. Gryspeert gives the approximate installation cost of a sprinkler system in a car park as 32 euros / m^2, including pipes, sprinkler heads and mounting service. The cost of a water pump, including engineering, switchboard and approval, is additional 85000 euros. It should be emphasized that all these values are approximate and for simple car park layout, e.g. without ceiling beams and obstacles [78]. These values are given for the Belgium context and may not be the same for another region.

The total cost of sprinkler system installation can also be estimated from existing design projects. However, this kind of data is primarily private and not available to the general public. OFR Consultants got 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 [79]. Because most of the base scenarios are performed in the UK context, the value of £24.3/m^2 is used in the analysis as upfront installation cost (C_0).

The annual maintenance cost was taken from the New Zealand CBA 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, in that research [42]. Taking into account currency exchange rate and inflation, Table 15 summarises findings on sprinkler system cost. For the US scenario, the same installation and maintenance costs were assumed as for the UK ones.

Table 15: Upfront and annual maintenance costs of a sprinkler system



	Upfront cost, C_0	Annual maintenance, m
Dataset 1994-2005	14.3 £/m^2	247 £/year + 0.008 £/year/ m^2
Dataset 2010-2020	24.3 £/m^2	375 £/year + 0.012 £/year/ m^2

4. RESULTS AND DISCUSSION

The collected input data has allowed results to be obtained for nine scenarios, as shown in Table 3: “UK All”, “UK MSCP”, “England All”, “England MSCP”, “England Underground” and “England Other”, “Scotland All”, “Wales All” and “US All”. Since several input parameters use values based on estimations, a sensitivity analysis and “what-if” analysis have also been carried out.

Table 16 provides the summary of input parameters and derived quantities for the J-value calculation for the “England All” scenario. For the other eight scenarios one can refer to the Appendix B. Calculated J-value results are shown in Figure 4, which shows that the installation of a sprinkler system in car parks for all nine base scenarios was found to be not cost-beneficial since all J-values exceed unity. Out of all nine scenarios, sprinkler installation is the most beneficial for underground and MSCP. Between the two MSCP datasets, 1994-2005 and 2010-2020, the J-value is less for the older dataset. This can be explained by the relatively higher annual fire occurrence rate (refer to Figure 5). As far as underground car parks are concerned, the reasons for the relatively smaller J-value compared to the other scenarios are the more significant cost of damage (refer to Figure 10), which was derived from construction costs, and larger fire occurrence rate (refer to Figure 5).

Furthermore, Figure 4 shows that the largest J-value of 555 is calculated for England car park type “other”. As mentioned earlier, this category contains all car park types except underground and MSCP, 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 in Section 1.1, pose relatively fewer fire risks than closed ones. From Figure 5 it can be seen that the “England Other” scenario also has the lowest annual fire occurrence rate.

Table 16: Input parameters and derived values for the "England All" scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	27521
C_x	years	Demographic constant	17.2
q	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2629784
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0.0013
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	228029
ζs_i	£/injury	Average cost per slight injury	17579
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	0.0013
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	0
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.0114
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.0036
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	20557
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	8634
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	24.3
m	£/year	Annual maintenance cost	423
C_0	£	Upfront cost	97200
m_γ	£	Discounted maintenance cost over lifetime	10884
ΔD_f	£/year	Life preservation benefit	11.9
ΔD_i	£/year	Injury reduction benefit	1.8
ΔD_d	£/year	Damage reduction benefit	42.7
ΔD_γ	£	Total discounted benefits	1459
C_γ	£	Total discounted costs	108084

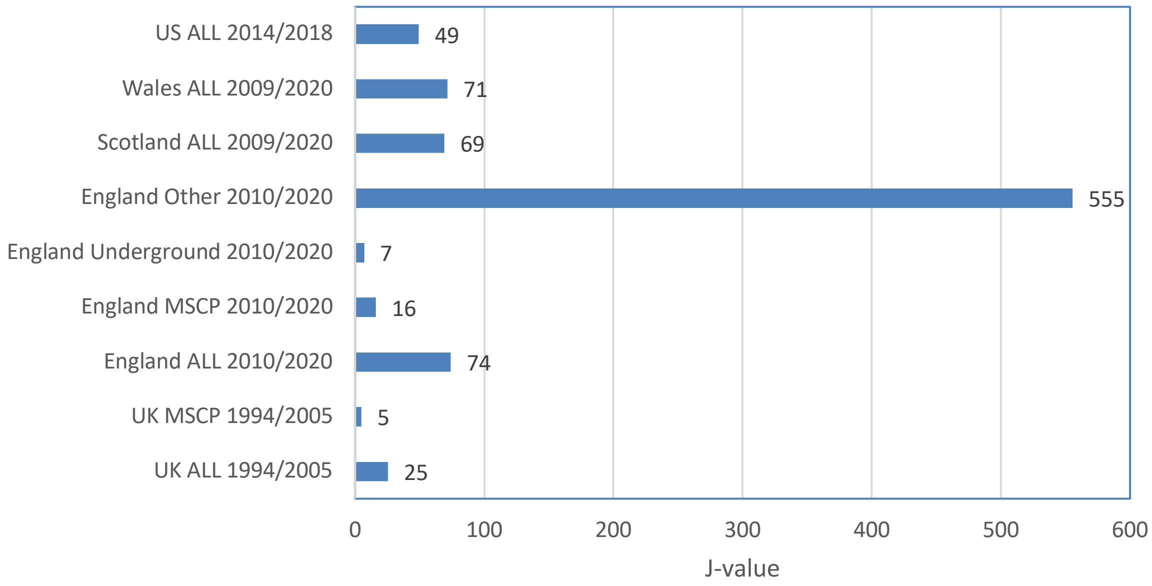


Figure 4: J-value results for all nine scenarios. A J-value of less than 1 is required in order for the fire safety investment to be cost-beneficial.

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 parks types separately. The fact that each car par 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 MSCP. From described earlier the US and Belgium regulations, it can be observed that a sprinkler system is required only for a particular car park configuration. However, behind code requirements may be other factors than CBA. Those factors were not studied in this work.

