Fire spread in car parks

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Executive summary

In 2006 Communities and Local Government (CLG) Sustainable Buildings Division commissioned BRE to carry out a three year project titled Fire Spread in Car Parks.

The existing guidance for fire safety in car parks in England and Wales is in Approved Document B (Fire safety) to the Building Regulations in England and Wales (AD B). The basis for this guidance for fire safety strategies in car parks relates to fire initiation and fire growth involving cars whose designs are decades old. There has been increasing concern about the consequences of fires in car parks associated with modern car design (e.g. plastic fuel tanks) and how these fires may spread to other vehicles parked adjacently and nearby. This concern has been heightened by the entry into the market place of cars powered by alternative fuels such as LPG.

Fires in car parks are rare, and, although there have been few deaths or injuries recorded to date in the UK, there are concerns regarding new and emerging risks from modern cars and alternative fuels. There was a need to gather up-to-date information on fires involving cars in car parks in order that the current fire safety guidance could be reviewed and, if necessary, updated.

The overall aim of the project has therefore been to gather information on the nature of fires involving the current design of cars and to use this new knowledge as a basis, if necessary, for updating current guidance in AD B (and possibly other Approved Documents) on fire safety strategies for car parks.

This report describes the project, the findings and conclusions.

The project started with the formation of an Advisory Group, who represented a range of stakeholder interests. The programme of work has included a world wide literature review, laboratory tests on car materials, a review of UK fire statistics, computer modelling, and the series of eleven full-scale fire tests, burning a total of sixteen cars (some cars were used in more than one test). The main tests involved fires starting in a passenger compartment (with good ventilation - representing an arson attack) and examined fire spread between three cars in a mock-up car park rig under the BRE calorimeter (to examine the speed of fire spread and heat release rates), and fire spread between four cars in the car park rig, moved to HSL Buxton, (where the fire performance of a car with a full LPG tank was examined). Tests on single cars looked at fires starting in a sealed passenger compartment, fires starting in the engine, and fire spread by radiant heat. One test was carried out involving two cars on a “stacker” test rig.

Over the three years of the programme, a very large quantity of data, photographs and video footage has been acquired. In this report data is presented that is intended to be of value to designers, fire engineers, computer modellers and enforcers, involved in the design of car parks and the fire safety provisions that are appropriate.

Disclaimer: The cars used in the tests in this research programme were selected solely on the basis of age, size and availability. No cars were selected on the basis of make or model. All cars were to be either less than five years old, or, if older, be of a current model. None of the findings in this research programme should be taken as suggesting that any particular make or model of car performs better or worse in fire, compared with any other make or model.
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Appendix A – Summary of the Research
1 Introduction and Objectives

In 2006 Communities and Local Government (CLG) Sustainable Buildings Division commissioned BRE to carry out a three year project titled Fire Spread in Car Parks.

The overall aim of the project has been to gather information on the nature of fires involving the current design of cars and to use this new knowledge as a basis, if necessary, for updating current guidance in AD B (and possibly other Approved Documents) on fire safety strategies for car parks.

The existing guidance for fire safety in car parks in England and Wales is in Approved Document B (Fire safety) to the Building Regulations in England and Wales (AD B) (Ref. 1). The basis for this guidance for fire safety strategies in car parks relates to fire initiation and fire growth involving cars whose designs are decades old. There has been increasing concern about the consequences of fires in car parks associated with modern car design (e.g. plastic fuel tanks) and how these fires may spread to other vehicles parked adjacently and nearby. This concern has been heightened by the entry into the market place of cars powered by alternative fuels such as LPG.

Fires in car parks are rare, and, although there have been few deaths or injuries recorded to date in the UK, there are concerns regarding new and emerging risks from modern cars and alternative fuels.

There was a need to gather up-to-date information on fires involving cars in car parks in order that the current fire safety guidance could be reviewed and, if necessary, updated.

This report describes the project, the findings and conclusions. Over the three years of the programme, eleven full-scale tests were carried out and sixteen fairly new, modern, cars were burned. Consequently, a very large quantity of data, photographs and video footage has been acquired. In this report data is presented that is intended to be of value to designers, fire engineers, computer modellers and enforcers, involved in the design of car parks and the fire safety provisions that are appropriate.

2 Programme of work

2.1 Programme

The work programme comprised ten key tasks. These are described below:

ESTABLISH AN ADVISORY GROUP

The first task was the identification and engagement of stakeholders, and the selection of a representative group to advise the project, and to organise a conference and produce articles about the project.

The Advisory Group met on three occasions; the initial meeting was in October 2006, and subsequent meetings in November 2007 and November 2008. The Advisory Group, at various times, comprised representatives of the following organisations:

Communities and Local Government Scottish Building Standards Agency
British Standards Fire Committee BSI LABC (Local Authority Building Control)
FSH25
The Advisory Group provided valuable assistance and technical input to the research and advised on the direction of the programme. A number of the Advisory Group members witnessed various of the fire tests.

The Group provided assistance to the programme on two particular issues. Firstly, it became evident that the results of the full-scale tests (Tests 1 to 4, see later) raised a significant question for the project regarding why there are (have been) not more big (multi-car) fires in car parks in the UK? It was the clear opinion of the Group that the project needed to review the statistics and consider ignition scenarios that were slower than that used for the full-scale tests, such as engine fires, or fires where all the windows are closed. This was agreed and the project was extended to examine these issues experimentally. Secondly, the Advisory Group expressed concerns regarding the fire safety of “stackers”; automated car parking devices of various types, but where cars are located above one another, with no fire resisting floor or ceiling between them. This was also agreed and the project was extended to carry out one experiment on a “stacker” rig.

During January 2007, BRE hosted a Conference on Fires in Enclosed Car Parks, sponsored by CLG. Over 120 delegates attended this event and a large amount of useful information was exchanged which has been utilised during the course of the project.

Early in the programme a number of papers were published describing the work (Refs. 2, 3 and 4).

DATA COLLECTION AND LITERATURE REVIEW.

This work comprised “desktop studies” and involved collecting and analysing information and data on the identified topics (see later). The method of collecting the information and data was mainly via a combination of a questionnaire, literature review and a web search. Questionnaires were distributed beyond the stakeholder group, among a wide range of bodies, including building control bodies, the motor industry, fire design consultancy, the fire and rescue service, fire investigators and insurance companies. This task is reported in more detail in Section 2.3, below.
A detailed review of the Communities and Local Government fire statistics data base was carried out. All relevant FDR1 (the UK fire and rescue service incident reports) data on fires in car parks was obtained from Communities and Local Government (Ref. 5). This task is reported in more detail in Section 2.4, below.

In the period covered by this programme there were five fires in car parks which were brought to the attention of BRE and which, with CLG approval, were attended by the BRE fire investigation team (who also happened to be members of this project team).

These fires were:

Monica Wills House, Bristol; December 2006,

Brent Cross; December 2007,

Shaw Lodge, Manchester; April 2008,

Smithfield Gates, Dublin; August 2008,

Ancoats, Manchester; November 2008.

The on-site investigation of these fires provided valuable insight and understanding of many of the issues of concern. Of particular interest in all these incidents was the spread of fire between cars and the extent of fire spread, structural damage and smoke spread.

In December 2008, some of the project team examined a “stacker” car park, under construction in London.

**MODELLING STUDY – SMOKE SPREAD IN ENCLOSED CAR PARKS**

CFD modelling has been used at various stages throughout the project to guide the research, assess findings and validate current methodologies.

The modelling was conducted using the BRE CFD model JASMINE, and based on the findings from this project, supplemented by published information, and tested against the Monica Wills House fire, has led to the development of an effective and practical car fire/fire spread scenario.

This task is reported in more detail in Section 2.5, below.

**EXPERIMENTAL STUDY – FIRE BEHAVIOUR OF MATERIALS**

The objective of this task was to determine the critical exposure conditions, e.g. intensity and duration of incident thermal radiation, for a range of external materials used on typical road vehicles, which has assisted determining the spread of fire between cars.

This task is reported in more detail in Section 2.6, below.

**EXPERIMENTAL STUDY – FIRE SPREAD BETWEEN CARS**

The objectives of this task were to benchmark car fire sizes for a range of vehicle types, determine the spread of fire between cars and the severity (heat release) of car fires and to seek to determine the associated conditions (heat, smoke, toxic gas) to car park occupants exposed to such a fire, under typical conditions.

Three large scale fire tests were carried out in a car park test rig under the large calorimeter hood in the BRE Burn Hall, each involving three cars.

This task is reported in more detail in Sections 2.7 to 2.11 below.
EXPERIMENTAL STUDY – BURNING BEHAVIOUR OF CARS FUELLED BY LPG

The objectives of this task were to determine the behaviour of fires (and explosions; if such were to occur) involving cars fuelled by LPG and to seek to determine the associated effects on an enclosed car park, and adjacent cars, from such a fire.

Due to the risk of an explosion, the large scale fire test was carried out in a car park test rig at the Health and Safety Laboratory (HSL), Buxton, involving four cars.

This task is reported in more detail in Section 2.12, below.

ANALYSIS

The analysis was intended to examine the findings from all of the tasks to seek to resolve the following issues:

The severity of car fires in modern car design, potential for spread and fire size; benchmarking car fire size given a range of vehicle types

- The combustion products and likely survivability of such fires
- The potential hazards arising from fuel leakage/spillage in unventilated/underground/enclosed car parks.

Additional hazards arising from cars designed to utilise alternative fuel(s); the potential explosion effects of cars powered by alternative fuels, or other risks of cars powered by hybrid systems, e.g. using a diesel or petrol engine primary power supply, with a secondary power supply using batteries.

The need, or otherwise, for different considerations for underground, enclosed and open-sided car parks

The review of the findings and analysis are presented in Section 3, below.

SINGLE CAR TESTS

The objectives of this task were as follows:

To examine the time to full development and heat release rate of a fire starting in the passenger compartment of a modern people carrier, with windows closed (i.e. with limited air).

To examine the time to full development and heat release rate of a fire starting in the engine bay of a modern car (with the bonnet closed).

To examine the processes of fire spread and the time to full development of a fire developing in a passenger compartment of a modern car, with windows closed, from a car adjoining another on fire, using a radiant panel.

Seven tests in all were carried out, on single cars. This task is reported in more detail in Sections 2.13 to 2.19, below.

STACKER TEST

The objective of this test was to examine the processes of fire spread from the lower car to the upper car on a "stacker", and the time to full development and heat release rate of the fire, starting in the passenger compartment of the lower car with driver’s window open.
2.2 General background

This project has been concerned with fire spread in enclosed car parks. The car parks being studied were those that fall under the England and Wales Building Regulations (Ref. 6), and include open-sided car parks, fully enclosed car parks, and basement car parks.

Car parks may be stand-alone structures or they may be directly linked (via doors) to a complex (e.g. a transport interchange or shopping complex, or they may be the lower floors of, or beneath (as basement levels), another occupancy (e.g. an office block or flats).

The project has necessarily been restricted to consider only private domestic cars, but including sports cars, minis, small family cars, medium family cars, people-carriers and domestic 4X4s.

The project has not considered HGVs, lorries, vans, minivans or motorbikes, although it is recognised that these may be found (or, indeed, parked) inside buildings and other structures that are subject to the Building Regulations. Minivans and motorbikes may be found in the car parks of interest, but only in very limited numbers.

The project was limited in the number of variables that could be assessed. The experimental programme was supplemented and supported by computer modelling. For example, it was not possible to examine forced ventilation; only natural ventilation was provided in the tests.

Methods of fire fighting in car parks are of concern, especially as vehicle designs change. Although not a primary objective of the current programme, the findings from the work should provide useful information for use in the training of fire-fighters and planning for incidents.

2.3 Literature review

Relevant information was obtained from a number of sources including a literature review, web searches, questionnaires and personal contacts. A number of surveys were circulated to members of the International Association of Arson Investigators UK Branch regarding actual incidents of fires in car parks, and issues with LPG cars.

Information was sought on the following topics:

General relevant literature.

Car design. (Including new designs and trends in the design of cars, vehicle dimensions, fuels and internal and external materials, electric vehicles, the increasing use of plastics, wiring and battery capacity, plastic fuel tanks and recyclable components.)

Fuels. (Including new fuels as well as petrol, diesel, alcohol and other green fuels)

Car park design (Including ventilation provisions and trends, fire protection systems; sprinkler systems and detection systems, and BS 7346-7; 2006. Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered parking areas for cars. (Ref. 7))
Current guidance for fire safety in car parks. Current guidance in AD B pertinent to car parks, e.g. B3 (Internal fire spread) and B5 (Access and facilities for the fire service). Current guidance in AD A (Ref. 8) and AD F (Ref. 9) pertinent to car parks, e.g. F1.219 (Ventilation of car parks).

Car fires (reports of car park fire incidents and test).

Research: car park fire tests (and to include relevant work on ro-ro ferries and road tunnels).

Over 200 items were reviewed, mostly from the UK but many from overseas. It is not possible to explicitly cover all of these here but some key, relevant, findings are summarised below. On some topics very little relevant information was located.

CAR DESIGN

There are very limited regulations of fire safety in cars. The main regulation is the Motor Vehicles (Approval) Regulations 2001 (Ref. 10) which requires fuel and electrical systems to be designed to minimise the risk of fire. Plastic fuel tanks have to conform to ECE Regulation 34 (Ref. 11) which includes a fire test. It is estimated that 85% of new cars in Europe have plastic tanks (Ref. 12).

Over time there has been an evident increase in the quantities of plastics used in cars. This may be affected by the moves towards more recyclable components.

Concerns were expressed regarding the toxicity of materials used in road vehicles, in particular electric or hybrid vehicles, and the variety of new types of batteries, which potentially create new hazards for fire fighters.

Electric and hybrid vehicles are likely to become increasingly popular, and are likely to introduce new and/or different fire risks, such as hydrogen venting, which will need to be monitored.

By way of example; during a vehicle fire in the US, an explosion occurred when firefighting water came into contact with magnesium in the structure of the vehicle (Ref. 13).

FUELS

There are numerous articles and reports on fuels for the future. As well as petrol, diesel, and LNG, fuels that have been identified include CNG, hydrogen, dimethyl ether, dimethyl ether diesel blends, methanol, ethanol, ethanol-diesel blends, ethanol petrol blends, fatty acid methyl ether, bio-diesel (e.g. from chip fat), and vegetable oil-diesel mix. (There are legal restrictions on the quantity of recycled bio-diesel that an individual is permitted to produce.) The UK Government has proposed to set a target of 5% biofuels in fuels from 2010 (Ref. 14).