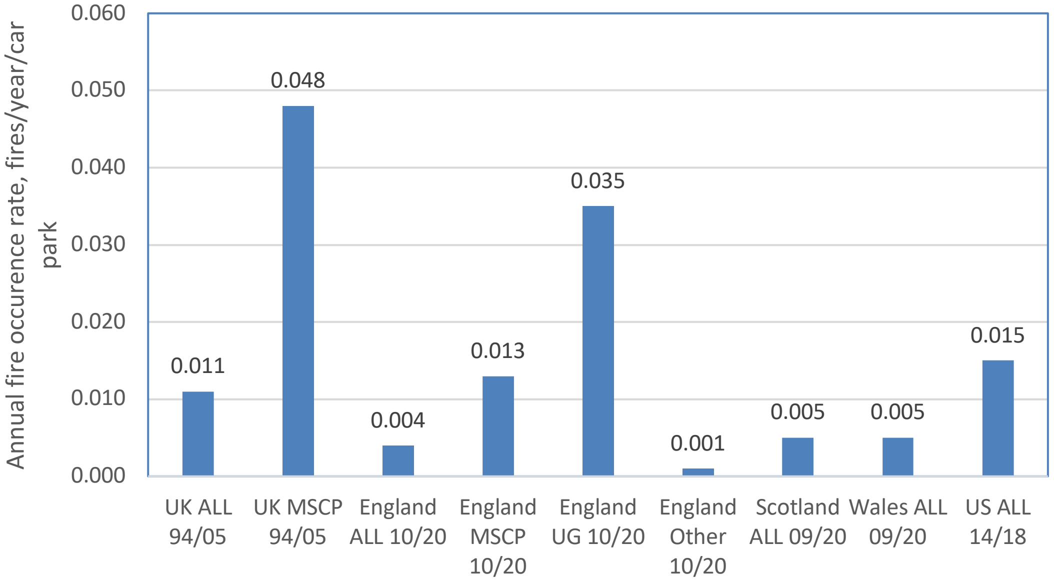


Figure 5: Annual fire occurrence rate for different types of car parks

The breakdown of benefits and costs is illustrated in Figure 6. The percentage here refers to the proportion out of the sum of costs and benefits. In another words, the sum of the numerator and denominator in the J-value formula. Since for all nine scenarios, the J-value is less than unity, it is expected that costs have the largest proportion. This value varies from 83% to almost 100%. Benefits constitute subsequently from almost 0% to a maximum of 17%, the maximum being logically for the scenario with the lowest J-value result and vice versa. As far as sprinkler system cost composition is concerned, since same data was used for all nine scenarios, similar to Table 15, Figure 7 distinguishes between two datasets, 1994-2005 and 2010-2020. It can be seen that the installation cost accounts for the largest part, 89% - 90% from total sprinkler system costs, whereas maintenance costs contribute 10% - 11%.

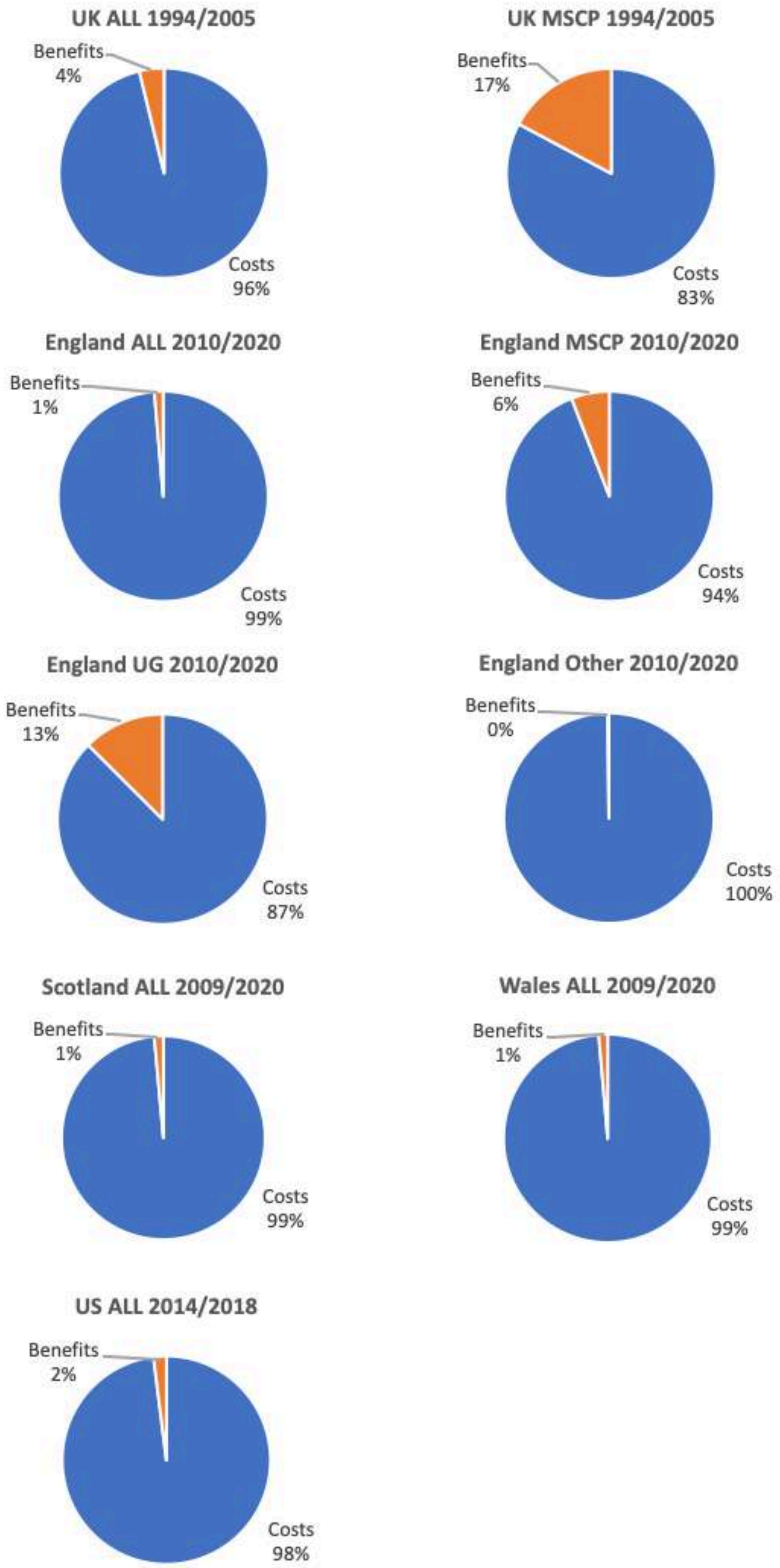


Figure 6: Breakdown of benefits and costs for all nine scenarios

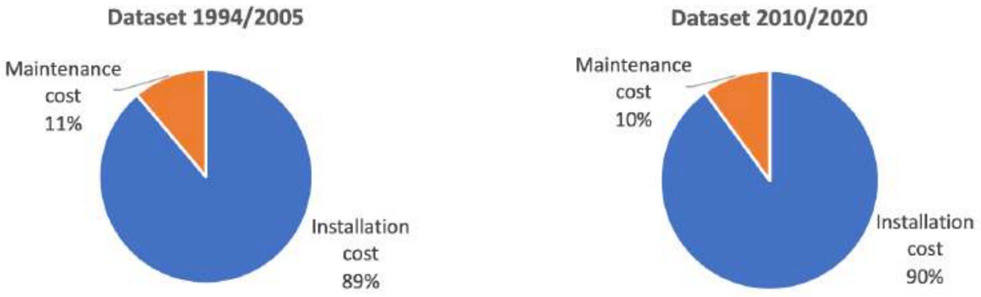
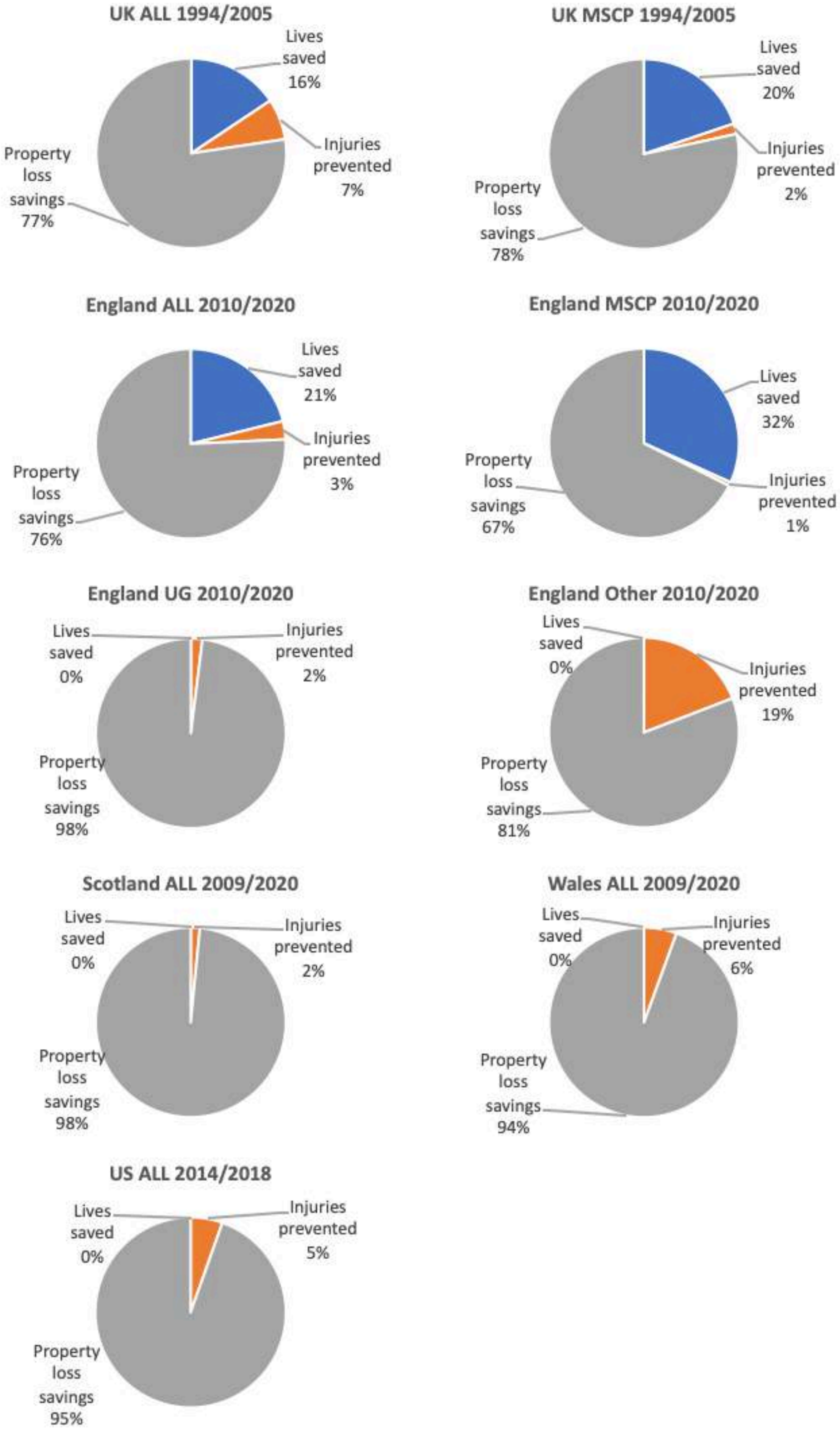