From a fire safety perspective, there is little difference between “normal” petrol and diesel and their bio-substitutes. Concerns have been raised regarding DIY conversions, and the need to maintain quality, since there was a spate of road vehicle fires in the 1980s linked to DIY conversions to unleaded petrol.

The potential explosion risks associated with gas-fuelled cars, in particular LPG, and, potentially hydrogen, do not appear to be of concern to firefighters and only a few anecdotal cases of LPG explosions have been reported to BRE. The pressure relief
valves appear to work effectively; where an explosion has been reported these appear to be a result of deliberate tampering.

CAR PARK DESIGN

There are a selection of design guides for car parks (Refs.15 and 16). These design guides tend to say little about fire safety and refer to AD B (see below).

Automated car parks (“stackers”) are becoming increasingly common and there are a variety of different automated car parks types, some involving a hollow, atrium-type interior, others using simple jack ramps to double capacity. Some (possibly most) automated car parks using stackers appear to be fitted with a fire suppression system (sprinkler or water mist) although the effectiveness of these is uncertain.

The use of combustible (polymeric) insulated foam for thermal insulation in car parks (typically on their ceiling) has been raised as a concern. (Ref. 17)

A paper presented at Interflam 2007 refers to multi-storey car parks in Norway, constructed of timber (Ref. 18). The use of timber in car park construction needs to be kept under review. While multi-storey timber car parks are unlikely (since they would not readily conform to the recommendations in AD B with regards to non-combustibility and/or fire resistance), ground floor or basement car parks under timber frame constructions (such as flats) are a possibility. Timber cladding also appears to be becoming popular since it “softens” the usual stark appearance of the building (Ref. 19).

The use of car parks for purposes other than the temporary parking of cars is reported, including car washes, car boot sales and general storage.

The build-up of CO in car parks is the subject of some studies (Refs. 20 and 21, for example). Ventilation for smoke clearance is the most common fire safety measure, but the effectiveness of jet fans appears to be uncertain. Some car parks are provided with sprinklers. Some “fire engineered” car parks have smoke ventilation instead of sprinklers. Often CFD modelling is employed, but with the assumption of a limited size of fire, based on a single car.

Increased use of electric/hybrid cars may lead to the provision of recharging points in car parks, with new fire risks for both the public and firefighters.

CURRENT RECOMMENDATIONS FOR FIRE SAFETY IN CAR PARKS

The current recommendations for fire safety in car parks in the UK largely derive from the Post-War Building Studies (Ref. 22). This study set out to review the situation regarding the danger of fires and explosions occurring within underground car parks. This dealt both with methods of preventing the incidence of such fires and explosions as well as methods of dealing with fires and explosions, should they occur. It should be noted that the recommendations made in this study are reflective of the time period during which this study took place. The main considerations made in this study in terms of prevention are with respect to fuel spillages and the formation of fuel vapour clouds. The materials used in the construction of cars are treated as a secondary issue.

In England and Wales, recommendations for the fire safety of car parks are primarily those in Approved Document B (AD B Section 11) (Ref. 1). B1, paragraphs 5.46-5.53 recommends that mechanical ventilation systems should ensure that smoke is directed away from escape routes. These systems should be of appropriate construction to operate under fire conditions and compatible with other ventilation and air conditioning systems in order to maximise performance. In B3, paragraphs 11.2-11.6, car parks are
considered separately from other storage premises due to their relatively low fire loads. The principle concern regarding car parks is their level of ventilation. There are three types of car park defined by ventilation. These are open-sided, naturally ventilated and mechanically ventilated. The level of ventilation possessed by a car park will determine its requirements in terms of fire resistance. BS 5588 – Part 10:1991 for shopping centres (Ref. 23) which calls for car parks to be sprinklered.

BS 7346-7: 2006 (Ref. 7) sets out requirements for covered parking areas in terms of smoke and heat control systems. Design fires with heat release rates of 4 (sprinklered) and 8 MW (unsprinklered) are used for the determination of the requirements. BS 7346-7: 2006 deals specifically with the methods of achieving adequate ventilation using natural ventilation, mechanical extraction and impulse ventilation. It provides specific figures regarding opening areas for natural ventilation and the performance of mechanical systems. It recommends using experimental data (where such exists). Some advice on the use of computer models is also provided for those who wish to provide a more advanced solution.

For buildings located within the inner London area, the requirements of the London Building Act 1939 Section 20 (Ref. 24) apply; “proper arrangements will be made and maintained for lessening so far as is reasonably practicable danger from fire in buildings.” The London District Surveyors Association Fire Safety Guide, No. 1: Fire Safety in Section 20 Buildings, published in 1990, contains detailed information on fire resistance requirements for high risk buildings within the inner London area. The main differences from AD B with regard to structural fire resistance are that basement car park requirements are more onerous than those in AD B. Also, mandatory sprinklers are introduced in high rise, non-residential buildings above 25 m. However, it appears that the recommendations of AD B are often applied in these cases.

Automated car parks are addressed in a US Standard (Ref. 25). This document describes the requirements of automated parking facilities being set up in the United States. It is largely concerned with the dimensional and mechanical requirements of these facilities but also contains a section specifically dealing with fire safety. This section states that fires in these facilities are rare but that sprinkler systems are unlikely to have any significant effect on such a fire. Recommendations are made that non-combustible materials be used in the construction of the facility and that a passive fire protection system providing a minimum of 2 hours fire resistance be used to separate the facility from any buildings beneath which it is located.

The Code of Practice for Ground Floor, Multi Storey & Underground Car Parks, issued by the Association for Petroleum and Explosives Administration, (Ref. 26) outlines the design features that are acceptable and necessary, depending on the type of car park being designed. Measures relating to the separation of car park and adjoining buildings are mentioned, as well as the provision of adequate ventilation by both natural and mechanical means.

It has generally been the case that car fires in car parks are only rarely expected to spread beyond the first vehicle and many car park designs based on fire engineering principles assume only a single vehicle burning.

As mentioned above, the potential explosion risks associated with gas-fuelled cars, in particular LPG but also, potentially, hydrogen, do not appear to be of concern to
firefighters and only a few, anecdotal, cases of LPG explosions have been reported to BRE. The pressure relief valves appear to work effectively; where an explosion has been reported these appear to be a result of deliberate tampering. Belgium has introduced new regulations to limit the access of LPG cars to car parks (Ref. 27) but the reasons for this, or the evidence to justify it, have not been established.

CAR FIRES

A large number of reports of car park fires have been reviewed. Few car park fires involve more than one car. In a number of incidents, a running fuel fire was reported, which spread the fire. In general, little major structural damage occurs. In no cases reviewed did fire spread beyond the floor of origin but smoke can affect many floors. Services are often damaged. A number of incidents had the fire starting in other materials (not a car) and injuries have occurred to people sleeping rough in the car park.

In a number of cases, abandoned cars caused problems for fire fighters. In one case, people refused to leave their cars despite a fairly severe fire.

Where cars are left in gear, they may drive off if the fire shorts connections and actuates the starter motor.

Manser and Pentony (Ref. 28) report the details of a fire that occurred in a car park situated in the ground floor of a block of flats. One feature was the spread of the fire, which eventually involved a total of seven cars plus other items located in the car park. The flames of the fire attained the height of the third level of the flats and were able to break windows and ignite combustibles in a building the other side of a 3.2 metre wide laneway. Smoke and heat release by the fire were also significant. Particular mention is made of the ever increasing prevalence of plastics in the construction of cars and how these plastics are increasing the fire load that each car represents in a car park. Numerical analysis of the incident, particularly the damage caused to the building opposite the fire, indicated that the heat release rate of the fire was around 32.3 MW. The average peak heat release rate for each vehicle was calculated from this figure to be around 4.75 MW.

The most serious reported car park fire was that in Switzerland (Refs. 29 and 30). Seven Swiss fire fighters were killed when the roof of an underground car park collapsed on them. Four fire fighters survived, three of whom freed themselves, and one was rescued. A car is believed to have been on fire in the underground car park at the time of the collapse. The car park was part of an apartment complex in Gretchenbach, Switzerland. The car park itself was located beneath a playground. The collapse left a crater 30m across and 3m deep.

Soon after the start of the current project, a major semi-basement car park fire occurred in Monica Wills House, a residential home in Bristol (Ref. 31). Twenty two cars were destroyed and there was one fatality, in a flat above the car park, resulting from the fire spread up the side of the building. The building was fully sprinklered – except the car park. There was substantial structural damage to the car park ceiling. This incident has been the subject of fire modelling as part of the current project (see later).

RESEARCH

The earliest experimental study of fires in car parks was by E.G. Butcher, G.J. Langdon-Thomas, and G.K. Bedford in 1968 (Ref. 32). Three full scale burns each involving 9 cars (3 x 3 configuration) were carried out, simulating a multi-storey car park, in order to assess the fire hazards associated with multi-storey car parks. Two of these tests were
set up as open-sided multi-storey car parks and one was set up as a closed multi-storey car park. In each case a fire was lit in the central car and simply allowed to burn until it burned itself out or the temperatures became too low to be significant, at which point the fire brigade ensured complete extinguishment of the fire. The most severe of the three fires was produced under open conditions using a lightly constructed van as the fuel source. The closed test, involving a soft-top saloon, produced the most rapid development but less severe temperatures than the van. The least severe of the tests involved a luxury saloon in the open layout. This is believed to have been due to the car’s heavy (mostly steel) construction, which restricted the growth of the fire. The fire did not achieve sustained burning on any adjacent cars during any of the experiments. The findings of the experiments indicated that fires were unlikely to spread beyond the first car, at least before intervention by the fire and rescue service. The conditions within the compartment were also deemed to remain well within the requirements of the fire and rescue service, for fighting the fire, throughout the tests. It should be noted that the cars used are not specified in the report but appear to be predominantly pre-1960s. Whilst this was not a major consideration at the time of the experiments, it is likely that the fuel load of these cars would have been different to those of the period (and certainly different from modern (2009) cars). This research has underpinned the recommendations in AD B.

Thomas and Bennett’s report the findings of nine tests, involving twenty cars, looking at fire development in closed car parks (Ref. 33). The experimental work was undertaken by the Melbourne research laboratories of BHP. The objective of the testing was to establish the effect of a fire started in one car in a closed car park, with the minimum required sprinkler and ventilation systems operating. The test looked at fires where only the ventilation system operated, the sprinkler system operated and finally neither system operated. The tests investigated the likelihood of fire spreading to multiple cars, the temperatures reached in the air and structural members. The results of the test can be summarised as follows:

- The sprinkler system was effective at controlling a developing fire.
- The sprinkler system was equally as effective at controlling a fully developed fire.
- Without sprinklers fire is likely to spread from car to car.
- With sprinklers spread of fire is unlikely.
- Without sprinklers, dangerous levels of smoke are likely for long periods.
- With sprinklers, dangerous levels of smoke are likely for long periods.

Structurally it was concluded that the steelwork was not affected until thirty minutes of fire exposure. With sprinklers present the steelwork remained unaffected for the duration of the test. It was concluded that in sprinklered car parks fire protection is not necessary.

BHP Melbourne Research Laboratory undertook additional tests on partially closed and open deck car parks BHP (Ref. 34). As in the previous tests the objectives were to “better understand those features that influence fire development” and “to evaluate the performance of steel structures in building fires”. The main conclusions of the experimental programme can be summarised as follows:

Sprinkler activation resulted in temperatures that did not influence the steels integrity. It was concluded that, where automatic sprinklers are implemented, fire protection to the structure was not required.

Fires in partially open car parks behave in a very similar manner to fully closed car parks in terms of obscuration and toxic product concentrations.
Fire conditions in partial and fully closed car parks are much more severe than in open sided car parks.

J Mangs and O Keski-Rahkonen (Ref. 35 and 36) carried out three experimental burns on cars in order to measure features such as heat release rate, mass change, rate of mass change, heat flux, CO and CO₂ production rate, smoke production rate, gas temperatures above the car as well as temperatures at specific points on the structure of the car. The peak heat release rates obtained from the three tests were 1.5, 1.75, and 2 MW (data tabulated below). The outcome of this work was the production of a set of data for each car, enabling characteristics of a car fire to be determined as a function of its heat release rate. This was achieved via the parameterization of the heat release rate curves using Boltzman curves and Gaussian curves. These curves could then be adjusted in terms of position and dimension in order to form generalisations about car fires.

<table>
<thead>
<tr>
<th>Test</th>
<th>Car</th>
<th>Ignition Source</th>
<th>Energy Released (GJ)</th>
<th>Peak HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indicative</td>
<td>Ford Taunus</td>
<td>Under seat</td>
<td>3.3</td>
<td>1.5</td>
</tr>
<tr>
<td>1</td>
<td>Datsun 160J sedan</td>
<td>Under engine</td>
<td>3.0</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>Datsun 160B sedan</td>
<td>Under engine</td>
<td>3.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

TABLE 2.3.1: RESULTS FROM J MANGS AND O KESKI-RAHKONEN

B. Zhao, J. Kruppa, and M.L. Janssens (Ref. 37) have carried out experiments during two research projects involving CTICM and ARBED, in which several car fires were conducted in real car parks constructed from steel columns and composite slabs. The results indicated that, despite the increased fire load in cars, additional fire protection in steel structures is not necessary to obtain overall stability of the structure. Structural modelling conducted during the course of the research indicated the possibility that the use of more economical steel structures may be feasible.

Daniel Joyeux reports (Refs. 38 and 39) on a set of ten experiments that were carried out in order to collect heat release data from scenarios involving cars parked in a variety of states of enclosure, all of which included a ceiling. Some of the details of the tests are tabulated below:

<table>
<thead>
<tr>
<th>Test</th>
<th>No. Cars</th>
<th>Car 1</th>
<th>Car 2</th>
<th>Enclosure</th>
<th>Ignition Source</th>
<th>Energy Released (GJ)</th>
<th>Peak HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>Mazda 323</td>
<td>Talbot Solara</td>
<td>Corner</td>
<td>Under seat</td>
<td>4.98</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Renault 18</td>
<td>-</td>
<td>Corner</td>
<td>Under seat</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Renault 5</td>
<td>-</td>
<td>Corner</td>
<td>Under seat</td>
<td>2.1</td>
<td>3.5</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Renault 18</td>
<td>-</td>
<td>Corner</td>
<td>Under seat</td>
<td>3.08</td>
<td>2.15</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>BMW</td>
<td>Renault 5</td>
<td>Corner</td>
<td>Under seat</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>Citroën BX</td>
<td>Peugeot 305</td>
<td>Closed</td>
<td>Under seat</td>
<td>8.51</td>
<td>1.7</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Renault Laguna</td>
<td>-</td>
<td>Open</td>
<td>Under seat</td>
<td>6.67</td>
<td>8.3</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>Renault Twingo</td>
<td>-</td>
<td>Open</td>
<td>Under car</td>
<td>4.09</td>
<td>4.07</td>
</tr>
</tbody>
</table>
Seven of the tests were ignited using a 1.5 litre tray of petrol under the passenger seat (denoted “under seat”). The remaining three were ignited using 1 litre of petrol under the gearbox. The heat release data collected from these experiments was aimed at increasing the amount of data that is available regarding car park fires. It should be noted that tests 1 – 6 involved cars built during the eighties, and tests 7 – 10 involved cars built during the nineties. The principle finding of this piece of research was that cars produced during the nineties possess a greater calorific potential than cars produced during the eighties.

Two full-scale car fire tests were conducted by Shipp and Spearpoint for the Channel Tunnel Safety Authority (Ref. 40) under fully instrumented hoods in order to measure heat release rate, temperature and other parameters in order to assess the severity of fires which are likely to occur. The data showed that car fire could reach peak outputs within the space of 10 minutes and that these outputs could exceed 7.5MW. It was also noted that, based on the findings of other studies, the severity of the fire was highly dependant on the conditions under which the fire took place. The findings enabled judgements to be made regarding the safety measures necessary on Channel Tunnel shuttle train wagons to safely contain such fires.

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Car 1</th>
<th>Car 2</th>
<th>Enclosure</th>
<th>Ignition Source</th>
<th>Energy Released (GJ)</th>
<th>Peak HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Renault Twingo</td>
<td>Renault Laguna</td>
<td>Open</td>
<td>Under car</td>
<td>8.89</td>
<td>7.5</td>
</tr>
<tr>
<td>10</td>
<td>Renault Laguna</td>
<td>Renault Twingo</td>
<td>Open</td>
<td>Under car</td>
<td>8.38</td>
<td>8.31</td>
</tr>
</tbody>
</table>

**TABLE 2.3.2: RESULTS FROM JOYEUX**

**FIGURE 2.3.1: RESULTS FROM JOYEUX**

Seven of the tests were ignited using a 1.5 litre tray of petrol under the passenger seat (denoted “under seat”). The remaining three were ignited using 1 litre of petrol under the gearbox. The heat release data collected from these experiments was aimed at increasing the amount of data that is available regarding car park fires. It should be noted that tests 1 – 6 involved cars built during the eighties, and tests 7 – 10 involved cars built during the nineties. The principle finding of this piece of research was that cars produced during the nineties possess a greater calorific potential than cars produced during the eighties.

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<table>
<thead>
<tr>
<th>Test</th>
<th>Car</th>
<th>Ignition Source</th>
<th>Peak HRR (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indicative</td>
<td>Alfa Romeo Giulietta 1.6</td>
<td>Under engine</td>
<td>1.5</td>
</tr>
<tr>
<td>1</td>
<td>Austin Maestro 1.3l</td>
<td>Crib on seat</td>
<td>7.5-9</td>
</tr>
<tr>
<td>2</td>
<td>Citroen BX 14 RE</td>
<td>Under engine</td>
<td>4.5</td>
</tr>
</tbody>
</table>

**TABLE 2.3.3: RESULTS FROM SHIPP AND SPEARPOINT**
2.4 Review of UK fire statistics

A detailed review of the Communities and Local Government fire statistics data base was carried out. All relevant FDR1 data on fires in car parks was obtained from Communities and Local Government (Ref. 5). The data reviewed was for (all) fires in areas of buildings designated as a “car park”, and therefore included car parks in other purpose-group buildings as well as purpose-built car parks.

12 years of data was reviewed (from 1994 to 2005 (the most recent year for which data was available to BRE)) for fires involving car parks in buildings, and some selected results are shown below. The data set includes fires starting in vehicles and fires starting in other sources. For the purposes of this research project, all sources are considered relevant.

(Note: The bulk of the UK fire statistics are collected by the CLG (formerly Home Office) Research, Development and Statistics Directorate. They are based on the FDR1(94) forms filled in by the fire brigades after a fire has been attended. Since 1994, only a fraction of all reported fires have been transferred to the electronic database. However, all fires where there was injury or death are in the database. Each reported fire thus has a weighting figure (>1) which is the reciprocal of the fraction of reported fires recorded (varying from brigade to brigade). Also, because the statistics are only based on fire brigade reports, the sample is biased when it comes to considering the population of all fires. There will be a large number of small fires that are unreported. This bias in the sample obviously requires that care be taken when interpreting the statistics. These data are subject to rounding errors.)

- In the 12 year period studied there were 3096 fires reported in car parks in buildings. Of these, 1592 started in a vehicle (i.e. 1504 were not in a vehicle).

- The average number of fires in car parks in buildings over the period was therefore 258 per year. However, the number of car park fires per year shows an overall (but not consistent) decline, with 401 in 1994 but only 142 in 2005, see figure 2.4.1, below.

![Number of car parks fires reported by year (1994-2005)](image)

Figure 2.4.1: Numbers of car park fires reported in buildings by year (1994 – 2005)
The number of fires in car parks reported by UK fire and rescue services represents a very small percentage of all fires in the UK (i.e. the number of all fires were 426,200 in 2006 – hence fires in car parks were less than 0.1%).

The majority classification of fires in car parks in buildings generally (but also for purpose-built car parks) is “accidental”. However, when fires reported as being “malicious” or “deliberate” are added together as “non-accidental” then these form the substantial majority. There are inevitably a large number reported as “not known” and “doubtful”.

Most fires (68%) occur in buildings reported as “car park buildings”. 6% occur in “flats”. See figure 2.4.2, below:

Figure 2.4.2: Type of property where vehicle fires are reported (1994 – 2005)

- The majority of fires in flats are reported as “deliberate” cause. In other buildings the major cause in “malicious/deliberate”.

- The greatest number of fires are reported to have resulted in damage of 1m² to 20m². A substantial (although far fewer) number resulted in damaged reported to be in excess of 200m².

- Fires that are reported to have resulted in damage of less than 1m² are mostly accidental. Those of 1m² to 20m² are mostly non-accidental. Fires involving greater areas of damage are predominantly non-accidental (see figure 2.4.3, below).
Figure 2.4.3: Area of damage and relationship between total area damaged and cause (1994 – 2005)

- Small fires (less than 1m²) are mostly due to non-vehicle sources of ignition. There are no trends evident, for larger fires, between vehicle sources of ignition and other sources of ignition.

- Most fires in car parks do not spread to a vehicle (from non-vehicle sources of ignition), or to another vehicle (from vehicle sources of ignition). A few vehicle sources of ignition (19) and non-vehicle sources of ignition (12) result in the involvement of one (other) car. However, when the involvement of more than one (additional) car is considered, then fires starting in vehicles are the major “cause” of fire spread to other cars.

- The great majority of fires in car parks do not spread beyond the floor of origin. However some (two) are reported to have involved seven floors (this is almost certainly smoke damage).

Figure 2.4.4: Number of additional floors where fire spread (1994 – 2005)
There are no particular trends visible over the years for injuries in fires involving vehicles in buildings. In 1994 there were eight injuries reported, in 2005, seven.

During the 1994-2005 period, two fatalities and eighty seven non fatal injuries are reported.

The first fatality was a result of a fire starting in the passenger compartment of a 1983 petrol vehicle. It was located in on the ground floor of a single storey car park used for retail/trade. The car was not running at the time and ignition was reported as deliberate by an adult. The use of a fuel accelerant is reported. The vehicle was 100% burned out and the ‘room’ it occupied was reported as having 3-4 sq. m. of direct damage. No further damage was reported to the structure. From the time of the emergency call it took 17 minutes in total to extinguish the fire.

The second fatality was a result of suicide by fire. This took place on the 8th floor of a 9 floor car park building. The use of fuel as an accelerant is reported. The fire was extinguished within 18 minutes of the emergency call and caused damage to a total area of 5-9 square meters in the surrounding area.

Most injuries from fires in car parks occur in car park buildings (45%), followed by flats (26%); 6% of fires are causing 26% of the injuries (flats) while 68% of the fires are causing only 45% of the injuries (car parks). It follows that fires in flats are the most dangerous.

Figure 2.4.5: Number of injuries by type of property (1994 – 2005)

- This is equivalent to 134 injuries per 1000 fires in flats against 18 injuries per 1000 fires in purpose-built car parks. This may be compared with the injury rates in other purpose groups, see figure 2.4.6, below:
Figure 2.4.6: Injury rate by building use; injuries per thousand fires

- This shows that while (purpose-built) car parks have a low injury rate (only offices are “safer”), the injury rate for car park fires in flats is high.

- As in most fires, injuries from fires in car parks mostly occur to individuals. However, in two incidents (in the 12 year period) five people were injured. See Figure 2.4.7, below.

Figure 2.4.6: Number of injuries per incident

Of the 3096 reported fires in car parks between 1994 and 2005, only 285 (9.2%) had an automatic alarm in the area of origin. Of the 285 incidents where automatic alarms were present, 38 (13.3%) did not operate, 34 (11.9%) operated but did not raise the alarm and 211 (73.7%) operated and raised the alarm. (Note that those that “did not operate” are likely to be because the fire was too small.)
Only 174 incidents (5.6%) were in car parks which had a ‘fixed fire fighting/venting system’ in the area of origin. Of the 174 incidents which had a system in place, 5 (2.8%) had a drencher system, 7 (4%) had venting and 162 (95.9%) had sprinklers. In the case of the 162 incidents which had sprinklers, 16 (9.9%) operated and extinguished the fire, 84 (51.9%) operated and contained/controlled the fire, 1 (0.6%) operated but did not contain/control the fire and 61 (37.6%) did not operate. (Note again that those that “did not operate” are likely to be because the fire was too small.)

![Figure 2.4.7: Suppression system effectiveness](image)

- Data for fuel types are anomalous and inconsistent. This is likely to be the result of the difficulty of identifying fuel type after a fire. It is not possible at this time to derive any findings in this regard.

- Averaged over the whole data set, there is a general relationship between area damaged and the time for the fire and rescue service to arrive at the scene. However, this correlation is not so apparent when the individual incidents are plotted since there is a wide variation in the data.

- As in building fires, most fires occur on the ground floor. A substantial number occur in the “basement”, i.e. first level underground car park. However, these data may reflect the distribution of car park heights (and depths) in England and Wales, i.e. reflect the existing building stock rather than fire locations.
Figure 2.4.8: Floor of origin of car park fires (1994 – 2005)

A breakdown of these statistics for fires in purpose-built car parks is given in Table 2.4.1 below:

<table>
<thead>
<tr>
<th>Fire origin</th>
<th>Type of fire</th>
<th>Deaths</th>
<th>Injuries</th>
<th>Vehicles damaged</th>
<th>Extra floors damaged (Note 1)</th>
<th>No. of fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car park area</td>
<td>Other fire</td>
<td>1</td>
<td>9</td>
<td>16</td>
<td>39</td>
<td>406</td>
</tr>
<tr>
<td>Car park area</td>
<td>Vehicle fire</td>
<td>1</td>
<td>14</td>
<td>1081</td>
<td>119</td>
<td>979</td>
</tr>
<tr>
<td>Other area (Note 2)</td>
<td>Other fire</td>
<td>0</td>
<td>14</td>
<td>6</td>
<td>73</td>
<td>578</td>
</tr>
<tr>
<td>Other area</td>
<td>Vehicle fire</td>
<td>0</td>
<td>2</td>
<td>195</td>
<td>9</td>
<td>175</td>
</tr>
<tr>
<td>TOTALS</td>
<td></td>
<td>2</td>
<td>39</td>
<td>1298</td>
<td>240</td>
<td>2138</td>
</tr>
</tbody>
</table>

Table 2.4.1: Consequences of multi-storey car park fires in the period 1994~2005

Note 1: Does not include floor of fire origin.

Note 2: Includes ramps, stairways and offices, etc.

Some statistics on fires in car parks overseas have been obtained and reviewed (Ref. 41, for example).

2.5 Computer modelling studies

Computer modelling is often an important element of car park design, especially where complex smoke control systems are proposed. Modelling has also been used within this project to assist with the design of the experimental facilities and to investigate the fire incident at Monica Wills House.
CURRENT POSITION

The current requirements for smoke control systems in car parks prescribed in Approved Document B (Ref. 1) are either:

Mechanical systems providing a total extraction rate of 10 air changes per hour with the extract points distributed equally at high and low level. The system should also be arranged to operate as two independent systems.

Natural systems where ventilation is provided by open sides with a total area of 1/20 of the total floor area of the car park, half of which should be equally distributed on two opposite sides.

In addition, if other systems such as SHEVS (Smoke and heat exhaust systems) or jet fan systems are used these are described in BS 7346 part 7 (Ref. 7).

The designs of systems other than those prescribed in AD B, such as those described in BS7346 part 7, are based on fire engineering principles and are strongly dependant on the selection of an appropriate design fire. The standard offers two steady state fire heat release rates for sprinklered and non sprinklered fires. If a transient design fire is used then it should be based on experimental data and the design documentation should record the experimental details so that the relevance of the data to the actual design can be considered.

Until this current work there was very little data in the public domain that could be used for design fires for fire engineered car parks. The data presented here should also allow the designer to consider the possibility of car to car fire spread.

DESIGN FIRE SPECIFICATION

Development of a car park ventilation system using a fire engineered approach usually has two calculation phases:

A design phase to establish ventilation extraction rates and provision of makeup air

Simulations to demonstrate that for various scenarios (fire locations, wind conditions etc) various tenability conditions (for life safety, accessibility for fire fighters and structural requirements) are maintained within the space

The design calculations maybe based on various calculations found in documents such as PD7974 parts 1 to 7 (Ref. 42) and BS7346:7. These typically take a design fire then use a plume entrainment equation to estimate the volume and temperature of the smoke and hot gases that need to be extracted from the space. Further calculations such as flame height would allow consideration of fire spread to adjacent cars or other combustible items in the car park. Ceiling jet calculations would allow estimation of the operation times of detectors and sprinkler heads. Both standards include tenability conditions.

Simulations would usually involve computer software including zone and CFD (computational fluid dynamics) programs. Subject to various assumptions these predict the temperature and depth of a hot smoke layer, concentration of combustion products, visibility and heat transfer to objects (other cars, walls, roof, structural elements) adjacent to the fire. The CFD approach is more flexible as it does not assume the presence of a hot gas layer, allows spatial dispersion of energy and products and can be used with very complex building geometries and ventilation systems.
Methodologies to ensure the correct used of the simulation tools (especially the CFD programs) have been published by Kumar and Cox (Ref. 43) and the Smoke Control Association (Ref. 44).