Figure 7: Sprinkler system cost composition for two datasets

As far as benefits are concerned, the J-value assessment has been performed both from life safety and property protection perspectives. Figure 8 shows the breakdown of assessed benefits: lives saved, injuries prevented and property loss savings. The benefit in property damage reduction significantly outweighs benefits in fatalities and injuries reductions for all nine scenarios, as illustrated in Figure 8. The proportion of property loss savings among other benefits ranges from 67% to 98%. 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. This seems to be logic, as discussed in Section 0, because people are not continually present in car parks. It is also can be seen that depending on casualty statistics (refer to Figure 9) 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 in fatality reduction. The greatest value associated with lives saved 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 9. 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 10).



UK ALL 1994/2005

UK MSCP 1994/2005

England ALL 2010/2020

England MSCP 2010/2020

England UG 2010/2020

England Other 2010/2020

Scotland ALL 2009/2020

Wales ALL 2009/2020

US ALL 2014/2018

Figure 8: Breakdown of benefits for all nine scenarios

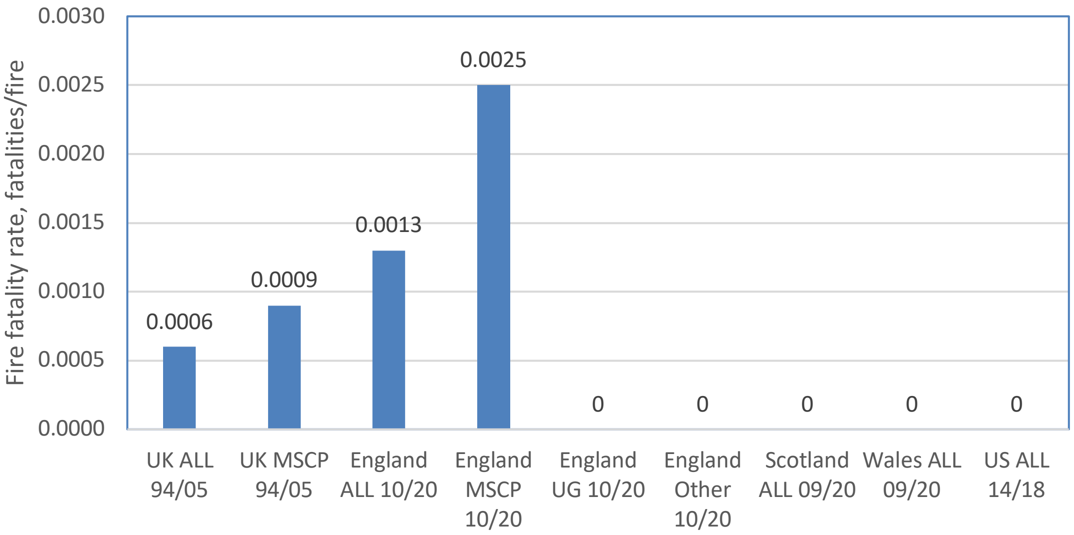


Figure 9: Fire fatality rate for each of the scenarios considered. Note that five of the scenarios have no history of fatalities.

Since the reduction in property damage plays the most important role among all benefits, it is worth looking closer at different estimated costs of damage. From Figure 10 it can be seen that the highest cost of damage directly correlates with the lowest J-value results, which is for "England Underground" and "England MSCP" scenarios. At the same time, the lowest cost of damage is for the US scenario. It should be remembered that the US cost was not estimated from average fire damage area and construction costs as for the other eight scenarios, but as readily available value from previous NFPA research [7]. The second-lowest cost of damage loss correlates with the highest J-value results, which was calculated for the "England Other" scenario.

It is necessary to point out that the "US All" scenario contains several shortcomings: approximate estimation of the number of car parks, the adoption of the same injury costs and sprinklers costs as for the UK scenarios. Even if this case contains several assumptions, the assessment has been made to obtain an approximate idea of the J-value for the country, where sprinklers are actually required for specific car park structures (refer to Section 1.3). It was found that the J-value for the presented US scenario is 49. Since in the NFPA88A [20] an automatic sprinkler system is required only for particular car parks configurations and J-value was calculated for all car parks in the US, 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.