The key element for both the design and simulation processes is the specification of the design fire. The basic requirements are:

- fire heat release rate as a function of time
- fire area or perimeter

Some calculations/programs may also require:

- The proportion of energy released as radiation
- An effective heat of combustion
- The production rate of "smoke" and combustion products (e.g. CO, CO2), often as a function of the burning rate.

To predict fire spread from car to car an ignition criterion (e.g. a critical heat flux) is required.

**DESIGN FIRE DATA**

Figure 3.1.1 (see later) shows the heat release rate data measured during the current experimental programme. It should be noted that these are the total heat release rates of all the cars burning during a test and not for individual cars (except tests 7 and 8 where only one car was burnt). It is possible to approximate a total heat release rate curve from the summation of individual curves based on those of Joyeux (Ref. 38, see Figure 2.3.1 above) at different time intervals corresponding to the car receiving an irradiance of 10kWm⁻². This gives a close approximation to the total heat release rate curve measured in the current programme (Test 1, see later), Figure 2.5.1. This involves some speculation, but supports the use of Joyeux’s heat release rate data for small cars.

![Heat release rate data graph](image)

**FIGURE 2.5.1 INDIVIDUAL AND TOTAL HEAT RELEASE RATE FOR TEST 1**

From the small scale materials tests (Table 2.6.2 later) the value of 10kWm⁻² has been taken as the criterion for the ignition of a secondary car.
DESIGN OF EXPERIMENTAL RIG

The experimental rig for this project was designed to accommodate an 8MW fire (based on the design fire from BS7347 part 7 and Joyeux’s data). Figure 2.5.2 shows the geometric model of the experimental rig used by JASMINE and figure 2.5.3 shows the predicted temperature contours within the rig with one car burning (10 minutes, 2.5MW).

FIGURE 2.5.2 EXPERIMENTAL RIG MODEL

FIGURE 2.5.3 PREDICTIONS OF TEMPERATURE IN THE RIG

The predicted temperatures show a hot gas layer with a temperature of up to 350°C (light blue) and a ceiling jet (green) of 500°C extending over the second car. These simulations were to establish that the gas temperatures would be within the capabilities of the laboratory.

MONICA WILLS FIRE SIMULATION

On the 20th December 2006 a fire occurred in the car park under Monica Wills House, Bristol. This fire spread to involve all 22 cars in the car park and flames up the external walls of the building broke some of the windows allowing fire spread into the residential
section of the building. Internal fires were controlled by the action of sprinklers. One resident died as a consequence of the fire.

The car park was open sided and naturally ventilated with permanent openings with a total area of 165m² on two adjacent sides. This exceeds the provision in AD B for a total ventilation area of 1/20th of the floor area (which would be 50m² in the case of the Monica Wills House car park), however AD B also has a provision that the ventilation openings should be distributed so that at least half of the openings are evenly distributed on two opposing walls. This was not the case at Monica Wills House. It was not clear if this aspect of the design of the car park Monica Wills House had a significant impact on the development of the fire.

The BRE fire simulation program JASMINE (a computation fluid dynamics, CFD model) has been used to conduct computer simulations of two scenarios:

**Scenario 1:**

Car Park of Monica Wills house with car locations and ventilation openings as on the day of the fire. The heat release rate of the initial fire was based on experimental measurements reported by Joyeux. The ignition of subsequent cars was triggered by attaining a specified radiant heat flux (10kW/m²) at the car location. The secondary car fires also followed the Joyeux heat release rate data. On the day of the fire very low wind speeds were recorded in the area and hence wind effects were not included in the simulations.

**Scenario 2:**

Car Park of Monica Wills house with ventilation openings rearranged to conform to the configuration recommended by AD B. Other details of the car park, the locations, heat release rate of the burning cars and ignition criteria were as in the first simulation.

The intention was that the only difference between the two simulations would be the distribution of the ventilation openings. The simulations were run up to the time when all the cars in the car park had ignited.

Combustion of the thermal insulation on the ceiling of the car park was not included in the simulations, although the thermal properties were. The material would have added a fire load equivalent to eight additional cars, however burning this additional fuel was not required to achieve fire spread between the cars.

![Figure 2.5.4: External Plume - Iso Surface Containing Flaming Region (Over 300C)](image)
The results of Scenarios 1 and 2 were very similar, all the cars ignited at similar times (within 30-40 seconds) and in a similar sequence. This indicates that under the conditions that prevailed on the day of the fire (low wind), the arrangement of ventilation openings at the Monica Wills car park did not have a significant influence on the development of the fire.

It should be noted that these were not exact simulations of the fire that occurred in the car park of Monica Wills House. There are a large number of random variables in the real event that were impractical to include in these simulations. The assumed heat release rate and ignition criteria for the cars are based on experimental measurements and lead to predictions that are consistent with the actual fire.

The modelling that was conducted using the BRE CFD model JASMINE, based on the findings from this project, supplemented by published information, and tested against the Monica Wills House fire, has led to the development of an effective and practical car fire/fire spread scenario.

2.6 Materials tests

2.6.1 INTRODUCTION AND OBJECTIVES

In a car park scenario where the distance between vehicles in adjacent spaces is typically less than 1 metre there is a realistic risk of fire spread by radiation, convection and direct flame contact (from a liquid fuel or molten plastics pool fire). In the last decade the growing use of plastic components in modern vehicles has increased the potential for sustained flaming and fire spread outside the original source.

The objective of this task was therefore to investigate the burning characteristics of typical exterior car components, and determine their likely contribution to fire spread between cars in a fire scenario.

It was the aim of this work to provide data to identify high risk components, if any, by determining their critical irradiance level for ignition with a pilot source (to represent a
burning ember). The findings would also aid in the selection of vehicles for the subsequent large scale tests and provided data for the modelling of fire spread.

2.6.2 METHOD
A list of external car components was drawn up out of discussions with the BRE project team and input from the Advisory Group, to investigate their burning characteristics and contribution in a fire scenario. Ten samples from this list were chosen for cone calorimetry testing to determine their critical irradiance levels for piloted ignition based on their location, percentage area covered and perceived potential for ignition.

Testing was carried out on a selection of the samples to determine their heat release rate in accordance with ISO 5660:2002 (cone calorimeter) (Ref. 45).

2.6.3 RESULTS
The results of the cone calorimeter tests are summarised in table 2.6.1, below.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Time to ignition (Seconds)</th>
<th>Irradiance level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10kW/m²</td>
<td>20kW/m²</td>
</tr>
<tr>
<td>Hubcap</td>
<td>NI</td>
<td>205</td>
</tr>
<tr>
<td>Mud flap</td>
<td>380</td>
<td>57</td>
</tr>
<tr>
<td>Bumper grill</td>
<td>NI</td>
<td>114</td>
</tr>
<tr>
<td>Fuel tank</td>
<td>NI</td>
<td>354</td>
</tr>
<tr>
<td>Roof box</td>
<td>NI</td>
<td>121</td>
</tr>
<tr>
<td>Wheel arch</td>
<td>NI</td>
<td>81</td>
</tr>
<tr>
<td>Bumper</td>
<td>NI</td>
<td>450</td>
</tr>
<tr>
<td>Bumper trim</td>
<td>415</td>
<td>83</td>
</tr>
<tr>
<td>Mohair soft top</td>
<td>51</td>
<td>28</td>
</tr>
<tr>
<td>PVC soft top</td>
<td>67</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 2.6.1: Time to ignition of sample at multiple irradiance levels

A critical irradiance value was determined for each sample using the method for thermally thin materials described in Drysdale (Ref. 46), see table 2.6.2, below.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Critical Irradiance Level (kW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hubcaps</td>
<td>17.5</td>
</tr>
<tr>
<td>Mud flaps</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2.6.2: Critical Irradiance Level for each sample
Table 2.6.2: Determined Critical Irradiance Levels (based upon a thermally thin assumption).

Additionally, the heat release rate, and hence, total heat release for a selection of the samples at an irradiance of 20 kW/m² are presented in Table 2.6.3, below.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Irradiance Level kWh/m²</th>
<th>Time to Ignition s</th>
<th>Total Heat Release MJ/m²</th>
<th>Peak Rate of Heat Release kW/m²</th>
<th>Average rate heat release kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tyre</td>
<td>20</td>
<td>240</td>
<td>135.2</td>
<td>300.88</td>
<td>86.68</td>
</tr>
<tr>
<td>Tyre</td>
<td>20</td>
<td>249</td>
<td>124</td>
<td>302.69</td>
<td>79.91</td>
</tr>
<tr>
<td>Fuel Tank</td>
<td>20</td>
<td>293</td>
<td>102.2</td>
<td>494.01</td>
<td>177.70</td>
</tr>
<tr>
<td>Fuel Tank</td>
<td>20</td>
<td>294</td>
<td>91.7</td>
<td>525.34</td>
<td>179.90</td>
</tr>
<tr>
<td>Bumper</td>
<td>20</td>
<td>184</td>
<td>94.1</td>
<td>426.94</td>
<td>164.73</td>
</tr>
<tr>
<td>Bumper</td>
<td>20</td>
<td>209</td>
<td>100.2</td>
<td>459.98</td>
<td>161.71</td>
</tr>
<tr>
<td>Soft Top Mohair</td>
<td>20</td>
<td>33</td>
<td>11.5</td>
<td>235.20</td>
<td>79.36</td>
</tr>
<tr>
<td>Soft Top Mohair</td>
<td>20</td>
<td>22</td>
<td>12.2</td>
<td>277.86</td>
<td>90.64</td>
</tr>
<tr>
<td>Soft Top PVC</td>
<td>20</td>
<td>22</td>
<td>6.8</td>
<td>294.74</td>
<td>137.20</td>
</tr>
<tr>
<td>Soft Top PVC</td>
<td>20</td>
<td>22</td>
<td>8.4</td>
<td>291.82</td>
<td>149.35</td>
</tr>
</tbody>
</table>

Table 2.6.3: Heat release results

2.6.4 FINDINGS
The results obtained on the tyre samples show differences with previous data (Ref. 47). Whilst the critical irradiance level of the current sample was similar to those tested previously, a significant increase in peak heat release rate was present.

None of the samples tested were observed to exhibit unexpected burning characteristics. The mohair soft top sample displayed varying results which is attributed to its natural composition and behaviour in the presence of a heat source. The peak mass loss rate of this sample was found to be the highest of all samples tested and it occurred shortly after ignition.

2.6.5 CONCLUSIONS
The two soft top samples had the lowest critical irradiance levels of all tested, i.e. 8kW/m² and 9kW/m². Due to the nature of the materials, PVC and mohair, and their behaviour when exposed to a heat source, it would not take long in a fire for this item to burn away and, hence, for the inside of a vehicle to become exposed, increasing the fire load at an early stage.

In relation to the data comparison between the results obtained for tyres in 1993 and those of this experimental work; while the tyre in this report was approximately 14 years newer than those in the previous test, the data remains valid with regard to the critical irradiance level.

The critical irradiance levels determined for the components tested fell between 8 and 19kW/m². With the distance between cars in a car parks frequently less than 1 metre, there appears to be a significant likelihood of spread of fire to an adjacent vehicle in a car park fire incident once the first vehicle has become fully involved.

2.7 Full-scale test programme; general
All of the cars used in the tests in this research programme were selected solely on the basis of age, size and availability. No cars were selected on the basis of make or model. All cars were to be either less than five years old, or, if older, be of a current model.

None of the findings in this research programme should be taken as suggesting that any particular make or model of car performs better or worse in fire, compared with any other make or model.

The cars used in all of the tests were in full running order (though not necessarily legally roadworthy). The only modification made to any of the cars was that all test vehicles had their air conditioning gas removed. Gas struts, air bags, and other pressurised or pyrotechnic components were left in place.

In all tests, for each car the fuel tank contained 20l of fuel, except for Tests 9a, 9b and 10, where the fuel tank had been driven to “empty”.

Note: only Tests 4, 5 and 6 were allowed to burn out. All other tests were terminated.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Date</th>
<th>Location</th>
<th>Number of cars</th>
<th>Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 Sept. 07</td>
<td>BRE, Garston</td>
<td>3</td>
<td>Car park enclosure, free burning</td>
</tr>
<tr>
<td>2</td>
<td>20 Sept. 07</td>
<td>BRE, Garston</td>
<td>3</td>
<td>Car park enclosure, with sprinklers</td>
</tr>
<tr>
<td>3</td>
<td>27 Sept. 07</td>
<td>BRE, Garston</td>
<td>3</td>
<td>Car park enclosure, free burning, large cars</td>
</tr>
</tbody>
</table>
### TABLE 2.7.1: THE FULL-SCALE FIRE TEST PROGRAMME

<table>
<thead>
<tr>
<th>Year of manufacture</th>
<th>Year of last design revision</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Variant</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>2000</td>
<td>Renault</td>
<td>Laguna</td>
<td>V6 24v</td>
<td>Large hatchback</td>
</tr>
<tr>
<td></td>
<td>1998</td>
<td>Renault</td>
<td>Clio</td>
<td>RXE</td>
<td>Small car</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>Ford</td>
<td>Mondeo</td>
<td>LX TDCI</td>
<td>Large estate</td>
</tr>
<tr>
<td><strong>Test 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>1998</td>
<td>Renault</td>
<td>Grand Espace</td>
<td>RTX</td>
<td>MPV</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>Seat</td>
<td>Ibiza</td>
<td>S</td>
<td>Small car</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>Land Rover</td>
<td>Freelander</td>
<td>1.8i</td>
<td>4x4</td>
</tr>
<tr>
<td><strong>Test 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>1998</td>
<td>Renault</td>
<td>Espace</td>
<td>RT Auto</td>
<td>MPV</td>
</tr>
<tr>
<td></td>
<td>2004</td>
<td>Peugeot</td>
<td>307</td>
<td>SW Hdi</td>
<td>Mid-sized estate</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>Land Rover</td>
<td>Freelander</td>
<td>1.8i</td>
<td>4x4</td>
</tr>
<tr>
<td><strong>Test 4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>2000</td>
<td>Renault</td>
<td>Laguna</td>
<td>1.9 dCi</td>
<td>Large hatchback</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>Seat</td>
<td>Ibiza</td>
<td>1.2 16V</td>
<td>Small car</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>Land Rover</td>
<td>Freelander</td>
<td>1.8i</td>
<td>4x4</td>
</tr>
<tr>
<td></td>
<td>2003</td>
<td>Vauxhall</td>
<td>Vectra</td>
<td>1.8 LPG</td>
<td>Large hatchback</td>
</tr>
<tr>
<td><strong>Test 5</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>2001</td>
<td>Ford</td>
<td>Focus</td>
<td>1.6 LX</td>
<td>Mid-sized hatchback</td>
</tr>
<tr>
<td><strong>Test 6</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>1998</td>
<td>Renault</td>
<td>Espace</td>
<td>Authentique Auto</td>
<td>MPV</td>
</tr>
<tr>
<td><strong>Test 7</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>2001</td>
<td>Ford</td>
<td>Focus</td>
<td>1.6 LX</td>
<td>Mid-sized hatchback</td>
</tr>
<tr>
<td><strong>Test 8</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>1998</td>
<td>Renault</td>
<td>Espace</td>
<td>Authentique Auto</td>
<td>MPV</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>Peugeot</td>
<td>406</td>
<td>GLX</td>
<td>Large estate</td>
</tr>
<tr>
<td><strong>Test 9</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1999</td>
<td>1999</td>
<td>Peugeot</td>
<td>406</td>
<td>LX DT</td>
<td>Large estate</td>
</tr>
<tr>
<td><strong>Test 10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>1998</td>
<td>Renault</td>
<td>Espace</td>
<td>RT Auto</td>
<td>MPV</td>
</tr>
</tbody>
</table>
### TABLE 2.7.2: THE CARS USED IN THE FULL-SCALE FIRE TEST PROGRAMME

As well as the various instrumentation provided for each test, all tests were photographed and recorded on video. Some tests were also recorded using an infra-red (IR) video camera.

2.8 Full-scale tests with heat release rate measurements: introduction

#### 2.8.1 OBJECTIVES

The objectives of this task were to benchmark car fire sizes for a range of vehicle types in a typical car park, determine the spread of fire between cars and the severity (heat release) of car fires and to seek to determine the associated conditions (heat, smoke, toxic gas) to car park occupants exposed to such a fire, under typical conditions.

#### 2.8.2 METHOD

Three large scale fire tests were carried out in a car park test rig under the large calorimeter hood in the BRE Burn Hall, each involving three cars.

For all tests, three cars were located in the test rig, Cars 1 and 2 next to each other in adjacent bays, Car 3 separated by a space (equivalent to an un-used parking bay).

For all of these tests, the fire initiation simulated an arson attack. Car 1 driver’s window and offside passenger window were open (i.e. on the side furthest from Cars 2 and 3). All other car windows were closed. The fire was started using a No. 7 crib (Ref. 48) on the Car 1 driver’s seat.

After each test, destroyed or damaged cars were removed from BRE by a properly certified scrap dealer so that they were disposed in accordance with the appropriate regulations. (Note that some cars were used in more than one test).

All tests were carried out under naturally ventilated conditions.

#### 2.8.3 RIG DESIGN

The test rig was 12m long and 6m wide. The (underside) ceiling height was 2.9m from the floor. The rig comprised a steel frame, with breeze block infill. The roof was of hollow-core concrete slabs. The floor was screeded to 50mm (to allow load cells to be imbedded).

One end was open, but with a 0.5m deep down stand. Ventilation openings were provided along one side and the back wall.

Near one end, a “slot” 1.6m wide ran across the roof to channel the smoke via a deflector into the 9m calorimeter hood.
Figure 2.8.1: Car park test rig plan

Figure 2.8.2: Car park test rig in BRE Burn Hall
2.8.4 INSTRUMENTATION

Instrumentation was similar for all the tests. It comprised three thermocouple columns within the test rig, thermocouples on the roof slabs (above and below), thermocouples within and on the surface of each car (not Test 1). Heat flux meters were located in five positions and gas sampling (CO, CO₂ and O₂) in three locations. The cars were each located on four load cells so that the contribution of each car to the total heat release (as measured by the calorimeter) might be assessed. For Tests 2 and 3, insulated and instrumented (with thermocouples) steel test samples were provided by CORUS. These were suspended from the ceiling to assess the effectiveness of the insulation on the sample.

Fire gases were collected in the 9m hood and analysed for heat release rate.
Smoke production rate (in the collection system) was also monitored. (Results for smoke production rate are given in units of $m^2/s$, and total smoke production in units of $m^2$. See Ref. 49.)

The cars were equipped with thermocouples, the locations of which were tailored to suit the requirements of each test (figure 2.8.4 shows the key to thermocouple locations).

### Figure 2.8.4: Diagram Key of Thermocouple Locations

<table>
<thead>
<tr>
<th>A</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>External Passenger Side Front Footwell</td>
</tr>
<tr>
<td>C</td>
<td>External Passenger Side Rear Footwell</td>
</tr>
<tr>
<td>D</td>
<td>High Internal</td>
</tr>
<tr>
<td>E</td>
<td>Mid Internal</td>
</tr>
<tr>
<td>F</td>
<td>Low Internal</td>
</tr>
<tr>
<td>G</td>
<td>Fuel Tank</td>
</tr>
<tr>
<td>H</td>
<td>Sunroof Two</td>
</tr>
<tr>
<td>I</td>
<td>Engine Compartment</td>
</tr>
<tr>
<td>J</td>
<td>Door Seal</td>
</tr>
<tr>
<td>K</td>
<td>LPG Tank*5</td>
</tr>
<tr>
<td>L</td>
<td>Driver's Door External</td>
</tr>
<tr>
<td>M</td>
<td>Driver's Door Internal Lining</td>
</tr>
<tr>
<td>N</td>
<td>Driver's Door Internal</td>
</tr>
<tr>
<td>O</td>
<td>Driver's Door Internal</td>
</tr>
</tbody>
</table>

2.9 Test 1: Three cars in car park test rig

Test 1 was carried out on 6th September 2007. This was a freely burning test with no sprinklers fitted.

Car 1 was a Renault Laguna (petrol - 2002), Car 2 was a Renault Clio (petrol - 1998) and Car 3 was a Ford Mondeo Estate (diesel - 2003).
2.9.1 OBSERVATIONS AND RESULTS

Following ignition, the fire grew involving Car 1 and burned for 20 minutes at around 2 MW. At this time, the exterior combustible trim and paint on Car 2 ignited. This was followed, a few minutes later, by the breaking of Car 2 windows and immediate full involvement of Car 2, the interior of which had become pre-heated prior to local ignition.

During this stage the fire rapidly increased in intensity, reaching a momentary peak of around 16 MW, with air temperatures in the top of the rig (i.e. beneath the ceiling) reaching 1100°C. Heat fluxes at all measuring locations exceeded 25 kW/m² (i.e. in excess of critical irradiance of most combustible materials).

The severity of the fire, and in particular the temperature of the smoke/ceiling jet, ignited Car 3, which then continued to burn.

The very severe fire then died back for a while before growing again with the contribution of Car 3, at which point the test was terminated.

There was extensive spalling of the concrete roof slabs during this test which added mass to the cars and consequently measurements of mass loss (from the load cells) were not of any value.

Note: for this test, Test 1, the measurements of smoke production (in the duct) were not recorded.
Figure 2.9.2: Test 1 Heat release rate

Figure 2.9.3: Test 1 temperature measurements; thermocouple tree 1
Figure 2.9.4: Test 1 temperature measurements; thermocouple tree 2

Figure 2.9.5: Test 1 temperature measurements; thermocouple tree 3
Figure 2.9.6: Test 1 heat flux measurements

Figure 2.9.7: Test 1 gas concentration measurements
Figure 2.9.8: Test 1 Total heat release

Photograph 2.9.1: Test 1 prior to ignition
Photograph 2.9.2: Test 1, 6 minutes after ignition

Photograph 2.9.3: Test 1, 21 minutes after ignition
Photograph 2.9.4: Test 1 After the test

2.10 Test 2: Three cars in car park test rig with sprinklers

Test 2 (with sprinklers) was carried out on 20th September.

Car 1 was a Renault Grand Espace (petrol - 2000), Car 2 was a Seat Ibiza (petrol - 2002) and Car 3 was a Landrover Freelander (petrol - 2002).

An IR video recorder was used on this test.

Figure 2.10.1: Test 2 instrumentation schematic
The sprinkler system was designed and installed as representative of a system in place in a typical multi-storey/underground car park. The sprinkler system therefore was designed in accordance with BS EN 12845:2004 (Ref. 50) with OH2 classification, 5mm/min and 12m² per head (see Fig. 2.10.2. below).

![Figure 2.10.2: Test 2 sprinkler system schematic](image)

**2.10.1 OBSERVATIONS AND RESULTS**

The fire grew within Car 1 and the nearby sprinklers operated. However, the fire continued to burn and grow, eventually (after 55 minutes) breaking out and reaching a peak of around 7 MW. The first sprinkler actuated after 4 minutes. All six sprinklers eventually operated. However the fire did not spread to Car 2 or Car 3.

After 1 hour from first sprinkler head actuation the water supply was switched off. (This was to represent a tank supplied system holding the minimum recommended quantity of water.) By this time the fire in Car 1 was dying down and, despite the cessation of sprinkler operation, continued to diminish. Soon after this the fire was terminated by the Fire Brigade.

The IR video recorder used on this test proved valuable since the downdrag of the smoke made it otherwise difficult to view the progress of the fire.
Figure 2.10.3: Test 2 Heat release rate

Figure 2.10.4: Test 2 temperature measurements; thermocouple tree 1
Figure 2.10.5: Test 2 temperature measurements; thermocouple tree 2

Figure 2.10.6: Test 2 temperature measurements; thermocouple tree 3
Figure 2.10.7: Test 2 heat flux measurements

Figure 2.10.8: Test 2 temperatures in Car 1
Figure 2.10.9: Test 2 gas concentration measurements

Figure 2.10.10: Test 2 smoke production (measured in duct)
Figure 2.10.11: Test 2 total smoke production (measured in duct)

Figure 2.10.12: Test 2 total heat release (measured in duct)
Figure 2.10.13: Test 2 pump pressure to sprinklers

Table 2.10.1: Test 2 sprinkler water delivery

<table>
<thead>
<tr>
<th>Number of heads</th>
<th>Operation time</th>
<th>Flow rate l/min</th>
<th>Area m²</th>
<th>Delivery mm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4:02</td>
<td>115</td>
<td>12</td>
<td>9.6</td>
</tr>
<tr>
<td>2</td>
<td>4:10</td>
<td>223</td>
<td>24</td>
<td>9.3</td>
</tr>
<tr>
<td>4</td>
<td>42:20 42:42</td>
<td>395 395</td>
<td>48</td>
<td>8.3</td>
</tr>
<tr>
<td>6</td>
<td>45:02 45:26</td>
<td>510 510</td>
<td>72</td>
<td>7.1</td>
</tr>
</tbody>
</table>
Photograph 2.10.2: Test 2, 1 minute 40 seconds after ignition

Photograph 2.10.3: Test 2, 41 minutes 30 seconds after ignition
2.11  **Test 3: Three large cars in car park test rig**

Test 3 (no sprinklers) was carried out on 27\textsuperscript{th} September 2007.

Car 1 was a Renault Espace (petrol - 1998), Car 2 was a Peugeot 307 (diesel - 2004) and Car 3 was a Freelander (petrol – 2002; survived from Test 2).

An IR video recorder was used on this test.
2.11.1 OBSERVATIONS AND RESULTS

Following ignition, the fire grew involving Car 1 and after 4.5 minutes burned for about a further 5 minutes at around 6 MW. This was followed by the full involvement of Car 2, the interior of which had become pre-heated prior to local ignition.

The fire then rapidly increased in intensity, reaching a momentary peak of around 11 MW, with air temperatures in the top of the rig (i.e. beneath the ceiling) reaching over 1000°C. Heat fluxes at all measuring locations achieved or exceeded 25 kW/m² (i.e. in excess of critical irradiance of most combustible materials).

As in Test 1, the severity of the fire, and in particular the temperature of the smoke/ceiling jet, ignited Car 3. The test was then terminated.

Note that some temperature measurement curves show anomalous spikes or discontinuities which are a result of thermocouple faults.
Figure 2.11.2: Test 3 Heat release rate

Figure 2.11.3: Test 3 temperature measurements; thermocouple tree 1
Figure 2.11.4: Test 3 temperature measurements; thermocouple tree 2

Figure 2.11.5: Test 3 temperature measurements; thermocouple tree 3
Figure 2.11.6: Test 3 heat flux measurements

Figure 2.11.7: Test 3 gas concentration measurements
Figure 2.11.8: Test 3 temperatures in Car 1

Figure 2.11.9: Test 3 temperatures in Car 2
Figure 2.11.10: Test 3 temperatures in Car 3

Figure 2.11.11: Test 3 smoke production (measured in duct)
Figure 2.11.12: Test 3 total smoke production

Figure 2.11.13: Test 3 total heat release
Photograph 2.11.1: Test 3 prior to ignition

Photograph 2.11.2: Test 3, 7 minutes 30 seconds after ignition
Photograph 2.11.3: Test 3 After the test

2.12 Test 4: Four cars in car park test rig with LPG

This fire test was conducted at the Health and Safety Laboratory, Buxton, on 3rd April 2008.

The objectives of this task were to determine the behaviour of fires (and explosions; if such were to occur) involving cars fuelled by LPG and to seek to determine the associated effects on an enclosed car park, and adjacent cars, from such a fire.

The test rig used for Tests 1, 2 and 3 was reconstructed on an explosion test pad at HSL Buxton. (See aerial view below). To limit the effects of wind, and due to the exposure of the test site, the layout was a “mirror image” of that in the BRE Burnhall. Only one test was carried out at HSL Buxton. Four cars were used in this test, with no unused spaces between them (unlike Tests 1 to 3, where there was an unused space between cars 2 and 3).

The LPG powered car purchased for this test was a converted Vauxhall Vectra. For the test it had a full tank of LPG. The cars used for this test were a Renault Laguna (2002) (Car 1), the LPG Vauxhall Vectra (2003) (Car 2), a Seat Ibiza (2002) (Car 3) and a Land Rover Freelander (2002) (Car 4).
The four cars were located in the test rig, next to each other in adjacent bays.

Car 1 was a Renault Laguna, Car 2 was a Vauxhall Vectra (converted for LPG), Car 3 was a Seat Ibiza (recovered from Test 2) and Car 4 was a Land Rover Freelander (recovered from Tests 2 and 3).

As in Tests 1, 2 and 3, the fire initiation simulated an arson attack. Car 1 passenger window and near side passenger window were open (i.e. on the side furthest from Cars 2, 3 and 4). All other car windows were closed. Again, the fire was started using a No. 7 crib on the Car 1 passenger's seat.