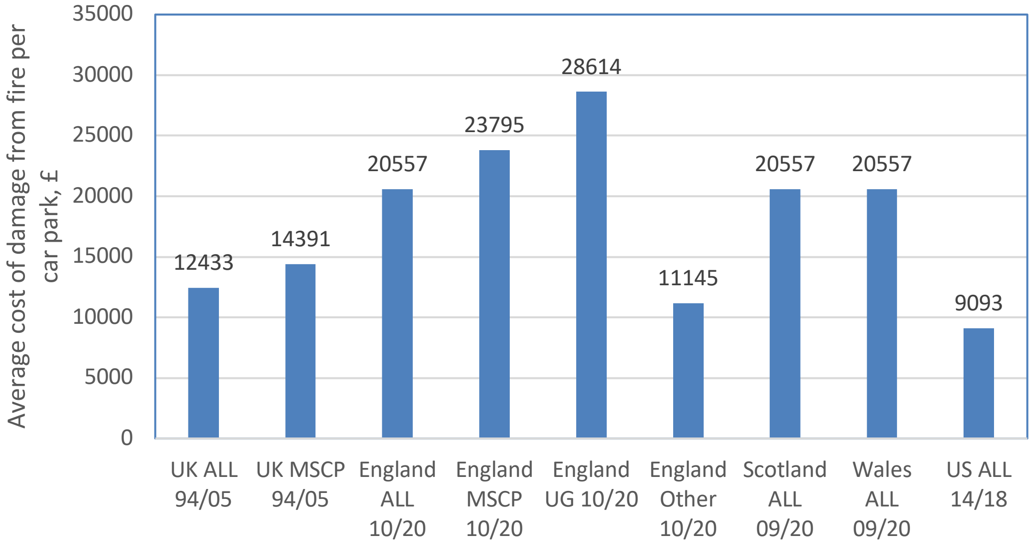
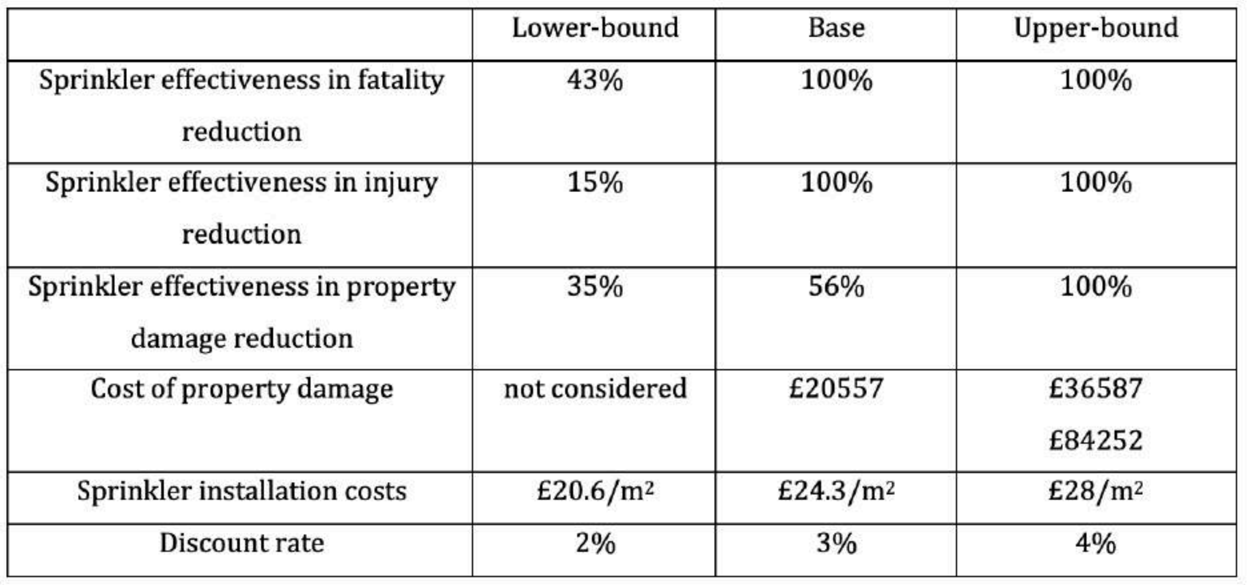


Figure 10: Average cost of fire damage per car park for each scenario

4.1 Sensitivity analysis for estimated parameters

It is clear that the results of the presented J-value assessment on the sprinkler system installation in car parks highly depends on the accuracy of input data. To be consistent with previous J-value studies in the field of fire safety engineering [80], a sensitivity analysis has been carried out for the parameters, where estimations and assumptions have been made. All these parameters are summarised in Table 17. Given that the same methodology has been applied for all nine base cases, sensitivity analysis is carried out for only one scenario, "England All", to observe an overall trend in the change of output result. In this scenario the calculated J-value was equal to 74.

Table 17: 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	£36587 £84252
Sprinkler installation costs	£20.6/m^2	£24.3/m^2	£28/m^2
Discount rate	2%	3%	4%

As mentioned earlier, there is no available data for sprinkler effectiveness in car parks. Therefore, ranges for sensitivity assessment were taken from two residential studies performed for Wales [27] [28] presented in Section 1.4. As a lower-bound value, from these two studies the lowest was taken to allow maximum variability: for the reduction in fatalities is then 43%, for injuries – 15% and for property damage – 35%. Because as base values 100% effectiveness was used both for fatalities and injuries, the same 100% is used for property damage as an upper-bound value. This allows to make an analysis of a case with the best possible sprinkler performance. From Figure 11 it can be seen that J-value can be reduced by 35% if sprinklers would be absolutely effective both in life safety and property protection aspects. If to use lower-bound values for sprinkler effectiveness, then J-value is increased by 66%. As expected, the more effective the sprinkler system is, the more beneficial it becomes to install it. However, even if sprinklers would be 100% effective, with given other input parameters, their installation is still not cost-effective since the J-value is greater than unity.

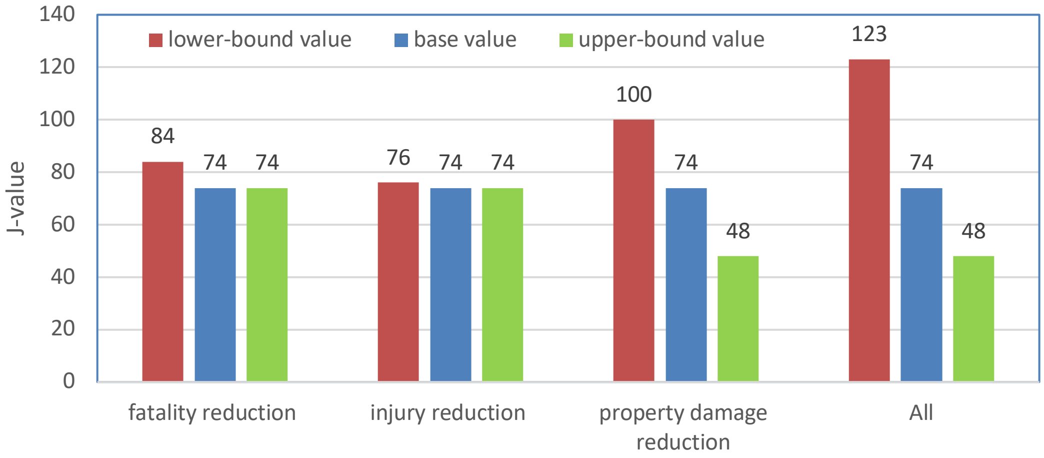


Figure 11: J-value sensitivity (fatality, injury and property damage) for varying sprinkler effectiveness. The lower- and upper-bound values are specified in Table 17.

As mentioned in Section 3.5, property loss costs were estimated without including events with large fire damage area. In addition, the cost of damaged cars was not included because the information was only available for the older dataset (1994-2005). If the analysis was to add the cost of damaged cars, then for the "England All" scenario, property loss before implementation becomes £36 587. Another possibility is to include events with extensive fire damage and the cost of damaged cars; then the value becomes £84 252. These two values were used as upper-bound estimations, the lower-bound value was not considered since with base parameters the J-value is already more than unity. Results of varying cost of damage can be seen in Table 18. As expected, the larger cost of damage in car park fire is, the smaller J-value will be and vice versa. For example, the cost of damage of £84 252, which is four times more than the base value, gives a 70% reduction in the J-value result. However, even for the scenarios with the lowest J-value, such an increase in the property damage cost does not bring J-value below unity.

Table 18: Sensitivity analysis results for varying cost of property damage

Cost of property damage	Base scenario (excluding large fire damage events)	Base scenario + cost of damaged cars	Including large fire damage events and damaged cars
J-value	74	47	22

Considering sprinkler installation costs, in Section 3.7 two values were obtained, for Belgium and the UK, and the latter was used as a base since not enough data was collected for Belgian scenario. Therefore, value for Belgian context is used in sensitivity analysis, which after currency conversion turns into £28/m^2. The lower-bound was found by mirroring the change, using the same increase/decrease step, which resulted in £20.6/m^2. Table 19 shows that the relation between change in the installation cost and the J-value output is proportional. The installation cost was increased and decreased by £3.7/m^2 and the J-value both increased and decreased by 10, which is 13.5% change. Note that the impact of the additional 85000 euros stated by Prof. Christian Gryspeert [78] was not assessed, because it is clear that such a substantial increase in the cost will lead to a larger J-value.