2.12.1 INSTRUMENTATION
Instrumentation was essentially identical (with some minor variations) for the full scale tests. It comprised two thermocouple columns within the test rig, thermocouples on the roof slabs (above and below), thermocouples within and on the surface of each car. Heat flux meters were located in two positions.

An IR video recorder was used on this test.

2.12.2 FINDINGS AND OBSERVATIONS
As in Tests 1, 2 and 3, following ignition, the fire grew involving Car 1. At 20 minutes 36 seconds, the exterior combustible trim and paint on Car 2 ignited. This was followed by the full involvement of Car 2 over the next 3 to 4 minutes.

The severity of the fire, and in particular the downwards thermal radiation from the smoke/ceiling jet, ignited Car 3 at 23 minutes 02 seconds, and then almost immediately Car 4, at 23 minutes 28 seconds.

The fire then continued to increase in intensity, with air temperatures in the top of the rig (i.e. beneath the ceiling) reaching over 1100°C. Heat fluxes exceeded 100 kW/m² (i.e.}
well in excess of the critical irradiance of most combustible materials) and peaked at 140 kW/m².

The LPG tank did not explode. However, it is evident from the rapid cooling shown by the temperature measurements on the LPG tank that the tank first vented at approximately 34 minutes into the test, and possibly again at around 46 minutes. The test was allowed to burn itself out over a period of about 2½ hours.

There was extensive spalling of the concrete roof slabs during this test.

Note that some temperature measurement curves show anomalous spikes or discontinuities which are a result of thermocouple faults.

Case studies of actual incidents involving exploding LPG vehicles were sought to inform and assist the analysis of the results of this experiment.

Figure 2.12.1: Test 4 instrumentation schematic
Figure 2.12.2: Test 4 temperature measurements; thermocouple tree 1

Figure 2.12.3: Test 4 temperature measurements; thermocouple tree 2
Figure 2.12.4: Test 4 temperature measurements; Car 2 (LPG)

Figure 2.12.5: Test 4 heat flux measurements
Figure 2.12.6: Test 4 LPG tank temperatures

Photograph 2.12.1: Test 4 View of the test rig at HSL Buxton
Photograph 2.12.2: Test 4 View at HSL Buxton back towards the “block house”
Photograph 2.12.3: Test 4 prior to ignition (Note: Land Rover (Car 4) was recovered from Test 3).

Photograph 2.12.4: Test 4 during the test
Photograph 2.12.5: Test 4, 27 minutes 30 seconds after ignition (Note damage to camera lens shield)

Photograph 2.12.6: Test 4 After the test
2.13 Test 5: Single family car, closed interior
This test was conducted on 27th August 2008 in the BRE Burn Hall.

2.13.1 OBJECTIVE AND METHOD
The objective of this test was to examine the time to full development and heat release rate of a fire starting in the passenger compartment of a modern family car, with all windows closed (i.e. with limited air).

The car for this test was a Ford Focus (2001), with all windows closed. The ignition source was a No. 7 crib on the driver’s seat.

The test car was located under a steel roof/ceiling 6m long, 3m wide and 3m high, itself located under the BRE 9m calorimeter hood.

2.13.2 OBSERVATIONS AND RESULTS:
As soon as the crib fire was established, the driver’s door was closed. The fire then grew until flames were visibly touching the ceiling of the car but then died back and after 30 minutes was effectively out. Very little heat escaped from the car interior, see figure 2.13.1.

![Test 5 heat release rate](image)

**Figure 2.13.1:** Test 5 heat release rate
Figure 2.13.2: Test 5 temperatures

Photograph 2.13.1: Test 5 shortly after ignition

2.13.3 DISCUSSION
This test demonstrated that modern small cars are sufficiently well sealed that a fire starting within the passenger compartment is likely to go out through lack of air.

2.14 Test 6: Single MPV, closed interior
This test was conducted on 1st September 2008, in the BRE Burn Hall.

2.14.1 OBJECTIVE AND METHOD
The objective of this test was to examine the time to full development and heat release rate of a fire starting in the passenger compartment of a modern people carrier, with all windows closed (i.e. with limited air).

The car for this test was a Renault Espace (2001), all windows closed. The ignition source was a No. 7 crib on the driver’s seat.

The test car was located under a steel roof/ceiling 6m long, 3m wide and 3m high, itself located under the BRE 9m calorimeter hood.

2.14.2 OBSERVATIONS AND RESULTS
As in the earlier test, as soon as the crib fire was established, the driver’s door was closed. The fire then grew until flames were visibly touching the ceiling of the car but then died back and after 25 minutes was effectively out.

Figure 2.14.1: Test 6 heat release rate

Passenger Compartment Fire- Espace
All channels
2.14.3 DISCUSSION

This test demonstrated that modern large people-carrier types of car are sufficiently well sealed that a fire starting within the passenger compartment is likely to go out through lack of air.

NOTE

In both the above tests (Test 5; family car (Ford Focus), Test 6; MPV (Espace)) the fire went out through lack of air with only a very small amount of interior material consumed. The relatively undamaged state of these cars meant that they were both suitable for use in the immediately following engine fire test. This had the benefit of allowing both the
closed window test and the engine fire test (for each size) to be conducted on (literally) identical cars.

2.15 Test 7: Single family car, engine fire
This test was conducted on 27th August 2008.

2.15.1 OBJECTIVE AND METHOD
The objective of this test was to examine the time to full development and heat release rate of a fire starting (accidentally) in the engine bay of a modern family car.

The car for this test was a Ford Focus (2002), all windows closed. The ignition source was IMS soaked fibre-board in engine compartment. The bonnet was closed after the fire became well established.

The test car was located under a steel roof/ceiling 6m long, 3m wide and 3m high, itself located under the BRE 9m calorimeter hood.

2.15.2 OBSERVATIONS AND RESULTS
The fire slowly developed within the engine compartment, eventually breaking out. Once the windscreen broke, fire was able to spread into the passenger compartment from where the fire grew to around 4.8 MW.

![Graph showing heat release rate](image)

Figure 2.15.1: Test 7 heat release rate
Figure 2.15.2: Test 7 temperatures

Photograph 2.15.1: Test 7 at ignition (bonnet was then closed)
2.15.3 DISCUSSION
This test demonstrated that a fire starting in the engine compartment of a modern small car can grow within the engine compartment and can break through the bulkhead into the passenger compartment where a substantial fire can develop.

The 4.8MW peak is associated with a spillage of fuel.

The development of a fire in this manner can take a number of minutes since the fire initially develops within the confines of the engine compartment.

2.16 Test 8: Single MPV, engine fire
This test was conducted on 1st September 2008.

2.16.1 OBJECTIVE AND METHOD
The objective of this test was to examine the time to full development and heat release rate of a fire starting (accidentally) in the engine bay of a modern people carrier.

The car for this test was a Renault Espace (2001), all windows closed. The ignition source was IMS soaked fibre-board in engine compartment. The bonnet was closed after the fire became well established.

The test car was located under a steel roof/ceiling 6m long, 3m wide and 3m high, itself located under the BRE 9m calorimeter hood.

For this test, another car (a Peugeot 406 (2001)) was located with its front bumper 0.5m from the from the front bumper of the Espace. This additional feature of this test was to examine how readily a car facing a car on fire might be ignited. As soon as this “target” car had ignited it was moved away from the Espace and the local fire extinguished.
Photograph 2.16.1: Test 8 view of the front of the vehicles

2.16.2 OBSERVATIONS AND RESULTS
The fire slowly developed within the engine compartment, eventually breaking out. Once the windscreen broke, fire was able to spread into the passenger compartment from where the fire grew to around 3 MW, with a short peak of 3.5 MW when the fuel tank ruptured.

The nearby car ignited approximately 5 minutes into the test, in part due to thermal radiation, in part due to direct flame impingement (flames jetted from the headlamp sockets of the Espace) and in part from the spread of burning molten plastics.

Note that some temperature measurement curves show anomalous spikes or discontinuities which are a result of thermocouple faults.

Figure 2.16.1: Test 8 heat release rate
Figure 2.16.2: Test 8 temperatures internal

Figure 2.16.3: Test 8 temperatures external
2.16.3 DISCUSSION
This test demonstrated that a fire starting in the engine compartment of a modern large people-carrier type of car can grow within the engine compartment and can break through the bulkhead into the passenger compartment where a substantial fire can develop.

The development of a fire in this manner can take a number of minutes since the fire initial develops within the confines of the engine compartment.

2.17 Test 9a: Single family car, exposed to radiant heat
This test was conducted on 22\(^{nd}\) January 2009.

2.17.1 OBJECTIVE AND METHOD
The objective of this test was to examine the processes of fire spread and the time to full development of a fire developing in a passenger compartment of a modern family car, with windows closed, from a car adjoining another on fire, using a radiant panel.

The test was intended to examine the relative propensities for ignition of each of these exteriors and subsequent mechanism for spread into the passenger compartment and other parts of the vehicle.

The car for this test was a Peugeot 406 (1999), all windows closed.

The BRE radiant panel was brought up to operating temperature. The car was then rolled in front of the panel, at a distance of approximately 30 cm. At this distance the radiant flux on the vehicle was 30 ± 5 kWm².

2.17.2 OBSERVATIONS AND RESULTS
The exterior of the began to steam and then release volatile gases from the exterior trim. Eventually these ignited and burned.

The exposed rear window of the car then shattered, at which point the fire spread into the interior of the car.

The test was then terminated.

The radiant panel became unstable in this test and only a limit amount of data was obtained.

2.17.3 DISCUSSION
Because the radiant panel became unstable in this test only a limit amount of data was obtained.

This test demonstrated that the spread of fire into a car due to radiant heat did not occur as a result of the exterior trim or window seals burning but resulted only once a window failed. At this stage the (hot) interior of the car ignited very readily and burned very quickly.

2.18 Test 9b (Test 9a repeated): Single family car, exposed to radiant heat
This test was conducted on 9 February 2009. It repeated Test 9a (above) since the radiant panel had become unstable in Test 9a.

2.18.1 OBJECTIVE AND METHOD
To examine the processes of fire spread and time to full development of a fire developing in a passenger compartment of a modern family car, with windows closed, from a car adjoining another on fire, using a radiant panel.

The car for this test was the Peugeot 406 (1999), all windows closed, used in Test 9a. For this test the car was heated on its passenger side.

The BRE radiant panel was brought up to operating temperature. The car was then rolled in front of the panel, at a distance of approximately 30 cm. At this distance the radiant flux on the vehicle was 30 ± 5 kWm². After 30 minutes the radiant panel was moved closer to the car and at 45 minutes a flaming “pilot” source was introduced.
2.18.2 OBSERVATIONS AND RESULTS
As before, the exterior of the began to steam and then release volatile gases from the exterior trim. Eventually the wing mirror housing ignited and burned.

The fire eventually spread into the interior of the car via the wing mirror mounting.

The test was then terminated.

![Figure 2.18.1: Test 9b temperatures](image)

2.18.3 DISCUSSION
This test demonstrated that the spread of fire into a car due to radiant heat did not occur as a result of the exterior trim or window seals burning but resulted only once an opening into the car appeared, since the window remained intact.

2.19 Test 10: Single MPV, exposed to radiant heat
This test was conducted on 9 February 2009.

2.19.1 OBJECTIVE AND METHOD
To examine the processes of fire spread and time to full development of a fire developing in a passenger compartment of a modern people carrier, with windows closed, from a car adjoining another on fire, using a radiant panel. In addition to this, the exterior panels of the people carrier are predominantly constructed from glass reinforced polymers, as oppose to the mostly metallic exterior of the family car. The test would examine the relative propensities for ignition of each of these exteriors and subsequent mechanism for spread into the passenger compartment and other parts of the vehicle.

The BRE radiant panel was brought up to operating temperature. The car was then rolled in front of the panel, at a distance of approximately 30 cm. At this distance the radiant flux on the vehicle was $30 \pm 5$ kWm$^{-2}$. 

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2.19.2 OBSERVATIONS AND RESULTS

The car for this test was a Renault Espace (1998), all windows closed.

As before, the exterior of the car began to steam and then release volatile gases from the GRP bodywork and exterior trim. These eventually ignited.

The fire began to burn out without any sign of spread into the interior of the car. After 45 minutes the car window was broken manually and the interior then became involved. The test was then terminated.

Figure 2.19.1: Test 10 temperatures

2.19.3 DISCUSSION

This test demonstrated that the spread of fire into a car due to radiant heat did not occur as a result of the exterior trim or window seals burning but resulted only once an opening into the car appeared, or a window breaking.

2.20 Test 11: Two cars, located on a “stacker” frame

This test was conducted on 22nd January 2009

2.20.1 BACKGROUND

Prior to this task, the experimental programme had, with the full agreement of CLG and the Project Advisory Group, concentrated on “normal” car park layouts; i.e. typical row/column distributions of cars as found in most public car parks.

However, during the course of the programme many correspondents and Advisory Group members indicated serious concerns regarding car “stackers”; usually used in private car parks, this (usually hydraulic) equipment allows two cars to be parked on the “footprint” of a single car; see below.
The possibility of direct fire spread in the third dimension – upwards – was considered to be a possibility which it was believed had never been formally assessed in a laboratory. The effect of this configuration on the development of the fire and on the peak heat release rate was expected to be significant; potentially doubling or trebling the heat release rate. Communities and Local Government provided additional funding for one stacker car fire test.

2.20.2 OBJECTIVES AND METHOD
The objective of this test was to examine the processes of fire spread from the lower car to the upper car, and the time to full development and heat release rate of a fire starting in the passenger compartment of the lower car, with driver’s window open.

The additional test was to examine time to full development, volatile emissions, and heat release rate of a fire developing first in a passenger compartment of the lower car (with windows open) beneath another, upper car (with windows closed).

The lower car was a Land Rover Freelander (2001), driver’s window open, all other windows closed. The upper car was a Peugeot 406 Estate (2001), all windows closed. The ignition source was a No. 7 crib on the lower car driver’s seat.

The two cars used (a Land Rover and a Peugeot 406 Estate) had “survived” the previous tests, though both with minor damage (from a fire performance perspective).

The cars were located on a mock-up stacker, see figure below, located under the BRE 9m hood.

Figure 2.20.2: Test 11 Stacker design

For this test a steel and block work test rig, able to support one car above another, in a typical stacker configuration, was constructed under the BRE 9m hood. The stacker comprised a steel frame with ramps, with the main structural columns protected by blockwork (to prevent collapse). See also below:
Photograph 2.20.2: Test 11 Rig prior to test

The test cars were instrumented with thermocouples, as in earlier tests. Again for this test, a steel roof/ceiling 6m long, 3m wide and 3m high was positioned over the cars under the BRE 9m hood.

2.20.3 OBSERVATIONS AND RESULTS

The fire grew rapidly once started and quickly reached the underside of the car above. Flame entered the wheel arch of the upper car igniting the tyre. The fire developed within the passenger compartment of the lower car while growing in the engine of the upper car. Eventually the fire spread to the passenger compartment of the upper car.

<table>
<thead>
<tr>
<th>A</th>
<th>Upper Bonnet</th>
<th>O</th>
<th>Internal Passenger Side Rear Footwell</th>
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<tr>
<td>B</td>
<td>Lower Bonnet</td>
<td>P</td>
<td>External Passenger Side Front Footwell</td>
</tr>
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<td>C</td>
<td>Front Windscreen</td>
<td>Q</td>
<td>External Passenger Side Rear Footwell</td>
</tr>
<tr>
<td>D</td>
<td>Rear Windscreen</td>
<td>R</td>
<td>High Internal</td>
</tr>
<tr>
<td>E</td>
<td>Roof Upper</td>
<td>S</td>
<td>Mid Internal</td>
</tr>
<tr>
<td>G</td>
<td>Roof Lower</td>
<td>T</td>
<td>Low Internal</td>
</tr>
<tr>
<td>N</td>
<td>Internal Passenger Side Front Footwell</td>
<td>U</td>
<td>Fuel Tank</td>
</tr>
</tbody>
</table>

Figure 2.20.3: Test 11 Locations of thermocouples

Results are shown below:
Figure 2.20.4: Test 11 Heat release rate

Freelander (ignition car) temperature readings

Figure 2.20.5: Test 11 Lower car temperatures

Peugeot (top car) temperature readings

Figure 2.20.6: Test 11 Upper car temperatures
Figure 2.20.6: Test 11 Air temperatures

Figure 2.20.7: Test 11 Smoke production (in the duct)
Figure 2.20.8: Test 11 Total smoke production (in the duct)

Figure 2.20.9: Test 11 Total heat release (in the duct)

Photographs at various stages of the test are shown below.
Photograph 2.20.3: Test 11 Test in progress; 5min 22secs from ignition

Photograph 2.20.4: Test 11 Test in progress; 9min 42secs from ignition

Photograph 2.20.5: Test 11 Test in progress; 10min 10secs from ignition

Photograph 2.20.6: Test 11 Test in progress; 20min 59secs from ignition
2.20.4 DISCUSSION

This test demonstrated that an unsprinklered and fast growing fire in the lower car on a stacker could spread very rapidly to the car above.

These fires were shown to be a particular problem for firefighters.

3 Findings and analysis

3.1 Summary of heat release measurements

<table>
<thead>
<tr>
<th>Test number</th>
<th>Date</th>
<th>Number of cars in the test rig</th>
<th>Peak HRR (MW)</th>
<th>Time to peak HRR (Min)</th>
<th>Time of fire service intervention (Min)</th>
<th>Number of cars burning at peak HRR</th>
<th>HRR at 15 minutes (MW)</th>
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</thead>
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<tr>
<td>1</td>
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<td>3</td>
<td>16</td>
<td>21</td>
<td>24</td>
<td>2 (Note 1)</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
<td>7</td>
<td>55</td>
<td>85</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>27 Sept. 07</td>
<td>3</td>
<td>11</td>
<td>10</td>
<td>10.5</td>
<td>2 (Note 1)</td>
<td>0.1 (Terminated before 15 minutes)</td>
</tr>
<tr>
<td>4</td>
<td>3 April 08</td>
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<td>NA</td>
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<td>4 (Note 2)</td>
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<td>5</td>
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<td>46</td>
<td>1</td>
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<td>2</td>
<td>8.5</td>
<td>12</td>
<td>24.5</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Note 1: In Tests 1 and 3 the fire was terminated by Hertfordshire Fire and Rescue Service on request from BRE before all cars were involved, or fully involved. Note 2: Test 4 burnt out, and Tests 5 and 6 self-extinguished. All other tests were terminated by Hertfordshire Fire and Rescue Service on request from BRE.

TABLE 3.1.1: RESULTS FROM THE FULL-SCALE FIRE TEST PROGRAMME
FIGURE 3.1.1: HEAT RELEASE RATE RESULTS FROM THE FULL-SCALE FIRE TEST PROGRAMME
3.2 Statistics

1. The average number of fires in car parks each year reported by UK fire and rescue services is 258. This represents a very small percentage of all fires in the UK (i.e. 426,200 in 2006 – hence less than 0.1%).

2. Of these fires in car parks, about 50% did not start in a car.

3. Most fires in car parks do not spread (to a car (if the source is not a car) or to another car (if the source is a car)).

4. Most fires are in buildings classified (in the FDR1 form) as a “car park building”. Only 6% occur in “flats”.

5. About 7 people are injured in car park fires each year. (There are very few fatalities; on average less than one per year.)

6. Fires in car parks for which the building is classified as “flats” show an injury rate which is quite high compared with other types of premises. However, fires in car parks for which the building is classified as “car park” show an injury rate which is low compared with other types of premises.

3.3 Car park design

There have been serious concerns regarding car “stackers”; usually used in private car parks. This (usually hydraulic) equipment allows two (or more) cars to be parked on the “footprint” of a single car. The possibility of direct fire spread in the third dimension – upwards – is a possibility which is believed to have not previously been assessed in a laboratory. It was thought that the effect of this configuration on the development of the fire and on the peak heat release rate could be significant; potentially doubling or trebling the heat release rate. The additional test that was carried out on a stacker with two cars showed that, in the absence of any fire suppression, fire would spread very quickly from the lower car to the upper car, developing a very extensive and severe fire which might be expected to readily spread laterally to nearby cars. The test deliberately did not allow for any collapse of the stacker structure due to failure of the hydraulics or due to steel weakening but this might happen in practice. The potential risks from car stackers are clearly a concern. Such innovations also have implications for fire fighters due to the very rapid development of fire in the second car. The complexity of stacker structures may also cause difficulties in the application of fire fighting water.

“Zig zag” fire spread up the full height of a car park would appear to be possible, but there are few actual incidents where this has occurred.

There are designs for timber and/or timber-frame car park constructions. These need to be kept under review, since it is not clear if this is a one-off or a significant trend. Other innovative designs also need to be kept under review. For example, some new car park designs include quite long access tunnels. The design parameters for these are not well founded.

Much of the output from this research programme is of relevance to the structural performance of a car park (and potential structural damage from fire) and should be of interest to stakeholders with concerns other than life safety, such as insurers.
3.4 Car design and types of fuel

This programme has necessarily focussed on vehicles fuelled by petrol and diesel since these form the great majority of cars in England and Wales at present, and are most likely to do so in the immediate and medium term.

There are a variety of new types of cars entering the market place; in particular gas (LPG, CNG), but also electric and hybrid. It is likely that these may form a significant number of vehicles over the next 25 years.

It has not been possible in the current project to examine the fire safety implications of the use of hydrogen as a fuel as these are only currently in very limited use. While (and because) the hazards are evident, hydrogen technology is being developed with safety in mind. There is no evidence to date to suggest that that cars fuelled by hydrogen are likely to be a particular danger in fire. However, these developments need to be monitored. Further work may be required in this area in the future once the technology is more established and in wider use.

This programme has not examined experimentally the fire behaviour of electric or hybrid cars. Information reviewed indicates that the risks from such cars are primarily in fire fighting although their propensity for fire is currently unknown (since there are still so few). Batteries are a particular problem since their fire residues may be corrosive and/or toxic. Increased numbers of such cars might necessitate charging stations in car parks, with new risks.

Despite concerns overseas (e.g. in Belgium, where LPG cars are banned from some car parks) there is very little evidence to show that cars fuelled by LPG are a particular danger in fire. Clearly the pressure relief valve (PRV) must operate properly.

3.5 Fire development

The Monica Wills incident is the most recent incident to demonstrate that fire can spread between cars and that, in extreme cases, very many cars can burn out with a very high heat release rate (and substantial structural damage); the “traditional” view that car fires do not spread was substantively refuted by this incident.

The findings from this project should provide a valuable data resource for car park designers which will support current fire engineering design practice. However, there is no evidence to indicate that the current provisions in AD B for the protection of car parks need revision.

The experimental programme has demonstrated that:

- Where a fire starts in the passenger compartment of a car which is well-ventilated (i.e. open windows), very fast growing and severe fires have resulted, leading readily to fire spread to all nearby cars, and, potentially, all the cars in the car park. This actually occurred at Monica Wills House.

- Where a fire starts in the passenger compartment of a car which is poorly-ventilated (i.e. closed windows), the fire may go out.

- Fires in engine compartments will grow slowly, but spread to involve the whole car.
• Fire spread between cars by radiant heat can be slow. Ignition of exterior trim or body work does not necessarily spread into the car’s interior; some physical failure is needed (such as a breaking window) for the interior to become involved.

• Fire is likely to spread quite quickly to cars with soft tops; however, such cars are relatively few.

• Fire can spread between cars by direct flame contact from spilt fuel or molten plastics.

Recognising the important role of the fire and rescue service, these results largely account for the very few car park fires in the UK which lead to significant fire spread or cause substantial or significant structural damage.

There is the potential for heat-release rates in car park fires to become ventilation controlled, and the implications from this on the design of car parks and the adjoining structure needs consideration.

A fire starting and developing in the lower car in a stacker will spread very quickly to the car above. There is as yet no body of knowledge regarding fires in stackers and it appears likely that fires in car parks involving stackers will be more severe than is typical for those in “normal” car parks.

### 3.6 Fire suppression (sprinklers)

The effectiveness of sprinklers in limiting a fire to a single car has been demonstrated. This supports findings reported verbally by the fire and rescue service.

Sprinklers clearly assist in reducing structural damage. With regards to fire fighting these benefits need to be assessed in relation to cooling and downdrag.

The design parameters for fire suppression of stackers need to be developed.

### 3.7 Detection and alarm

The findings from this project have indicated that the provision of fire detection and alarm systems in certain types of car park (in particular, residential), could be of value, in particular where the other fire protection systems cannot be relied upon. Although quite variable, the growth times of the fires determined in the experimental programme are such that a rapid response by the fire and rescue service can be a benefit. Fire detection and alarm systems would need to be resistant to false activation by car fumes.

### 3.8 Fire resistance

Despite the potential for very severe (high heat release) fires, there need not be substantial structural damage from a car park fire. However, fires which spread to involve more than one car can sometimes result in significant structural damage.

There was extensive spalling of the concrete roof in two of the experimental fires and similar damage has been observed at some of the actual fires investigated (notably; Monica Wills House). As well as the structural damage caused, such spalling can be dangerous for firefighters.

There appears to have been a spate of car park fires involving structural damage in the period 2007 – 2008. This may be a reporting artefact resulting from this research project.
There are no cases to date in the UK of structural collapse of a car park due to fire. BRE is aware of at least two cases from overseas (Gretzenbach, Switzerland 2004; seven firefighter fatalities and Schipol, Netherlands (Ref. 51)).

The fire resistance recommendations for car parks (and associated premises) in AD B (and other guidance; e.g. BS 9999: 2008 (Ref. 52)) need to be kept under review. Fire load data can be derived from the test results and underpinned by the fire growth/fire spread model developed by the computer modelling.

Car parks made of non-traditional materials need special consideration. In addition, the use of timber in car park construction needs to be kept under review. While multi-storey timber car parks are unlikely (since they would not readily conform to the recommendations in AD B), ground floor or basement car parks under timber frame constructions (such as flats) are a possibility. Timber cladding also appears to be becoming popular since it “softens” the usual stark appearance of the building. Similarly, other modern methods of construction and innovative materials need to be kept under review, where used for, or in buildings attached to, car parks.

3.9 Ventilation and smoke control

The need, or otherwise, for revisions to the appropriate air-change and/or ventilation rates for enclosed car parks, have been considered.

The appropriateness of the current guidance in BS 7346-7:2006 (Functional recommendations and calculation methods for smoke and heat control systems for covered car parks (Ref. 7)), in particular with regards to assumed heat release rates and fire spread, have been reviewed in the light of the findings from this programme.

Current methods to calculate ventilation openings for smoke control or smoke clearance from open-sided car parks, and to calculate air quantities for smoke control or smoke clearance from basement or enclosed car parks need to be carefully considered.

It may be that the current values of heat release used for smoke control calculations (i.e. 8MW unsprinklered, 4MW sprinklered etc) may be still appropriate since the purpose of a smoke control system is to protect occupants while they make their way to a place of safety and any smoke control system is required to operate for only a limited period of time.

In two actual incidents there was substantial fire spread up the exterior of the building above a semi-basement car park, which, in the case of Monica Wills House, resulted in a fatality. Designers should consider the implications of external fire spread from car parks where the flames may impinge on a building above.

Note, however, the need to distinguish between smoke control and ventilation as used for different purposes under the Building Regulations. Smoke control may be provided to safeguard the escape of occupants (and, for example, provide an opportunity for extended travel distances). Alternatively, ventilation may be provided to reducing the fire resistance needs and/or assist in fire fighting by smoke clearance. These systems will have different design parameters.
3.10 Fire fighting

The implications for fire fighters (and Regulation B5 of the Building Regulations) from innovative designs of car parks need to be kept under review. For example, some new car park designs include quite long access tunnels. The fire fighting issues associated with stackers need to be considered separately since there is no history yet to call upon.

Running fires, where burning fuel spills from the tank of a hot burning or burnt vehicle, are difficult to extinguish with water. In these cases, powder appears to be a better medium.

4 Conclusions

4.1 General conclusions

Over the three years of the programme, a very large quantity of data, photographs and video footage has been acquired. In the report it is possible to present only a selected limited amount of the data collected.

The data presented here is intended to be of value to designers, fire engineers, computer modellers and enforcers, involved in the design of car parks and the fire safety provisions that are appropriate.

The key issues affecting car park design and fire safety have been identified. The programme of research tasks, including the full-scale fire tests, has achieved all of the objectives.

The ease with which a car fire in a car park might spread to nearby cars has been demonstrated. Once a very severe fire has developed, fire will spread to other cars separated by an un-filled parking bay.