Table 19: Sensitivity analysis results for varying sprinkler installation cost

	£20.6/m^2	£24.3/m^2	£28/m^2
J-value	64	74	84

In the given J-value assessment, the discount rate of 3% was assumed based on guidance from HM Treasury [54]. However, in the ISO2394 SCCR is presented for 2%, 3% and 4% discount rates [55]. Therefore, sensitivity analysis was made for these possible values of the discount rate. From Table 20 it can be observed that a higher discount rate gives a higher J-value and vice versa. The impact is between 18 to 20%.

Table 20: Sensitivity analysis results for varying discount rate

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

Overall, sensitivity analysis has shown that some input parameters influence the output more, while some have less effect. One of the main conclusions is that even if sprinklers were 100% effective both in life safety and property protection aspects, the installation of sprinklers is still not financially feasible for car parks. It is important to point out that the accuracy of data and the choice of range plays a significant role and influence the outcome. If more information about car parks was present, the analysis could have been extended.

4.2 “What - if” analysis to obtain a cost-effective result

As discussed, there are some challenges with quantification given lack of organized data related to the topic of this report. In order to cover these gaps, the following “what-if” analysis was done. Another reason for including the “what-if” analysis is to provide a closer look at some variables that can be of societal interest. Those are the ones society have control and can affect: the car park area and sprinkler installation cost. Only the installation cost was considered, since as was discussed before, maintenance costs have less impact on total system costs (refer to Figure 7). It has been analysed what manipulations with these parameters are required for a sprinkler system to become cost-effective for car parks. Since the lowest J-values were found for “UK MSCP” 1994/2005 and “England Underground” 2010/2020 scenarios, analysis is made only for these two scenarios. It is clear that much larger changes in input parameters will be required for all other scenarios since the J-value is significantly higher. Note that only one change at a time was performed. The summary of parameters used for the “what-if” analysis with corresponding base values can be seen in Table 21.

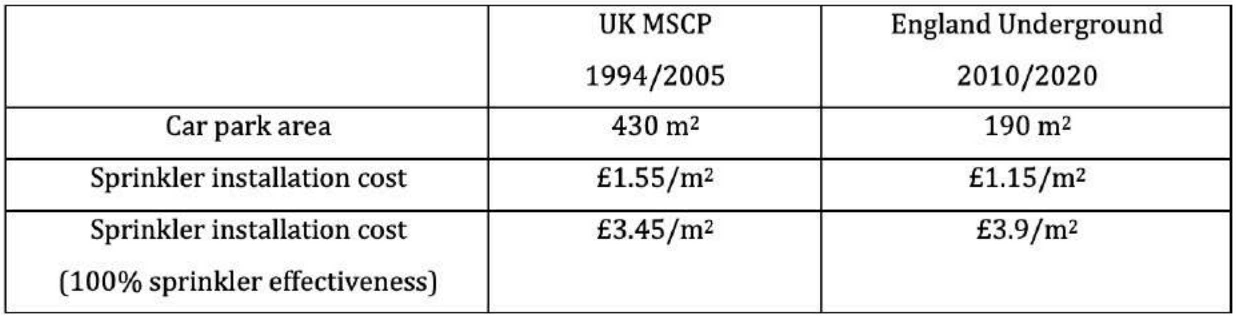
Table 21: Base values of parameters used for the “What-if” analysis

	UK MSCP 1994/2005	England Underground 2010/2020
Car park area	4 000 m^2	4 000 m^2
Sprinkler installation cost	£14.3/m^2	£24.3/m^2

In the assessment car park area of 4 000 m^2 was chosen based on the average size of “Park Mark" accredited car parks. By changing this value, it was found that with all other inputs remaining unchanged, J-value becomes unity for car park areas of 430 m^2 and 190 m^2 for “UK MSCP” and “England Underground” scenarios, respectively. Sprinkler installation becomes cost-effective for smaller car parks, because system installation cost is given per m^2 and subsequently linearly decreases as the size decreases. However, note that the cost of property damage did not change when the car park area decreased, because it was calculated based on average fire damage area statistics (Table 12) which has been assumed to be a fixed value and this also influenced the result. If statistics included the percentage of fire damage area out of 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 was studied as well. It has been found that, if all base parameters remain the same, the sprinkler installation cost should be around £1.5 ("UK MSCP") and £1.1 ("England Underground") per m^2 to make installation cost-effective. The latter is 20 times less than the baseline and it is clear that such values are difficult to imagine. Therefore, the same analysis was done, but assuming 100% sprinkler effectiveness both in reducing life safety consequences and property damage. The results are £3.45/m^2 and £3.9/m^2 for the "UK MSCP" and "England Underground" scenarios, respectively. The summary of the "what-if" analysis results can be seen in Table 22.

Table 22: Results of "what-if" analysis (J- value = 1)



	UK MSCP 1994/2005	England Underground 2010/2020
Car park area	430 m^2	190 m^2
Sprinkler installation cost	£1.55/m^2	£1.15/m^2
Sprinkler installation cost (100% sprinkler effectiveness)	£3.45/m^2	£3.9/m^2

The above presented manipulations for sprinkler system costs were done for the base car park area of 4000 m^2. The same analysis was done for the range of smaller car park areas: 500 m^2, 1000 m^2, 1500 m^2, 2000 m^2, 3000 m^2, to see the variation in the sprinkler installation cost. The evaluation was also made for two cases, base values and assuming 100% sprinkler effectiveness. Since two considered scenarios have similar outcomes, for simplicity, this analysis has been made only for the "England Underground" scenario. The results can be seen in Table 23. From this assessment, it can be concluded that with sprinklers been 100% effective, for small car parks of 500 m^2 and 1000 m^2 size, the maximum allowable system installation cost to obtain cost-effective result turns into more realistic values of £31.0/m^2 and £15.5/m^2, respectively.

Table 23: 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

4.3 Uncertainties and limitations

Results of the J-value assessment have shown that the installation of a sprinkler system in car parks is not a cost-effective investment from a societal point of view. However, it should be emphasised that the assessment is based on several assumptions and estimations due to the lack of systematically collected and organized data related to the fire safety of car parks. For example, injury costs in car parks are assumed to be similar to those in road accidents given by the UK DoT [72], which may not be necessarily true. Also, the proportion between slight and severe injuries are assumed to be the same for all scenarios, derived from English statistics [61], since no alternative data is available. The cost of property damage for all scenarios except the US was derived from two estimations: average fire damage area [73] and car park construction cost [74]. However, it needs to be emphasized that the degree of damage can be different from total collapse to minor superficial damage. Therefore, the average fire damage area alone cannot give a precise picture. The use of car park construction costs also needs to be assessed critically because it can be an overestimation for minor fire damages, as it includes the construction cost for a new structure.

Information for sprinkler effectiveness particularly for car parks was not found. Therefore, as a base value, data for public assemblies has been used [29], which may not be valid for parking structures. It is clear that more research is required on the effectiveness of sprinklers in car parks. Regarding sprinkler investments, the sprinkler installation cost was estimated from information obtained from OFR Consultants [79]. At the same time, maintenance cost was approximated from previous car park CBA, which was carried out for New Zealand context in 2004 [42]. Such approximations and estimations were made because no credible information or studies were found for installing sprinklers in car parks. Also, note that sprinkler costs obtained for the Belgian context are significantly larger, which also leaves space for further research.

It is also important to remember that fire statistical data is typically collected manually by the fire and rescue service. Therefore, accuracy and completeness cannot be guaranteed. The fact that some details, such as the extent of the fire damage, cars' power source and parking technology are not mentioned in fire statistics, several assumptions have to be made. In general, due to the absence of common terminology and organized data, used definitions of what is "car" and "car park" may not be the same in every context. In different studies those terms can have various meanings; this is also applicable for car park classification. Another limitation of this research is the fact that the J-value assessment for the Belgian context was not possible to perform due to the absence of fire statistics. Belgian and the US guidance were presented with the idea to compare J-values between countries where sprinklers are required for specific car park configuration (the US, Belgium) and where not (the UK). An attempt to make a calculation for the US context was made, but this scenario contains several shortcomings, as mentioned earlier.

It should be recalled that since selected scenarios have different time intervals and some information was obtained in foreign currency, data was adjusted accordingly using inflation and currency calculator. However, it is apparent that such an approach is not precise. Manual manipulations of "Park mark" data to fit collected fire statistical data also needs to be taken into account. Furthermore, the SCCR value was assumed to be the same for all UK countries because GDP was chosen for the whole UK and not for England, Scotland and Wales separately.

As was discussed earlier, as benefits only lives saved, injuries prevented, and property loss savings were assessed. Potential insurance premiums were not included since insurance is a transfer of money [41], and CBA is done from a societal view. It was also shown based on previous studies that from a societal perspective, fires do not cause indirect losses;

alternatively, another analysis from the point of view of industry or business owner can be done. Due to lack of data, it was challenging to quantify potential savings from environmental losses or emergency response. Moreover, the potential influence of car park fires on adjacent buildings and subsequent consequences were not addressed in this work. However, it is clear that fire and smoke from a car park can spread to surrounding buildings, causing property damage and posing a risk to life safety. The earlier presented example of a fire in Monica Wills House in Bristol [1] demonstrates that such a case can take place and lives can be lost.

It should be noted that some practical aspects of the sprinkler system were not discussed in this work. For example, as the most frequent reason for sprinkler failure is system shut-off [25], adequate maintenance procedures should be established. It is assumed that the relevant codes and practices will be consulted for further guidance. Also, possible external intervention or deliberate actions to disable the system were not considered in this work. In addition, account for the installation of a sprinkler system in regions where sprinkler pipework can be exposed to temperatures below zero was not made. In this case, additional insulation costs may be required, since the discussed sprinkler system is a wet type and water inside pipes can freeze. However, from previous studies it was found that malfunction of sprinklers is only in 2% of the cases due to freezing [25]. Other earlier mentioned concerns with installing sprinklers in car parks (Section 1.4), such as fogging effect, were not addressed in this work.

In the given assessment, as a possible fire protection solution, only a sprinkler system was evaluated. However, there are existing alternatives, like SHC. For example, one can observe in Belgian guidelines (refer to Section 1.3) that for some car park configurations, there is a choice between the installation of sprinklers and SHC. Another limitation is that assessment was made for traditional ICE cars and conventional parking systems. However, as indicated in Section 1.2, other modern changes, such as EVs and car stackers, may or may not influence the fire safety of car parks. In addition, new technologies and changes can emerge meanwhile. As noted by Spearpoint et al. [10], the future of vehicle transportation and thus car parking industry is “likely to continue to change”. It is clear that more research is needed in these areas to evaluate the influence of modern technologies on fire safety or car parks and how this will impact the J-value assessment.

5. SUMMARY AND CONCLUSIONS

Fires in car parks are relatively infrequent, and it appears that there is a somewhat established consensus that car parks have a low fire risk, primarily due to the low fire load and the low fire spread probability. However, modern changes in car and car park technologies, together with recent major car park fires such as the ones in Liverpool (UK) and Stavanger (Norway), have triggered the interest in installing sprinklers in car parks. Therefore, the aim of this work was to conduct a J-value analysis to evaluate the cost-effectiveness of the installation of a sprinkler system in car parks. The J-value was chosen among different CBA methodologies since it is based on the LQI and SWTP and not on the VSL or VPF. This allows a shift in the focus from the value of human life towards risk reduction measures that maximise societal benefits. Another merit of the J-value is that it acts as an objective indicator, which, if less than unity, indicates that the safety measure is cost-beneficial and vice versa.

From the literature review, it became clear that more research is required to assess the impact of modern technologies on the fire safety of car parks. The fact that statistics do not contain some details, such as the extent of fire damage, car power source and parking method, necessitated the use of several assumptions. Fire statistical data is also collected by humans and therefore, the accuracy of data cannot be guaranteed. Also, since there is no uniform and consistent terminology related to car parks, different interpretations may exist. Furthermore, there is no specific data on sprinkler effectiveness in car parks and the cost of property damage in car parks. Those were therefore based on estimations. In addition, the two collected figures for the system installation cost were considerably different, and the maintenance cost was taken from previous research. The impact of alternatively fuelled cars and modern parking methods was not included in this work due to the scarcity of data. Also, the fire spread from a car park to the adjacent buildings and consequences were not included in this work. The assessment also did not address other potential benefits from the sprinkler system and did not consider possible alternative fire safety measures apart from sprinklers.

Before conducting the J-value assessment, regulations of some selected countries were reviewed. This revealed that sprinklers are not required in car parks in the UK (England), whereas sprinklers are required for certain car park configurations in the US and Belgium. Therefore, it was aimed to conduct the analysis for both cases. To carry out J-value analysis, relevant input data was collected from various sources, such as the UK Home Office, Scottish Fire and Rescue Service, StatsWales, BRE, NFPA, and BPA. Overall, data was collected for nine scenarios: “UK All”, “UK MSCP”, “England All”, “England MSCP”, “England Underground” and “England Other”, “Scotland All”, “Wales All” and “US All”. The assessment was made both from life safety and property protection perspectives. Reduction in fatalities, injuries and property damage were considered as potential benefits after installing sprinklers. The analysis was made for the car park area of 4000 m^2 since it is the average size of “Park Mark” accredited car parks. However, the procedure can easily be applied to any other car park size.

The J-values for all 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. 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, based 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”, with a J-value of 555. Since “other” parking types infer to single-level surface car parks in this work, it was expected that sprinklers would not be feasible for such type of structures. It has also been found that the sprinkler installation in car parks is mainly the property protection benefit because property loss savings constitute from 67% to 98% from total benefits, depending on the scenario. The proportion of lives saved and injuries prevented benefits is subsequently smaller. This is mainly due to the relatively low fire casualty rate in such type of structures. For five out of nine scenarios, this value is zero. This appears logical since car parks are designed only for a periodic presence of people. Another finding is that the assessment needs to treat different car park types separately due to specifics of each parking type, such as different fire statistics and construction costs. The fact that Belgium and the US codes require sprinklers only for specific car park configurations, also supports this conclusion. However, a background for regulations can be other factors rather than CBA. Those factors were not considered in this work.

A sensitivity analysis revealed that even if sprinkler effectiveness would be 100% both in life safety and property protection aspects, the installation of sprinklers is still not cost-effective for car parks. They can become cost-effective only if the car park size or installation cost are significantly reduced, namely by a factor of 20. It is clear that such a reduction that leads to installation costs of £1-1.5/m^2 is unrealistic. The optimum combination for one of the scenarios with the lowest J-value is 100% sprinkler effectiveness and a car park area of 500 m^2 or 1000 m^2, leading to £31.0/m^2 or £15.5/m^2 installation costs, respectively, whereas the baseline cost is £24.3/m^2.