In this situation, where a number of cars are burning simultaneously, the fire is exacerbated by heat-feedback and heat release rates in excess of 16 MW might be achieved from two or three cars. In Test 1 the initial car fire, Car 1, burned at around 2 MW for about 20 minutes and it was only then that Car 2 became involved (although Car 3 then ignited very soon after). However in Test 3, all three cars were burning after around 10 minutes. In Test 4 (Buxton – LPG), Car 2 was alight after 21 minutes and all four cars were burning after around 23 minutes. In Test 8, an engine fire test with a nearby car “nose to nose” the fire spread to the second car within 5 minutes. In Test 10, the stacker test, the fire spread up to involve the second car within 6 minutes and fully involve it within 9 minutes.

The ventilation limitations on such a fire in an enclosed car park result in a very hot ceiling jet, which spreads the fire to nearby cars with the dominant mechanism of heat transfer being radiation from the flames and hot gas layer, but with some direct flame contact. There were only a limited number of cars in each of the tests (a maximum of four); however escalation to many cars within a specific proximity in an actual car park must be expected under these conditions. Computer modelling has been employed to examine these larger scenarios.

Gas temperatures in the enclosed rig (beneath parts of the ceiling) reached 1100°C in all the enclosure tests, exceeding 1200°C briefly in Test 4.

The LPG tank did not explode in Test 4 since the pressure relief valve provided with the LPG tank appeared to work effectively even in quite a severe multi-car fire; this is
consistent with reports from actual fire incidents involving LPG. The evidence does not support any need for special car parking conditions for cars powered by LPG.

The potential benefits of sprinklers in preventing (or delaying) fire spread between cars have been demonstrated, but also their limitations with regards to the impact on the severity of the fire in the initiating car.

The additional tests have demonstrated that a fire in a sealed (i.e. windows closed) passenger compartment is unlikely to develop. It may be presumed that most cars left in public car parks will have their windows closed. It has also been demonstrated that engine compartment fires can spread to involve the whole vehicle, but that such a development requires an extended time-scale and, most probably as a result, the peak heat release rate is somewhat reduced compared with a freely burning, well-ventilated, passenger compartment fire. It has been demonstrated that cars, in general, are quite resistant to fire spread due to radiant heat (although soft-top vehicles will be an exception). These findings provide evidence that accounts for the very few multiple-car car park fires that occur in the UK, and also demonstrates the effectiveness of the fire and rescue service.

The fire statistics have been analysed. Many fires in car parks start in materials other than cars and indicate the need for good management and “housekeeping”. While there are very few reported fatalities, findings show that fires in car parks associated with flats are causing far more injuries than fires in purpose-built car parks.

The findings from this work should support the standards referred to by AD B, specifically BS 7346-7; 2006 Components for smoke and heat control systems – Part 7: Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered parking areas for cars. Similarly, the findings from this research, in particular the “raw” experimental results, will provide a data resource for the fire safety engineering of car parks.

The modelling that was conducted using the BRE CFD model JASMINE, based on the findings from this project, supplemented by published information, and tested against the Monica Wills House fire, has led to the development of an effective and practical car fire/fire spread scenario.

5 References


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<tr>
<th>Name</th>
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Dan Dynes  Laboratory support.
Bob Mallows  Video.
Louise Jackman  Sprinkler system.
Eric Michaelis  Sprinkler system.

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Appendix A – Summary of the Research

Disclaimer: The cars used in the tests in this research programme were selected solely on the basis of age, size and availability. No cars were selected on the basis of make or model. All cars were to be either less than five years old, or, if older, be of a current model.

None of the findings in this research programme should be taken as suggesting that any particular make or model of car performs better or worse in fire, compared with any other make or model.

In 2006 Communities and Local Government (CLG) Sustainable Buildings Division commissioned BRE to carry out a three year project titled Fire Spread in Car Parks.

The existing guidance for fire safety in car parks in England and Wales is in Approved Document B (Fire safety) to the Building Regulations in England and Wales (AD B) (Ref. 1). The basis for this guidance for fire safety strategies in car parks relates to fire initiation and fire growth involving cars whose designs are decades old. There has been increasing concern about the consequences of fires in car parks associated with modern car design (e.g. plastic fuel tanks) and how these fires may spread to other vehicles parked adjacent and nearby. This concern has been heightened by the entry into the market place of cars powered by alternative fuels such as LPG.

Fires in car parks are rare, and, although there have been few deaths or injuries recorded to date in the UK, there are concerns regarding new and emerging risks from modern cars and alternative fuels. There was a need to gather up-to-date information on fires involving cars in car parks in order that the current fire safety guidance could be reviewed and, if necessary, updated.

The overall aim of the project has therefore been to gather information on the nature of fires involving the current design of cars and to use this new knowledge as a basis, if necessary, for updating current guidance in AD B (and possibly other Approved Documents) on fire safety strategies for car parks.

This project has been concerned with fire spread in enclosed car parks. The car parks being studied were those that fall under the England and Wales Building Regulations (Ref. 2), and include open-sided car parks, fully enclosed car parks, and basement car parks.

The programme of work included the following tasks:

ESTABLISH AN ADVISORY GROUP.

The first task was the identification and engagement of stakeholders, and the selection of a representative group to advise the project, and to organise a conference and produce articles about the project.

DATA COLLECTION AND LITERATURE REVIEW.

This work comprised “desktop studies” and involved collecting and analysing information and data on the identified topics. Over 200 items were reviewed, mostly from the UK but many from overseas. Topics reviewed included:
• car design, trends in car design, new fuels (in particular, bio-fuels), electric and hybrid vehicles,
• Car park design, and trends in car park design;
• Case studies of car fires; and
• Relevant research.

A review of the UK fire statistics has been carried out, for the 12 years 1994 to 2005 (the most recent year for which data was available to BRE) (Ref. 3).

In the 12 year period studied there were 3096 fires reported in car parks in buildings. Of these, 1592 started in a vehicle (i.e. 1504 were not in a vehicle). The average number of vehicle fires in buildings over the period is 248 per year. However, the number of vehicle fires per year shows an overall (but not consistent) decline, with 400 in 1994 but only 120 in 2005.

Most fires (68%) occur in buildings reported as “car park buildings”. 6% occur in “flats”. Most injuries from fires in car parks occur in car park buildings (45%), followed by flats (26%); 6% of fires are causing 26% of the injuries (flats) while 68% of the fires are causing only 45% of the injuries (car parks). It follows that fires in flats are the most dangerous.

MODELLING STUDY – SMOKE SPREAD IN ENCLOSED CAR PARKS

CFD modelling has been used at various stages throughout the project to guide the research, assess findings and validate current methodologies.

EXPERIMENTAL STUDY – FIRE BEHAVIOUR OF MATERIALS

The objective of this task was to determine the critical exposure conditions, e.g. intensity and duration of incident thermal radiation, for a range of external materials used on typical road vehicles, which has assisted determining the spread of fire between cars.

Testing was carried out on a selection of the samples to determine their heat release rate in accordance with ISO 5660:2002 (cone calorimeter) (Ref. 4). A critical irradiance value was determined for each sample using the method described in Drysdale (Ref. 5). It was assumed that the specimens tested were thermally thin. The critical irradiance levels determined for the components tested fell between 8 and 19kW/m².

EXPERIMENTAL STUDY – FIRE SPREAD BETWEEN CARS

The cars used in all of the tests were in full running order (though not necessarily legally roadworthy). The only modification made to any of the cars was that all test vehicles had their air conditioning gas removed). Gas struts, air bags, and other pressurised or pyrotechnic components were left in place. For most tests each car the fuel tank contained 20l of fuel.

The objectives of this task were to benchmark car fire sizes for a range of vehicle types, determine the spread of fire between cars and the severity (heat release) of car fires and to seek to determine the associated conditions (heat, smoke, toxic gas) to car park occupants exposed to such a fire, under typical conditions.

Three large scale fire tests were carried out in a car park test rig under the large calorimeter hood in the BRE Burn Hall, each involving three cars.
For all tests, three cars were located in the test rig, Cars 1 and 2 next to each other in adjacent bays, Car 3 separated by a space (equivalent to an un-used parking bay). For all of these tests, the fire initiation simulated an arson attack. Car 1 driver’s window and offside passenger window were open (i.e. on the side furthest from Cars 2 and 3). All other car windows were closed. The fire was started using a No. 7 crib (Ref. 6) on the Car 1 driver’s seat.

The test rig was 12m long and 6m wide. The (underside) ceiling height was 2.9m from the floor. It comprised a steel frame, with breeze block infill. The roof was of hollow-core concrete slabs. One end was open, but with a 0.5m deep down stand. Ventilation openings were provided along one side and the back wall.

Instrumentation was essentially identical (with some minor variations) for all the full scale tests. It primarily comprised two thermocouple columns within the test rig, thermocouples on the roof slabs (above and below), and thermocouples within and on the surface of each car (not Test 1). Heat flux meters were located in five positions and gas sampling (CO, CO₂ and O₂) in one location. Fire gases were collected in the 9m hood and analysed for heat release rate.

Three tests were carried out: Test 1 was a freely burning test with no sprinklers fitted.

![Test 1]

Photograph 3: Test 1 21 minutes after ignition

Test 2 was a similar test to Test 1 but included a sprinkler system. Test 3 was a repeat of Test 1 buy with larger vehicles.

Heat release rate measurements for all the relevant tests are shown below.

EXPERIMENTAL STUDY – BURNING BEHAVIOUR OF CARS FUELLED BY LPG

The objectives of this task were to determine the behaviour of fires (and explosions; if such were to occur) involving cars fuelled by LPG and to seek to determine the associated effects on an enclosed car park, and adjacent cars, from such a fire.

Due to the risk of an explosion, the large scale fire test was carried out in a car park test rig at the Health and Safety Laboratory (HSL), Buxton, involving four cars. Instrumentation comprised two thermocouple columns within the test rig, thermocouples on the roof slabs (above and below), and thermocouples within and on the surface of each car. Heat flux meters were located in five positions.
The LPG tank did not explode. Case studies of actual incidents involving exploding LPG vehicles were sought to inform and assist the analysis of the results of this experiment.

ANALYSIS

The analysis was intended to examine the findings from all of the tasks to seek to resolve the following issues:

The severity of car fires in modern car design, potential for spread and fire size; benchmarking car fire size given a range of vehicle types

- The combustion products and likely survivability of such fires
- The potential hazards arising from fuel leakage/spillage in unventilated/underground/enclosed car parks.

Additional hazards arising from cars designed to utilise alternative fuel(s); the potential explosion effects of cars powered by alternative fuels, or other risks of cars powered by hybrid systems, e.g. using a diesel or petrol engine primary power supply, with a secondary power supply using batteries.

The need, or otherwise, for different considerations for underground, enclosed and open-sided car parks.

SINGLE CAR TESTS

Seven tests in all were carried out, on single cars. The objectives and findings of this task were as follows:

To examine the time to full development and heat release rate of a fire starting in the passenger compartment of a modern family car and a people carrier, with windows closed (i.e. with limited air). These tests demonstrated that modern cars are sufficiently well sealed that a fire starting within the passenger compartment is likely to go out through lack of air.

To examine the time to full development and heat release rate of a fire starting in the engine bay of a modern family car and a people carrier (with the bonnets closed). These tests demonstrated that a fire starting in the engine compartment of a modern car can grow within the engine compartment and can break through the bulkhead into the passenger compartment where a substantial fire can develop.

To examine the processes of fire spread and the time to full development of a fire developing in a passenger compartment of a modern car, with windows closed, from a car adjoining another on fire, using a radiant panel.

STACKER TEST

The objective of this test was to examine the processes of fire spread from the lower car to the upper car on a "stacker", and the time to full development and heat release rate of the fire, starting in the passenger compartment of the lower car with driver’s window open.

For this test a steel and block work test rig, able to support one car above another, in a typical stacker configuration, was constructed under the BRE 9m hood.
Photograph 5: Test 11 Test in progress; 10min 10secs from ignition

Findings and conclusions

The key issues affecting car park design and fire safety have been identified. The programme of research tasks, including the full-scale fire tests, has achieved all of the objectives.

The ease with which a car fire in a car park might spread to nearby cars has been demonstrated. Once a very severe fire has developed, ignition will occur even to cars separated by an un-filled parking bay.

In this situation, where a number of cars are burning simultaneously, the fire is exacerbated by heat-feedback and heat release rates in excess of 16 MW might be achieved from two or three cars. In Test 1 the initial car fire, Car 1, burned at around 2 MW for about 20 minutes and it was only then that Car 2 became involved (although Car 3 then ignited very soon after). However in Test 3, all three cars were burning after around 10 minutes. In Test 4 (Buxton – LPG), Car 2 was alight after 21 minutes and all four cars were burning after around 23 minutes.
In Test 8, an engine fire test with a nearby car “nose to nose” the fire spread to the second car within 5 minutes.

In Test 10, the stacker test, the fire spread up to involve the second car within 6 minutes and fully involve it within 9 minutes.

The ventilation limitations on such a fire in an enclosed car park result in a very hot ceiling jet, which spreads the fire to nearby cars with the dominant mechanism of heat transfer being radiation from the flames and hot gas layer. There were only a limited number of cars in each of these tests (a maximum of four); however escalation to many cars within a specific proximity in an actual car park must be expected under these conditions. Computer modelling has been employed to examine these larger scenarios.

Gas temperatures in the enclosed rig (beneath parts of the ceiling) reached 1100°C in all tests, exceeding 1200°C briefly in Test 4.

The LPG tank did not explode in Test 4 since the pressure relief valve provided with the LPG tank appeared to work effectively even in quite a severe multi-car fire. This is consistent with reports from actual fire incidents involving LPG.

The potential use of computer modelling in predicting the spread of fire and smoke in car parks has been demonstrated.

The potential benefits of sprinklers in preventing (or delaying) fire spread between cars have been demonstrated (in Test 2), but also their limitations with regards to the impact on the severity of the fire in the initiating car.

The additional tests have demonstrated that a fire in a sealed (i.e. windows closed) passenger compartment is unlikely to develop. It may be presumed that most cars left in public car parks will have their windows closed. It has also been demonstrated that engine compartment fires can spread to involve the whole vehicle, but that such a development requires an extended time-scale and, most probably as a result, the peak heat release rate is somewhat reduced compared with a freely burning, well-ventilated, passenger compartment fire.

The fire statistics have been analysed. While there are very few reported fatalities, findings show that fires in car parks associated with flats are causing far more injuries (per thousand fires) than fires in purpose-built car parks.

The findings from this work should be available to feed into standards referred to by AD B, specifically BS 7346-7; 2006 Components for smoke and heat control systems – Part 7: Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered parking areas for cars (Ref. 7). Similarly, the findings from this research, in particular the “raw” experimental results, will provide a data resource for the fire safety engineering of car parks.

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