Overall, based on collected input data and considered scenarios for the current analysis, the sprinkler system installation was found to be not cost-effective for car parks. However, to make more solid conclusions based on this type of analysis, further research of the topic is required due to the lack of data and new emerging technologies in the car and car park industry.

5.1 Future work

There are several aspects that would be interesting to study in future work, as they have the potential to improve upon the current analysis. As mentioned, a J-value assessment is heavily dependent on the input data. Therefore, collection of more systematic, descriptive and detailed fire statistics for car parks would allow to make deeper and wider analysis, and possibly show the impact of existing modern technologies on car park fire safety. It would also be beneficial to repeat this assessment with more specific information on property loss savings and sprinkler system costs, as this would provide a more accurate assessment.

Furthermore, in the current analysis only reduction in fatalities, injuries and property damage were considered as benefits. Quantification of other benefits, and an evaluation of the influence of a car park fire on adjacent buildings is needed to have a more complete assessment. The latter is of particular interest since car parks can sometimes be a part of another structure, such as a residential high-rise building or a shopping mall. In this case, the fire safety of another building can be endangered due to the car park fire and this impact needs to be evaluated. It would also be beneficial to conduct analysis on sprinkler installation for a country where sprinklers are mandatory for some types of car parks in order to assess what role the J-value can potentially play in making decisions at a regulatory level.

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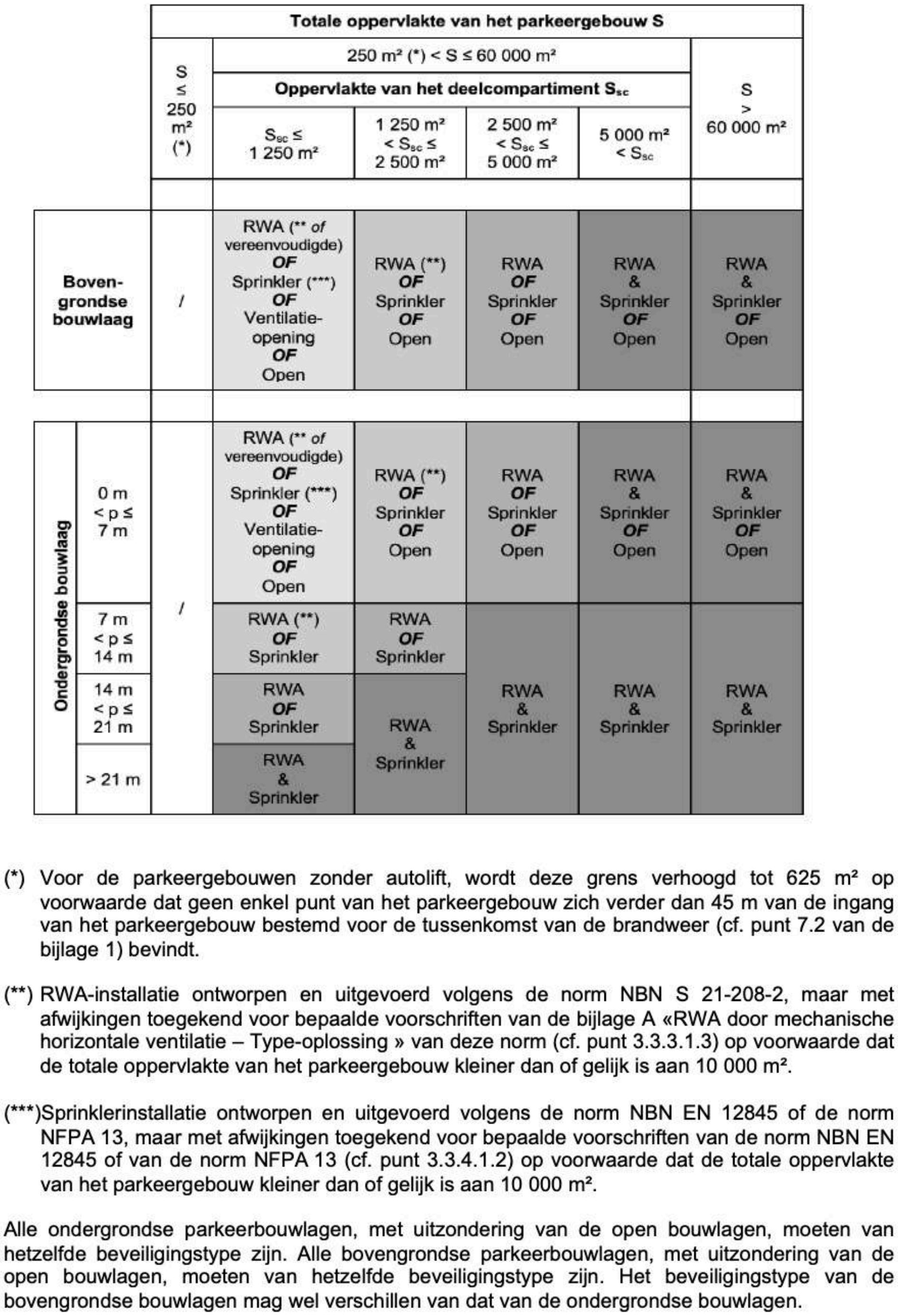
APPENDIX

A: Annex 7 of HR 1632 R3 (original Dutch version)



		Totale oppervlakte van het parkeergebouw S					
		S ≤ 250 m² (*)	250 m² (*) < S ≤ 60 000 m²				S > 60 000 m²
			Oppervlakte van het deelcompartiment S_{sc}				
			S_{sc} ≤ 1 250 m²	1 250 m² < S_{sc} ≤ 2 500 m²	2 500 m² < S_{sc} ≤ 5 000 m²	5 000 m² < S_{sc}	
Bovengrondse bouwlaag		/	RWA (** *of* vereenvoudigde) ***OF*** Sprinkler (***) ***OF*** Ventilatie-opening ***OF*** Open	RWA (**) ***OF*** Sprinkler ***OF*** Open	RWA ***OF*** Sprinkler ***OF*** Open	RWA & Sprinkler ***OF*** Open	RWA & Sprinkler ***OF*** Open
Ondergrondse bouwlaag	0 m < p ≤ 7 m	/	RWA (** *of* vereenvoudigde) ***OF*** Sprinkler (***) ***OF*** Ventilatie-opening ***OF*** Open	RWA (**) ***OF*** Sprinkler ***OF*** Open	RWA ***OF*** Sprinkler ***OF*** Open	RWA & Sprinkler ***OF*** Open	RWA & Sprinkler ***OF*** Open
	7 m < p ≤ 14 m		RWA (**) ***OF*** Sprinkler	RWA ***OF*** Sprinkler	RWA & Sprinkler	RWA & Sprinkler	RWA & Sprinkler
	14 m < p ≤ 21 m		RWA ***OF*** Sprinkler	RWA & Sprinkler			
	> 21 m		RWA & Sprinkler				

(*) Voor de parkeergebouwen zonder autolift, wordt deze grens verhoogd tot 625 m² op voorwaarde dat geen enkel punt van het parkeergebouw zich verder dan 45 m van de ingang van het parkeergebouw bestemd voor de tussenkomst van de brandweer (cf. punt 7.2 van de bijlage 1) bevindt.

(**) RWA-installatie ontworpen en uitgevoerd volgens de norm NBN S 21-208-2, maar met afwijkingen toegekend voor bepaalde voorschriften van de bijlage A «RWA door mechanische horizontale ventilatie – Type-oplossing » van deze norm (cf. punt 3.3.3.1.3) op voorwaarde dat de totale oppervlakte van het parkeergebouw kleiner dan of gelijk is aan 10 000 m².

(***)Sprinklerinstallatie ontworpen en uitgevoerd volgens de norm NBN EN 12845 of de norm NFPA 13, maar met afwijkingen toegekend voor bepaalde voorschriften van de norm NBN EN 12845 of van de norm NFPA 13 (cf. punt 3.3.4.1.2) op voorwaarde dat de totale oppervlakte van het parkeergebouw kleiner dan of gelijk is aan 10 000 m².

Alle ondergrondse parkeerbouwlagen, met uitzondering van de open bouwlagen, moeten van hetzelfde beveiligingstype zijn. Alle bovengrondse parkeerbouwlagen, met uitzondering van de open bouwlagen, moeten van hetzelfde beveiligingstype zijn. Het beveiligingstype van de bovengrondse bouwlagen mag wel verschillen van dat van de ondergrondse bouwlagen.

B1: Input parameters and derived values for the “UK All” scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	23580
C_x	years	Demographic constant	17.2
q	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2253200
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0.0006
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	134460
ζs_i	£/injury	Average cost per slight injury	10366
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	0.0029
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	0
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.0252
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.0105
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	12433
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	5222
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	14.3
m	£/year	Annual maintenance cost	279
C_0	£	Upfront cost	57200
m_γ	£	Discounted maintenance cost over lifetime	7179
ΔD_f	£/year	Life preservation benefit	15.3
ΔD_i	£/year	Injury reduction benefit	6.9
ΔD_d	£/year	Damage reduction benefit	75.9
ΔD_γ	£	Total discounted benefits	2541
C_γ	£	Total discounted costs	64379

B2: Input parameters and derived values for the “UK MSCP” scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	23580
C_x	years	Demographic constant	17.2
q	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2253200
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0.0009
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	N/A
ζs_i	£/injury	Average cost per slight injury	10366
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	N/A
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	N/A
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.0183
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.0484
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	14391
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	6044
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	14.3
m	£/year	Annual maintenance cost	279
C_0	£	Upfront cost	57200
m_γ	£	Discounted maintenance cost over lifetime	7179
ΔD_f	£/year	Life preservation benefit	102
ΔD_i	£/year	Injury reduction benefit	9.2
ΔD_d	£/year	Damage reduction benefit	404
ΔD_γ	£	Total discounted benefits	13353
C_γ	£	Total discounted costs	64379

B3: Input parameters and derived values for the “England MSCP” scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	27521
C_x	years	Demographic constant	17.2
q	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2629784
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0.0025
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	N/A
ζs_i	£/injury	Average cost per slight injury	17579
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	N/A
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	N/A
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.0074
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.0128
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	23795
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	9994
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	24.3
m	£/year	Annual maintenance cost	423
C_0	£	Upfront cost	97200
m_γ	£	Discounted maintenance cost over lifetime	10884
ΔD_f	£/year	Life preservation benefit	82.6
ΔD_i	£/year	Injury reduction benefit	1.7
ΔD_d	£/year	Damage reduction benefit	176
ΔD_γ	£	Total discounted benefits	6738
C_γ	£	Total discounted costs	108084

B4: Input parameters and derived values for the "England Underground" scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	27521
C_x	years	Demographic constant	17.2
q	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2629784
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	N/A
ζs_i	£/injury	Average cost per slight injury	17579
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	N/A
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	N/A
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.0189
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.0353
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	28614
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	12018
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	24.3
m	£/year	Annual maintenance cost	423
C_0	£	Upfront cost	97200
m_γ	£	Discounted maintenance cost over lifetime	10884
ΔD_f	£/year	Life preservation benefit	0
ΔD_i	£/year	Injury reduction benefit	11.7
ΔD_d	£/year	Damage reduction benefit	585
ΔD_γ	£	Total discounted benefits	15461
C_γ	£	Total discounted costs	108084

B5: Input parameters and derived values for the "England Other" scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	27521
C_x	years	Demographic constant	17.2
q	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2629784
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	228029
ζs_i	£/injury	Average cost per slight injury	17579
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	0.0058
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	0
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.0116
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.0009
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	11145
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	4681
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	24.3
m	£/year	Annual maintenance cost	423
C_0	£	Upfront cost	97200
m_γ	£	Discounted maintenance cost over lifetime	10884
ΔD_f	£/year	Life preservation benefit	0
ΔD_i	£/year	Injury reduction benefit	1.4
ΔD_d	£/year	Damage reduction benefit	6.1
ΔD_γ	£	Total discounted benefits	195
C_γ	£	Total discounted costs	108084

B6: Input parameters and derived values for the "Scotland All" scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	27521
C_x	years	Demographic constant	17.2
q	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2629784
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	N/A
ζs_i	£/injury	Average cost per slight injury	17579
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	N/A
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	N/A
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.0106
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.005
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	20557
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	8634
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	24.3
m	£/year	Annual maintenance cost	423
C_0	£	Upfront cost	97200
m_γ	£	Discounted maintenance cost over lifetime	10884
ΔD_f	£/year	Life preservation benefit	0
ΔD_i	£/year	Injury reduction benefit	0.9
ΔD_d	£/year	Damage reduction benefit	59.5
ΔD_γ	£	Total discounted benefits	1565
C_γ	£	Total discounted costs	108084

B7: Input parameters and derived values for the "Wales All" scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	27521
C_x	years	Demographic constant	17.2
q	-	Work-life balance parameter	0.18
SCCR	£	Societal Capacity to Commit Resources	2629784
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	N/A
ζs_i	£/injury	Average cost per slight injury	17579
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	N/A
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	N/A
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.04
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.0046
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	20557
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	8634
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	24.3
m	£/year	Annual maintenance cost	423
C_0	£	Upfront cost	97200
m_γ	£	Discounted maintenance cost over lifetime	10884
ΔD_f	£/year	Life preservation benefit	0
ΔD_i	£/year	Injury reduction benefit	3.3
ΔD_d	£/year	Damage reduction benefit	55.2
ΔD_γ	£	Total discounted benefits	1514
C_γ	£	Total discounted costs	108084

B8: Input parameters and derived values for the “US All” scenario

Symbol	Unit	Description	Value
G	£/person/year	GDP per capita	38944
C_x	years	Demographic constant	13.1
q	-	Work-life balance parameter	0.22
SCCR	£	Societal Capacity to Commit Resources	2318938
γ	-	Discount rate	0.03
L	years	System lifetime	50
$N\lambda_{f,0}$	fatalities/fire	Fatalities per fire before implementation	0
$N\lambda_{f,1}$	fatalities/fire	Fatalities per fire after implementation	0
ζS_i	£/injury	Average cost per severe injury	228029
ζs_i	£/injury	Average cost per slight injury	17579
$N\lambda_{Si,0}$	injuries/fire	Severe injuries per fire before implementation	0.0005
$N\lambda_{Si,1}$	injuries/fire	Severe injuries per fire after implementation	0
$N\lambda_{si,0}$	injuries/fire	Slight injuries per fire before implementation	0.0102
$N\lambda_{si,1}$	injuries/fire	Slight injuries per fire after implementation	0
λ_{ig}	fires/year/car park	Annual fire occurrence rate	0.0152
$\Delta\zeta_{d,0}$	£/fire	Cost of damage before implementation	9093
$\Delta\zeta_{d,1}$	£/fire	Cost of damage after implementation	3819
A	m^2	Car park area	4000
c_0	£/ m^2	Upfront cost per m^2	24.3
m	£/year	Annual maintenance cost	423
C_0	£	Upfront cost	97200
m_γ	£	Discounted maintenance cost over lifetime	10884
ΔD_f	£/year	Life preservation benefit	0
ΔD_i	£/year	Injury reduction benefit	4.6
ΔD_d	£/year	Damage reduction benefit	80
ΔD_γ	£	Total discounted benefits	2191
C_γ	£	Total discounted costs	108084